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What high altitude observations tell us about the auroral acceleration: A cluster/DMSP conjunction

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[1] Magnetic conjugate observations by Cluster and DMSP F14 satellites are used to study the field lines of auroral arc. Cluster is well above the acceleration region and observes upward keV ion beams and bipolar electric structures. The integrated potential at Cluster altitudes shows a dip that is consistent with the keV electron acceleration energy at low altitude. The earthward Poynting flux at Cluster altitudes is comparable to the electron energy flux at low altitudes. Thus, for this event the auroral acceleration can be described as a quasi-stationary potential structure with equipotential lines reaching the Cluster altitudes. The arc forms at the outer edge of the plasma sheet at a density gradient. Multiple Cluster satellite measurements allow us to study the density increase associated with the development of the arc, and to estimate the velocity of the structure. The quasi-potential structure itself may be part of an Alfvén wave. *INDEX TERMS:* 2704 Magnetospheric Physics: Auroral phenomena (2407). **Citation:** Vaivads, A., et al., What high altitude observations tell us about the auroral acceleration: A Cluster/DMSP conjunction, *Geophys. Res. Lett.*, *30*(3), 1106, doi:10.1029/2002GL016006, 2003.

1. Introduction

[2] Discrete auroral arcs, identified as inverted-Vs in the electron spectrograms of low altitude satellites, are formed by precipitating electrons that have been accelerated by parallel electric fields at altitudes of ~4,000–11,000 km. It has been shown that the lower part of the acceleration region (~4000 km altitude) in most cases can be described as an electrostatic potential structure [*McFadden et al.*, 1998]. In a recent case study the electrostatic nature of the acceleration region up to altitudes of $\sim 4 R_E$ has been demonstrated on field lines associated with downward current *Marklund et al.* [2001]. However, there are no studies up to date to indicate that the electrostatic potential description is reasonable for the auroral field lines of upward current regions at altitudes well above the acceleration region. It is still not clear where the equipotential lines close or where the potential description breaks down. The suggested models include U-, S-, and O- potentials or a combination of those [*Mozer and Hull*, 2001; *Janhunen and Olsson*, 2000]. Additional suggestions that parallel fields are formed by Alfvén waves imply that the parallel field is a combination of an electrostatic and inductive part [*Seyler et al.*, 1995]. However, there are numerical simulations that, by including nonlinear effects, suggest that the inductive part of the acceleration fields created by driven Alfvén waves can be small in comparison to the electrostatic part [*Rönnmark and Hamrin*, 2000]. For the quasi-static acceleration model, the linearized Knight's relation $j = K\phi$ between the current j and the voltage ϕ with the proportionality coefficient $K = e^2 n/\sqrt{2\pi m_e kT}$ depending on the source plasma density n and temperature T is often assumed. Many studies have checked this relation from indirectly derived source plasma parameters, but there are no previous examples where directly observed parameters are used. Whether the acceleration of the auroral particles is accomplished by a quasi-static potential structure or by Alfvén waves, the energy transport towards the acceleration region is given by the Poynting flux. It is generally assumed that the generator is in the outer magnetosphere. However, in such models as the O-shaped potential, the generator is located close above the acceleration region and the question what drives the generator is open [*Janhunen and Olsson*, 2000].

2. Conjugate Observations

[3] On 28 April 2001, 1915–1918 UT Cluster and DMSP F14 made conjunctive observations above a quiet time, AE < 250 nT, auroral arc. The conjunction is in the southern hemisphere at ~20 MLT. Cluster is crossing the auroral field lines at 4.7 R_E geocentric distance well above the main acceleration region. F14 is at ~850 km altitude which is well below the acceleration region. Figure 1a shows the footpoints of the Cluster and F14 satellites using the Tsyganenko model. The geomagnetic longitude of the Cluster spacecraft at the auroral field line crossing differs from that of the F14 by 1.5–3 degrees (~40–80 km at the ionosphere). Figure 1b shows the relative times and positions of the Cluster spacecraft with respect to the current sheet of the aurora estimated. The current sheet direction is estimated using minimum variance method and is approximately the same for s/c 2,3 and 4 (on s/c 1 an identification of the current sheet direction was impossible). The local velocity of the current sheet along the satellite orbit, in the fixed reference frame, is estimated to be ~4 km/s in the direction opposite to the satellite motion. That is the arc is moving poleward during a few minutes when all four Cluster spacecraft cross it.

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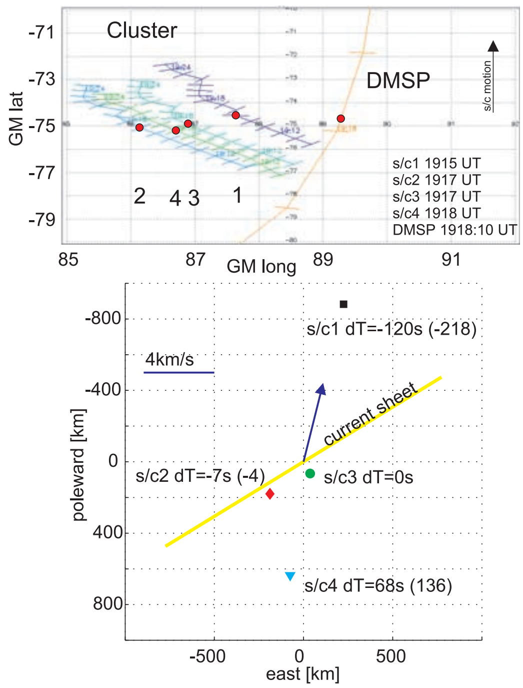

Figure 1. (a) Spacecraft magnetic footpoints in GM coordinates. The times when the spacecraft cross the field lines of the aurora are given in the figure and marked by red circles. The spacecraft move equatorward and every minute is marked by a tick. (b) The location of the Cluster spacecraft in a plane perpendicular to the local geomagnetic field. The yellow line represents the current sheet of the aurora (s/c 3). At each spacecraft is given the time difference of crossing the current sheet with respect to s/c 3, in parenthesis the expected time difference for a stationary current sheet. The blue line shows the velocity vector of the spacecraft.

[4] Figure 2 shows F14 data from the auroral zone crossing. Region I and II currents are marked. F14 observes inverted-V type electron precipitation with maximum acceleration energy of ~3kV at 1918:12 UT. According to ion data, Figure 2c, the aurora is located at the outer edge of the plasma sheet. The duration of the inverted-V is ~3 s corresponding to an auroral width of about 15–25 km in the ionosphere (Figure 2d). Assuming an isotropic downgoing electron distribution, the pitch angle data is not available, we obtain an electron energy flux with a peak value of ~20 mW/m^2 (projected to the ionosphere), Figure 2e. The electron energy spectrum from within the arc is consistent with ~3kV potential drop (Figure 2f). The integrated electron energy flux across the arc is ~180 W/m (per meter in the direction of constant geomagnetic latitude). Despite uncertainties (imperfect conjunction, imperfect mapping, electron isotropy assumption, temporal variations), we still can compare these values with the Cluster data.

[5] We use data from the EFW (electric field E), FGM (magnetic field B), CIS (ion) and PEACE (electron) instruments on the four satellite Cluster mission [*Escoubet et al.*, 1997 and references therein]. Figure 3 shows observations of the auroral zone crossing by s/c 3 (s/c 4 has a marginally better conjunction, obtains similar observations, but has a small data gap.). Figure 3a shows the magnetic field disturbance. Figure 3b shows that the aurora is a narrow structure, seen as a potential dip at ~1917 UT, within a larger region of convection reversal. Figure 3c shows approximately the source-cone population of electrons. The region around the field lines of auroral acceleration is characterized by an electron population with a thermal energy less than 100 eV while on the auroral field lines it is above 100 eV; this can be a signature that a small acceleration field of ~100 V is located above Cluster so that source electrons have been accelerated and heated. Figure 3c also shows electron energy flux along the ambient magnetic field. Inside the arc it reaches maximum values of ~0.05 mW/m^2 (~5 mW/m^2 at the ionosphere) and the integrated value across the arc is ~10 W/m in the ionosphere. The flux of loss-cone electrons, Figure 3d, significantly decreases within the arc, while shows beams of a few hundred eV outside the auroral field lines. The ion data in Figures 3e and 3f show that, in accordance with F14 data, the aurora is located on the outer edge of the several keV plasma sheet ion population. On the auroral field lines Cluster observes ~2 keV upward oxygen beam (pitch angle information not shown), that is slightly lower than ~3 keV predicted from electric field measurements. However, this in good agreement with earlier observations that distribution functions associated to ion beams peak at energies below the acceleration potential. The energy carried by ions along the auroral field lines is less than 0.005 mW/m^2 (data not shown) which is considerably less than the energy carried by electrons.

[6] Figure 4 shows 2 min of data around the crossing of the auroral field lines. The time scale of s/c 1,2,4 have

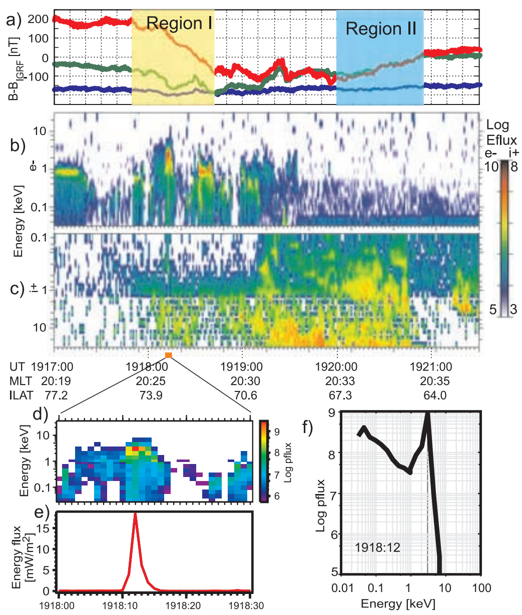

Figure 2. DMSP F14 observations. (a) Magnetic field with IGRF model subtracted. Components are approximately: red eastward, green poleward, blue upward. (b,c) electron and ion spectrograms. 30 s of data around the auroral arc, (d) electron spectra and (e) electron energy flux projected to ionosphere. (f) electron number flux spectra from inside the inverted-V event.

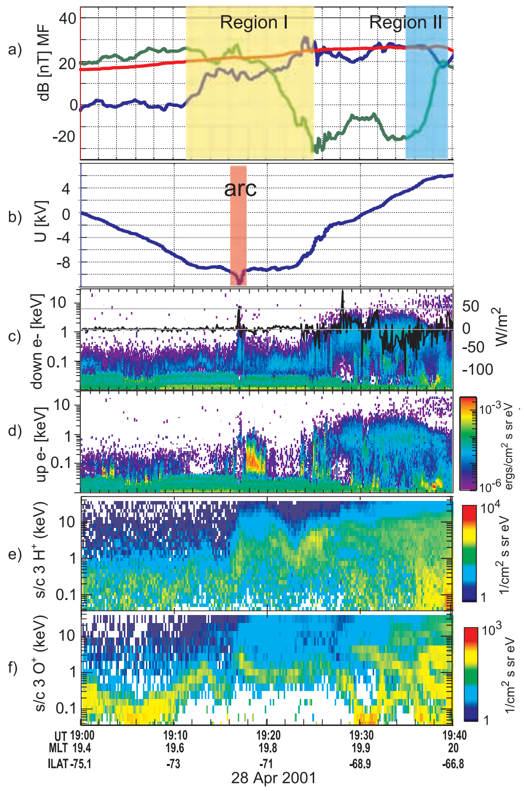

Figure 3. Overview plot of s/c 3 data. (a) Magnetic field disturbance dB, subtracting the Tsyganeko 89 model, in field aligned coordinates. The approximate directions are — green eastward, blue poleward, red field-aligned. (b) Potential integrating E along the satellite orbit. To obtain full E from EFW spin plane measurements we assume that $E_{\|} = 0$. (c, d) Spectrograms of electrons propagating parallel and antiparallel to B. (c) line plot shows integrated electron energy flux, labels are on the right side. (e, f) H^+ and O^+ spectrograms integrated over all pitch angles.

been shifted by 120, 7 and −68 s respectively so that the observations of the auroral field lines are aligned. Figures 4a–4d show that the bipolar structures associated with the arc have similar orientation for s/c 2,3,4 while s/c 1 is different. From magnetic field data it was also impossible to identify a clear current sheet orientation for s/c 1. Thus a simple plane or stationary current sheet is probably a bad approximation for s/c 1. The density estimates from the satellite potential depends on the electron density and in a less extent on the electron temperature in Figure 4e agree reasonably well with the density obtained from the ion instrument (not shown). One can see that the plasma density on the low latitude side of the aurora ∼0.3–0.4 cm^{-3} is about two times larger than on the high latitude side ∼0.2 cm^{-3}. Thus the aurora is located at the density gradient. S/c 2,3,4 observe a doubling of the density to ∼0.6–0.8 cm^{-3} on the auroral field lines. Figure 4f shows that the integrated potential has a dip at s/c 2,3,4 of ∼3–4 kV which is consistent with the ∼3 keV electron acceleration seen by F14. The potential at s/c 1 has a different form probably because of the non-planar or non-stationary current sheet at that time. The Poynting flux, shown in Figure 4g, is mainly earthward. The physical interpretation of the absolute value of Poynting flux requires caution. Figure 4h shows the integrated Poynting flux. The values of integrated Poynting flux depend on which background field model is used to calculate dB. However, for such a short period as 2 min the main difference originates from a constant offset in dB. If we choose the integration interval such that the integral of E is approximately zero over this interval, then the integrated Poynting flux will not depend on such an offset. For s/c 2 and 3 such an interval corresponds to the interval covering the whole bipolar electric field structure of the aurora while for s/c 4, partially because of the data gap, such an interval would cover most but not all of the bipolar structure (the ends of these intervals are marked by dots in Figure 4h). Thus, for s/c 4 one would most probably underestimate by ∼20% the integrated energy flux associated to the aurora. For s/c 1 such an interval seems not possible to find. The obtained energy flux values for s/c 2,3,4 are ∼80 W/m, ∼155 W/m and ∼115 W/m (per meter in the direction of constant geomagnetic latitude at the height of ionosphere). The uncertainties are

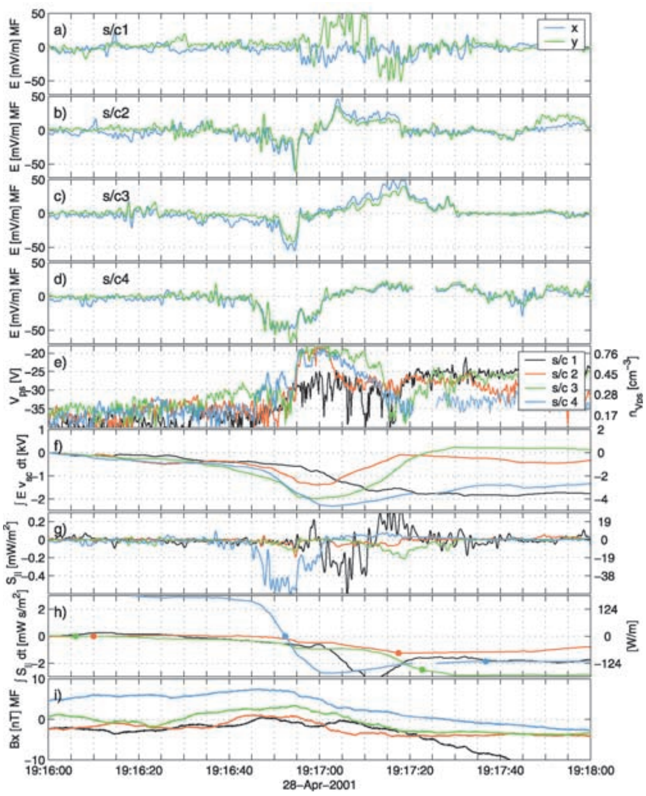

Figure 4. 2 min overview plot from all four s/c. The data have been low-pass filtered at 1 Hz. (a–d) E in mean field coordinates, x is poleward and y is eastward. (e) Probe to spacecraft potential and derived density estimate. (f) integrated potential, the labels on the right show values if the arc motion is taken into account. (g) Field-aligned Poynting flux calculated from total E and dB. (h) integrated Poynting flux, it is set to zero at the beginning of the interval, marked by dots, that is used to estimate the total integrated energy flux. For (g) and (h) labels on the right show values at the ionosphere. (i) Poleward component of dB in field aligned coordinates.

of the order 50%, related to mapping, magnetic field models and the choice of integration interval.

3. Results and Discussion

[7] The arc we study in detail appears at the density gradient corresponding to the outer edge of the plasma sheet ion population. This location at a gradient should not be surprising and is consistent with, for example, observations of strong large scale Alfvén waves at the plasma sheet boundary [*Wygant et al.*, 2000]. It is interesting to note that according to the Tsyganenko 96 and 2001 magnetic field models the auroral field lines map to some boundary layer at low latitudes not far from the magnetopause, $X_{GSE} \sim 0-10\ R_E$.

[8] Using data from the four Cluster satellites we have estimated the speed and planarity of an auroral arc, and the temporal evolution of parameters such as integrated potential and integrated Poynting flux. The potential dips and the energies of upgoing ions observed at Cluster altitudes give values of the parallel acceleration potential in good agreement with those derived from auroral electrons as seen by the low altitude DMSP spacecraft. This supports a scenario where the acceleration region during this event can be described by an U-potential model with equipotential lines reaching geocentric distances larger than ~4.7 Re.

[9] We check, to our knowledge for the first time, whether the parallel acceleration potential is consistent with the linearized Knight's relation $j = K\phi$ by using direct measurements of the source plasma (plasma at Cluster location is assumed to be the source plasma for the acceleration region below). Note that the linearized version of the Knight's relation neglects ionospheric contribution to the current. Using observations in the middle of the arc (s/c 2,3,4 give similar results) data from the electron instrument, see Figure 4 of *Wahlund et al.* [2002], show that maximum values of the current inside the arc are $\sim 6-10\ \mu A/m^2$, which agrees well with estimates from magnetic field perturbations. For the density values $\sim 0.8\ cm^{-3}$ and electron temperatures of ~150 eV we obtain $K \sim 1.7\ 10^{-9} S/m^2$ and an acceleration potential of ~3.5–6 kV. This is in a reasonable agreement with observed potential values.

[10] Both for acceleration by a quasi-static potential structure, and by an Alfvén wave, it is the Poynting flux that carries the energy to the acceleration region. We have shown that the measured energy flux carried by the Poynting flux most probably feeds the auroral electron acceleration. The integrated Poynting flux values at Cluster were in the interval 70–150 W/m (projected to the ionosphere) which can be compared with the estimate of the electron precipitation from DMSP of ~180 W/m. The energy carried by electrons and ions at Cluster altitudes is small and cannot supply the energy required for auroral acceleration in this case. This is consistent with an U-shaped potential, but not with an O-shaped potential closing below Cluster.

[11] An interesting feature that was observed is the density increase on the field lines of the auroral arc. It appears only on Cluster s/c 2,3,4 and is most likely associated with outflowing ions of ionospheric origin. While at low altitudes the auroral arc is associated with a density cavity, at high altitudes the ionospheric population removed from the cavity can, on time-scales of a few minutes, increase the density.

[12] Can the acceleration region be formed by an Alfvén wave? An estimate of E/B from Figure 4 gives values of $\sim 10^4$ km/s which is in a reasonable agreement with the local Alfvén velocity. This is consistent with some kind of Alfvén wave, but at first this idea seems to contradict our earlier discussion concerning the potential character of the acceleration region. However, the period of the Alfvén wave should be at least several minutes since on a scale of one minute s/c 2,3,4 observe the same phase of the wave. Accumulative effects of the inductive parallel electric field are important only on scales that are a significant part of the parallel wave length. Using local plasma parameters at Cluster altitude, a wavelength of more than 100 R_E is obtained. In reality the wave is damped on a scale of ~1 R_E and therefore the role of inductive fields should be insignificant. Thus, probably we have an Alfvén wave that for altitudes below Cluster can safely be regarded as a potential structure. And as our observations show, most of the Alfvén wave energy is converted into acceleration of electrons. The observed electron acceleration and sharp changes in E, resemble observations and simulations of solitary Alfvén waves at low altitude by [*Seyler et al.*, 1995]. Cluster observations of broadband ELF emissions during this event and their importance for energy transport and their possible relation to the formation of the potential drop are discussed by [*Wahlund et al.*, 2002].

[13] **Acknowledgments.** The DMSP particle detectors were designed by Dave Hardy of AFRL, and data obtained from JHU/APL. We thank Dave Hardy and Fred Rich for its use.

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