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Cluster observations of ULF waves with pulsating electron beams above the high latitude dusk-side auroral region

M. Morooka,[1] M. André,[1] J.-E. Wahlund,[1] S. C. Buchert,[1] A. N. Fazakerley,[2]
J. D. Winningham,[3] H. Rème,[4] I. Dandouras,[4] B. Lavraud,[4] A. Balogh,[5] and K. Igenbergs[1]

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[1] We report observations by the four Cluster satellites of particle acceleration associated with ULF (Alfvén) waves at an altitude of $6R_E$ above the dusk-side auroral region. All satellites observed upward accelerated ions and upgoing electron beams, which coincided with the upward field-aligned current around the plasmasheet boundary region. Here we study in detail one region of Alfvénic ULF waves observed together with upward electron beams, both having a quasi-periodicity of about 2 minutes. The ULF waves have a downward Poynting flux. Comparing data from different spacecraft, the observed electron beams are likely caused by the ULF waves in localized (0.5° latitude extension) flux tubes in the plasmasheet boundary region. The high-energy keV plasmasheet dispersive ion signatures showed similar periodicity, which suggests that the generation region of the ULF Alfvén waves is near the magnetospheric flank, and in turn induce time-varying particle energization. *INDEX TERMS:* 2764 Magnetospheric Physics: Plasma sheet; 2712 Magnetospheric Physics: Electric fields (2411); 2704 Magnetospheric Physics: Auroral phenomena (2407). **Citation:** Morooka, M., et al. (2004), Cluster observations of ULF waves with pulsating electron beams above the high latitude dusk-side auroral region, *Geophys. Res. Lett.*, *31*, L05804, doi:10.1029/2003GL017714.

1. Introduction

[2] Upward field aligned currents above discrete aurora [*Kamide et al.*, 1979], have been studied as the main energy source for auroral particle acceleration. However, recent studies around the high latitude plasmasheet boundary region indicate that ULF electro-magnetic (Alfvén) waves with large Poynting flux are important for the auroral phenomena [*Toivanen et al.*, 2001; *Wygant et al.*, 2003; *Keiling et al.*, 2003]. Kinetic Alfvén waves are one possible mechanism for auroral particle accelerations [e.g., *Nosé et al.*, 1998; *Wahlund et al.*, 2003].

[3] The four CLUSTER satellites [*Escoubet et al.*, 1997, and reference therein] have orbits passing above the classical auroral acceleration region at altitudes of 4–6 R_E. These orbits allow for detailed studies of the auroral region over long observation times. We present observations of a high latitude dusk-side auroral event made by the four Cluster spacecraft. In this event, the electric and magnetic field measurements showed quasi-periodic Poynting flux of ULF waves simultaneously with electron energization with the same periodicity. From the time difference of the observations between the spacecrafts it is inferred that the process is likely caused by the ULF waves within finite flux tubes. We discuss possible mechanisms to generate the periodic electromagnetic perturbations and their relationship to the auroral particle acceleration processes.

2. Observations

[4] During 01:30–04:00 UT, June 2001, the four Cluster spacecraft pass above the dusk-side auroral region in the southern hemisphere at altitudes of 5–7 R_E. Figure 1 shows the summary of this event obtained from S/C-1. The spacecraft goes through the high latitude auroral region between 01:50–02:34 UT, 18 MLT and 78–82 ILAT (marked with vertical lines) from higher to lower latitude. Panel a shows energy-time H^+ spectrogram data obtained by CIS/CODIF. Inverted-V like structured up-flowing ions are observed within the event region. Pitch angle data of the low energy (10–1000 eV) ions (panel b) indicates that the ion population is upgoing from the ionosphere. The electric field obtained by EFW (panel e and h) shows large bipolar electric field structures associated with ion beams (panel a). The magnitude of the potential change over the bipolar structure and the energy of the ion beams are comparable. For example, the bipolar electric field structure at 01:56 UT has a potential of ~1000 V along the spacecraft orbit, and the energy of the associated ion beam is ~1000 eV. These signatures indicate that a upward parallel electric field exists below the spacecraft. Positive slope of the eastward magnetic field (panel i) implies that Cluster crosses a region of roughly east-west aligned upward field-aligned current region. The coexistence of the upward parallel electric fields and the upward field-aligned current is consistent with the classical observation [e.g., *Kamide et al.*, 1979]. In addition, it is noticed that the magnetic field has disturbances from 01:50 UT.

[5] During the time interval 01:50–02:34 UT, we find that the electrons are also accelerated upward periodically and this correlates with periodic electric and magnetic perturbations. The upward energy flux of electrons (Figure 1, panel c) shows several spikes during 01:50–02:34 UT. These electrons have typical parameters (energy about tens to few hundreds eV, and density of ~0.1 cm^{-3}) for the electrons originating from ionosphere. Such coexistence of the upgoing electrons and ions cannot be explained by a simple static upward electric field below the observation point. The upward electron beams often have periodic

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[1] Swedish Institute for Space Physics, Uppsala, Sweden.

[2] Dept. of Physics, Mullard Space Science Laboratory, Univ. College, London, United Kingdom.

[3] Southwest Research Institute, San Antonio, Texas, USA.

[4] CESR/CNRS, Toulouse Cedex 4, France.

[5] Space and Atmospheric Physics Group, The Blackett Laboratory, Imperial College, London, United Kingdom.

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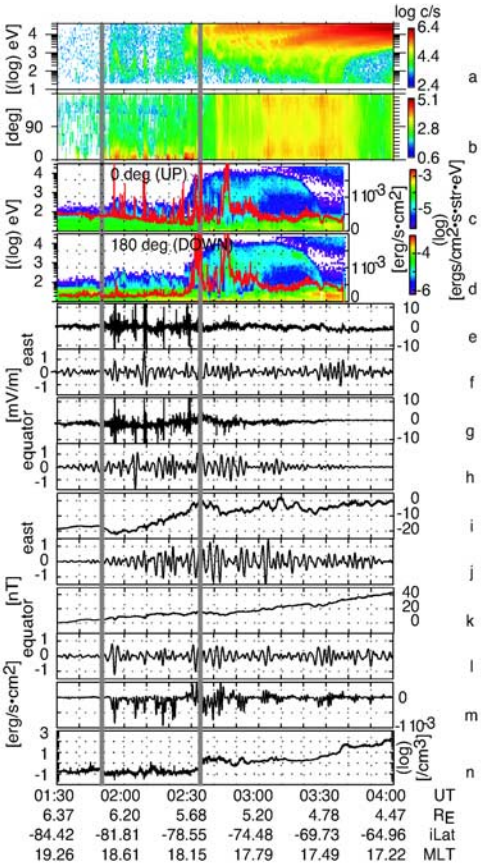

Figure 1. Summary of event 2001–06–20 obtained by Cluster s/c-1 in the southern hemisphere. a: Energy spectrogram of H^+. (Sum of the whole pitch angle) b: Pitch angle spectrogram of low energy (10–1000 eV) component of H^+. Ion data were taken by CIS/CODIF. c,d: Energy flux of electron by PEACE. (red line indicates the integrated energy flux). e–h: Perpendicular component of electric field data by EFW (e and f are raw data, f and h are band-passed with [5–10 mHz]). i–l: Perpendicular component of magnetic field data by FGM (i and k are deviation from the IGRF01 model, j and l are band-passed with [5–10 mHz]) m: Poynting flux derived from f, h, j, and l. Sign of minus indicates the earthward. n: Density derived from the spacecraft potential. To determine the field-aligned coordinate, zero magnitude of the electric field ($E \cdot B = 0$) is assumed. The parallel component of the magnetic field perturbation was less than 0.1 nT in this event (not shown).

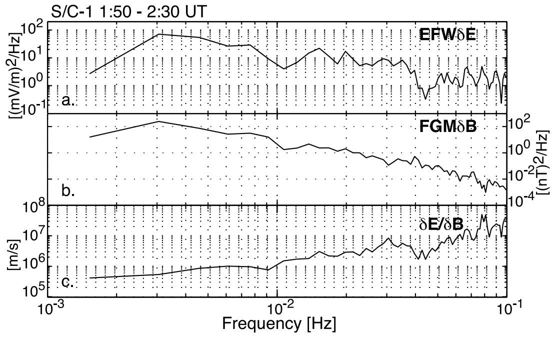

Figure 2. Power spectral density plot of electric field (a), magnetic field (b) and E/B ratio (c) of S/C-1 during the period of 01:50–02:30 UT.

structures. As indicated above, the magnetic and electric field also show variations during this event with a quasi-periodicity of ~2 minutes (panel e, g, i, and k). Band-pass filtered (5 mHz–10 mHz) electric and magnetic fields (panel f, h, j, and l) show that the disturbances start at 01:50 UT. Figure 2 shows spectrogram of the electric field and magnetic fields during the period of 01:50–2:30 UT. A spectral peak around 7.5 mHz (period of about 2.2 min) can be seen in both electric and magnetic field. The Poynting flux of these waves (panel m) is significantly toward the Earth during 01:50–02:30 UT, where the upward electron beams (panel c) are observed. However, a clear one-to-one correlation between the Poynting flux and electron beams is not easily be detectable. The Poynting flux shows that the wave energy ($\approx 8 \cdot 10^{-7}$ W/m^2), can supply the necessary energy to produce the electron beams ($\approx 7 \cdot 10^{-7}$ W/m^2 in panel b) below the observation altitude.

[6] Correlated fluctuations of electric field and magnetic field are interpreted either as due to field-aligned current structures or due to Alfvén waves [*Gurnett et al.*, 1984]. We interpreted the electromagnetic observations as ULF Alfvén waves, since the observed E/B-ratio ($\approx 10^6$ m/s, in Figure 2, c) approximately equals the Alfvén speed ($\approx 10^6$ m/s) using the parameter of the plasma density (≈ 0.1 cm^{-3}) estimated by the spacecraft potential and total magnetic field strength ($\approx 10^5$ nT). In this case, Alfvén conductivity ($\Sigma_A = (\mu_0 V_A)^{-1}$) of the ULF waves corresponds to ≈ 0.8 mho, which is smaller than the Pedersen conductivity ($\Sigma_P \approx$ few mho). The observed E/B-ratio is consistent with Alfvén waves above at least 4 mHz.

[7] Figure 3 shows the magnetic fields and the orbit in iLAT-MLT plane of three spacecrafts during 01:50–02:50 UT. Similar positive slope of the eastward magnetic field can be seen for black (S/C-1), red (S/C-2), and blue (S/

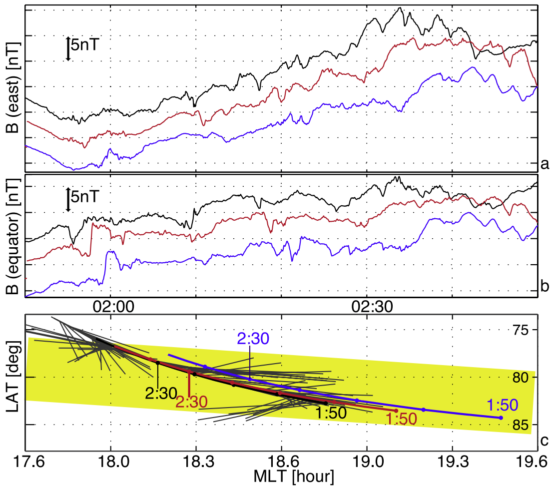

Figure 3. Magnetic field (deviation from the IGRF01 model) for three spacecrafts (a and b) and description of the current sheet structure in iLat-MLT plane. Colors indicate spacecraft identity (1:black, 2:red, 4:blue). Black vectors indicate the current sheet alignment estimated from the magnetic field data of S/C-1. Thick yellow line describes the expected current sheet location.

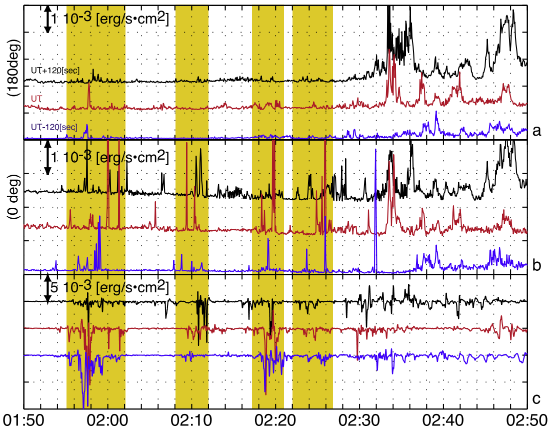

Figure 4. Energy flux of earthward and upward electrons (panel a and b) and Poynting flux of the ULF waves (panel c) for S/C-1, 2, and 4, during 01:50–02:50 UT. S/C-1 and 4 are time shifted in +120 sec and −120 sec, respectively.

C-4) lines. Black vectors on panel c represent alignment of the large-scale current sheet derived from panel a and b (using filtered data below 1 mHz). As a result, the upward field aligned current sheet was aligned approximately east-west direction as depicted by the yellow shaded area in panel c, and the three spacecraft pass through the current sheet structure with time a differences of 1–2 minutes.

[8] Figure 4 presents the energy flux of downgoing (panel a) and upgoing (panel b) electrons and the Poynting flux (panel c) obtained by S/C-1, 2 and 4. The time for S/C-1 and 4 is shifted 2 minutes and −2 minutes respectively, in order to correct for the slope of the large-scale current sheet (in Figure 3). During 01:50–02:40 UT, the three spacecraft often observe similar structures of strong Poynting flux (yellow hatched areas). The upward energy flux of electrons also coincides with the region of downward Poynting flux structures. The electric and magnetic field perturbations have been interpreted as ULF wave from the E/B-ratio, however, the similar variability of the Poynting flux and electron acceleration signatures suggest that the electron energization occurs in specific regions. The lack of one-to-one correlation between the Poynting flux and electron beams can be explained if there is a small angle between the propagation direction of the waves and the magnetic field. One-to-one correspondence would be also missed when there are upward electric fields below the observation point. The similarity in periodicity between the fields and particles indicate that the ULF emissions are related to the energization of the electrons in the auroral region.

[9] Upward electron beams and upward ions have often observed by low altitudes spacecrafts, and explained both as temporal [*Hultqvist et al.*, 1988] and spatial [*Marklund et al.*, 1997] signatures. *Marklund et al.* [1997] suggested that upgoing ions and electrons are observed when the auroral arcs consist of several positive and negative potential structures. Observed electric and magnetic field disturbances can in principle be explained as such structures, but structures do not cause a downward Poynting flux (Figure 1 panel b and c). The upgoing electron beams are sometimes observed coincident with upgoing ion beams, which agrees with the idea of the particle acceleration by Alfvén waves as suggested by *Hultqvist et al.* [1988]. Therefore, the upgoing electrons seem to be accelerated by the Alfvén waves within a region ~0.5 degrees thick.

[10] We expect that the generation mechanisms of the ULF waves relate to the LLBL and flank-side plasmasheet boundary. According to *Tsyganenko-96* magnetic field model [*Tsyganenko and Stern*, 1996], the magnetic field of the observed region was connected to the dusk flank-side magnetosphere. Particle data also indicate that the acceleration region is on field lines connecting to the plasmasheet boundary or LLBL. High-energy (~10 keV) dispersive ion injections, which is detected from ~02:30 UT (Figure 1, panels a and b), must have originated from the plasmasheet boundary or LLBL [*Newell and Meng*, 1992]. Before 01:50 UT, the spacecraft had to be located outside the plasmasheet, since no ions can be observed. The electron signatures (Figure 1, panels c and d) show two different regions. During 01:50–02:30 UT, low-energy (several tens of eV) and low-density (~10^4 m^{-3}) precipitating electrons are observed. We interpret that these electrons originate mostly from the lobe region.. Plasmasheet high-energy (several hundreds of eV to several keV) electrons are observed from ~02:30 UT. Between 01:50–02:30 UT we expect that the spacecraft were on field lines connected to the LLBL region or the plasmasheet boundary region; same as indicated by the magnetic field model.

[11] Observations of the dayside aurora [e.g., *Rostoker and Boström*, 1976] often implied a dynamic boundary region possibly driven by Kelvin-Helmholtz instability in the LLBL [e.g., *Potemra et al.*, 1990], or by temporal solar wind injections in the magnetosphere [e.g., *Woch and Lundin*, 1993]. These are the most reasonable candidates for the generation of the observed ULF waves. In this event, we noticed that the high-energy ion dispersion phenomena are periodic as well during 02:30–02:50 UT (Figure 1, panel a). The ion injections recurred every ~2 minutes. K-H instabilities driven in the magnetosphere flank region can therefore be a source of the observed ULF waves. The periodic dispersive ion signature can also be explained by recursive reconnection at the tail flank region. ULF waves with a period of 2 minutes associated with aurora at around the plasmasheet boundary region have recently been reported [*Toivanen et al.*, 2001; *Wygant et al.*, 2003], and discussed in connection with a substorm onset and magnetic reconnection. It resembles our observations in that such ULF wave activity often occurs at the higher latitude plasmasheet boundary region, where a density gradient exist. In their observations, higher frequency Alfvén waves coincided with the two minutes Alfvén waves. Within the acceleration region in our observations, the electric field data also showed higher frequency broadband activity associated with the ULF waves (Figure 1, panel e and g).

[12] If they are related to the reconnection process, as suggested by *Wygant et al.* [2003], then there are two other possible explanations for the periodic particle acceleration within ULF waves. The solar wind perturbations may induce the reconnection at the flank-side of the magnetosphere, or reconnection in the boundary region can be induced by magnetic pulsations in the inner parts of the magnetosphere.

[13] Note, the ULF waves were observed during whole interval of 01:50–04:00 UT, but upward electron and ion acceleration were observed only during 01:50–02:30 UT

when the density was low (Figure 1, panel n). At the low altitudes where the acceleration occurs, the ULF Alfvén waves are probably inertial and wave dissipation is most efficient when the $k_\perp^2 \lambda_e^2 \geq 1$, or for low densities given a $k_\perp$ [e.g., *Stasiewicz et al.*, 2000].

3. Summary

[14] Auroral particle acceleration in the dusk-side auroral region has been investigated using data from the four Cluster spacecraft. All satellites observed upward accelerated ions and electrons at an altitude of a few R_E.

[15] During the event we study in detail Alfvén (ULF) waves with a downward Poynting flux and a quasi-periodicity of about 2 minutes (7.5 mHz), which were observed together with upward electron beams with the same periodicity. The downward energy flux of the waves is large enough to power the upward electron beams. We have compared the Poynting flux and energy flux of electrons of three different spacecrafts, and concluded that the electrons are likely to be accelerated by the Alfvén waves within finite (0.5°) flux tubes. The temporal variations are interpreted as Alfvén waves since the observed E/B-ratio approximately equals the Alfvén speed. On the other hand, observations by three spacecraft indicate several enhanced Poynting flux regions.

[16] These Alfvén waves also include broadband emissions at higher frequencies. Similar ULF waves have been observed in the nightside plasmasheet region in connection with a substorm onset.

[17] Comparing the auroral particle acceleration and the associated electric fields with the magnetospheric background particle populations and the magnetic field model, shows that the auroral acceleration is located around the boundary of the plasmasheet as indicated by the density variation, i.e., close to the boundary between open and closed field lines.

[18] We expect that the following scenario is possible to explain our observations. ULF Alfvén waves are generated at the magnetosphere flank with a quasi-periodicity of about 2 minutes. The Alfvén wave emissions propagate and carry energy toward Earth. At Cluster observations altitudes the ULF waves are associated with higher frequency broadband waves. The Alfvén wave energy can be transferred to field-aligned acceleration of ions and electrons around the boundary between open and closed field lines.

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M. André, S. C. Buchert, K. Igenbergs, M. Morooka, and J.-E. Wahlund, Swedish Institute for Space Physics, Uppsala, Sweden. (morooka@irfu.se)

A. Balogh, Space and Atmospheric Physics Group, The Blackett Laboratory, Imperial College, Prince Consort Road, London, SW7 2BZ, United Kingdom.

H. Rème, I. Dandouras, and B. Lavraud, CESR/CNRS, 9 Avenue du Colonel Roche, B. P. 4346, F-31028 Toulouse Cedex 4, France.

A. N. Fazakerley, Dept. of Physics, Mullard Space Science Laboratory, Univ. College, London, London, United Kingdom.

J. D. Winningham, Southwest Research Institute, P. O. Drawer 28510, 6220 Culebra Road, San Antonio, TX 78238-0510, USA.