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# A magnetospheric generator driving ion and electron acceleration and electric currents in a discrete auroral arc observed by Cluster and DMSP

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[1] Simultaneous observations on April 28, 2001 by Cluster and DMSP-F14 reveal a stable discrete auroral arc and fluxes of field-aligned accelerated electrons and ions coincident with a magnetospheric plasma interface at an altitude of 4.5 $R_E$ in the dusk sector. We compare satellite data with a quasi-stationary magnetosphere-ionosphere coupling model based on a Vlasov solution for the magnetospheric generator. The model provides a self-consistent magnetospheric electric potential matching the Cluster observations. The ionospheric potential is derived from the current continuity equation and gives a field-aligned potential drop and a flux of precipitating energy in agreement with the DMSP data. Model results and data analysis suggest a quasi-stationary field-aligned acceleration of auroral electrons and ions with a magnetospheric generator. We associate the generator with the convergent perpendicular electric field at the interface of the plasma sheet boundary layer with the lobe or at the inner edge of the low latitude boundary layer. **Citation:** Echim, M. M., R. Maggiolo, M. Roth, and J. De Keyser (2009), A magnetospheric generator driving ion and electron acceleration and electric currents in a discrete auroral arc observed by Cluster and DMSP, *Geophys. Res. Lett.*, *36*, L12111, doi:10.1029/2009GL038343.

## 1. Introduction

[2] Magnetic conjunctions between the Cluster and DMSP satellites contribute new data on the acceleration of auroral electrons, the formation of discrete auroral arcs and their spatial scales. A very interesting example is the conjunction on April 28, 2001 analyzed by *Vaivads et al.* [2003] who suggest a number of open questions: (i) What can Cluster observations tell us about the generator of the auroral arc observed by DMSP? (ii) Which are the physical mechanisms determining the electrostatic potential and the plasma density observed by Cluster? and (iii) How can one link the spatial scale of the plasma interface crossed by Cluster to that of the discrete arc observed by DMSP?

[3] Experimental and theoretical studies show that quasi-static potential drops can explain most of the characteristics observed for precipitating electrons and up-going ions in discrete auroral arcs [e.g., *Mozer*, 1980; *Schriver et al.*, 2003]. Magnetospheric generators with stationary convergent electric fields sustain field-aligned potential drops and large-scale inverted-V events as shown in studies by *Chiu and Cornwall* [1980] and *Lyons* [1980]. Magnetospheric tangential discontinuities generate convergent E-fields with scales typical for discrete auroral arcs [*Roth et al.*, 1993; *Echim et al.*, 2008]. Observations from Cluster above the acceleration region reveal intense perpendicular, convergent and/or divergent electric fields at the interface between different plasma regimes [*Johansson et al.*, 2007]. In this paper we show that the observations during the Cluster-DMSP F14 conjunction can be explained by a stationary field-aligned potential drop sustained by the convergent perpendicular electric field generated by kinetic pressure gradients and velocity shears of a magnetospheric tangential discontinuity.

## 2. Data Analysis and Model Results

[4] Between 19:15 UT and 19:18 UT on April 28, 2001, the Cluster spacecraft recorded data at about 4.5 $R_E$ altitude, in conjunction with DMSP–F14 at 850 km altitude above the Southern Hemisphere auroral oval, in the 20 MLT sector. The magnetic footpoints of the five satellites map in a band between $-74°$ and $-76°$ in latitude and between 84° and 90° in longitude, as shown in Figure 1 (top). The Cluster spacecraft cross, from higher to lower latitudes, a magnetospheric interface at the dusk magnetospheric side, separating plasmas with different densities and temperatures (Figures 1a–1c). A minimum variance analysis of magnetic and electric field (not shown) gives a ratio between the normal component and the total magnetic field equal to $B_n/|B| = 0.02$ and well separated eigenvalues, suggesting that the transition is a tangential discontinuity (TD). The structure is stable for several minutes and is detected on field lines that map not far from the magnetopause [*Vaivads et al.*, 2003].

[5] An up-going 2 to 3 keV $O^+$ population is detected by Cluster in the central region of the TD (Figure 1a). The relative times of crossings between the Cluster spacecraft reveal that the structure has a velocity of the order of 3 km/s along its normal, in the GSE frame. The Cluster observations discussed below are determined by taking into account this motion (potential, field-aligned currents and distance to TD). The ion number density increases from 0.1 $cm^{-3}$ at the left hand side of the TD, to 0.35 $cm^{-3}$ at the right hand side, to reach a maximum of 0.6 $cm^{-3}$ at the center. The spatial scale of the density peak ranges from roughly 200 km (Cluster 4) to 350 km (Cluster 3, see Figure 1f). After transformation in the moving TD frame of the Cluster E-field measurements [*Gustafsson et al.*, 2001], the electric potential in that frame shows a dip of about 3 kilovolt in the center of the transition (see Figure 1d). Cluster magnetic field data [*Balogh et al.*, 2001] reveal an upward current

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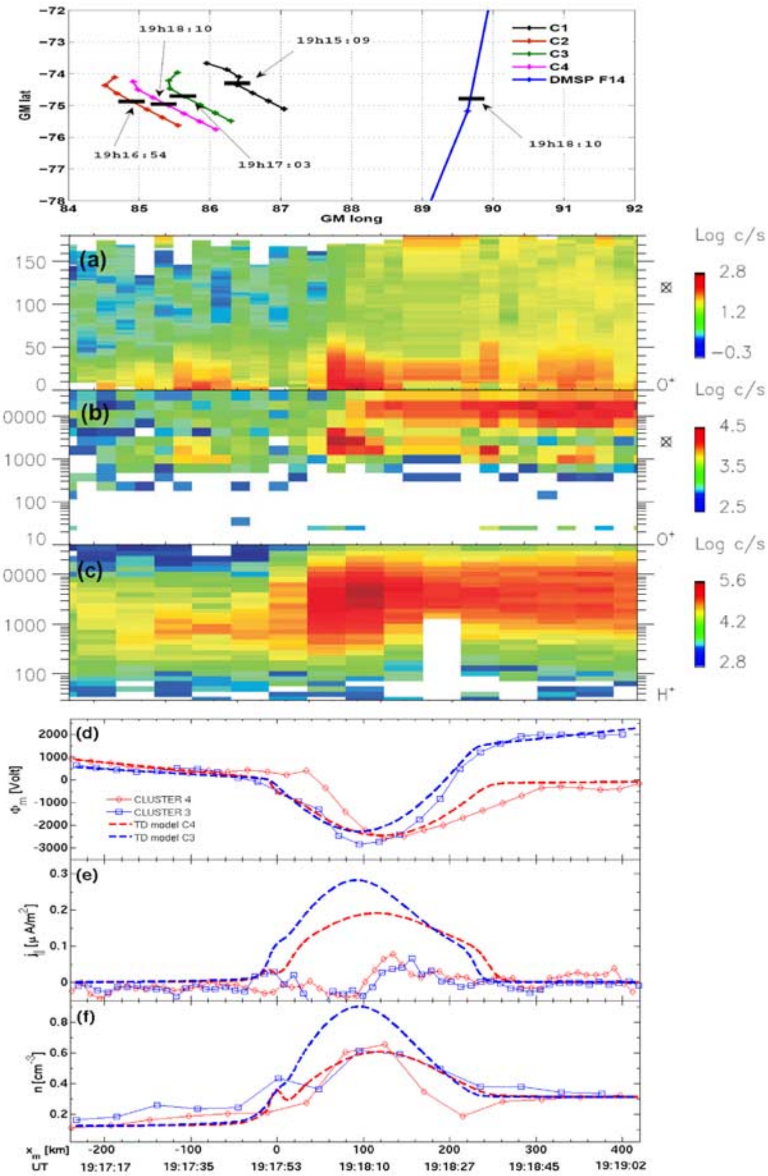


**Figure 1.** (top) Magnetic footpoints in geomagnetic coordinates of Cluster and DMSP. (a) Pitch angle distribution of $O^+$ ions, from Cluster 4 CIS [*Rème et al.*, 2001]; (b) $O^+$ and (c) $H^+$ energy spectrum from Cluster 4; (d) electrostatic potential, (e) field-aligned current density, positive for upward current, (f) number density. In Figures 1d–1f observed quantities (squares) and computed quantities (dashed lines) are illustrated, respectively, by blue curves (Cluster 3) and by red curves (Cluster 4). Cluster 3 data have been displaced in time to align the center of the transition for both spacecraft.

sheet, whose maximum current density coincides with the density peak (Figure 1e). The field-aligned current density, $j_{\|}$, is computed from the residual B-field resulting from subtraction of the Tsyganenko 1996 model field [*Tsyganenko*, 1995] and assuming an infinite and quasi-stationary planar current sheet.

[6] Between 19:18:00 UT and 19:18:16 UT, coincident with observations by Cluster 4 of the TD and of the $O^+$ outflows, and roughly at the same magnetic latitudes (see Figure 1, top), DMSP-F14 detects a flux of precipitating electrons with an inverted-V signature (Figure 2a). The curtain of accelerated down-going electrons is about 30–35 kilometers thick. At 19:18:12 UT DMSP-F14 measures the maximum flux of precipitating energy, of the order of 20 $mW/m^2$ [*Vaivads et al.*, 2003]. Precipitating electron spectra from DMSP and up-going $O^+$ ion spectra from Cluster are consistent with a field-aligned potential drop, $\Delta\Phi$ of the order of 3 kV, as illustrated by black symbols in Figure 2c.

[7] Cluster and DMSP observations are compared with the results of a quasi-stationary magnetosphere-ionosphere coupling model proposed theoretically by *Roth et al.* [1993] and developed quantitatively by *Echim et al.* [2007, 2008]. The main components of the model are: (1) a self-consistent, kinetic description of the generator, providing the magnetospheric electrostatic potential, $\Phi_m$, coupled to the auroral ionosphere; and (2) an ionospheric module that computes the ionospheric electrostatic potential, $\Delta\Phi$, from the current continuity equation. The magnetospheric module is a Vlasov-Maxwell equilibrium. It solves for the velocity distribution functions of component species, their moments

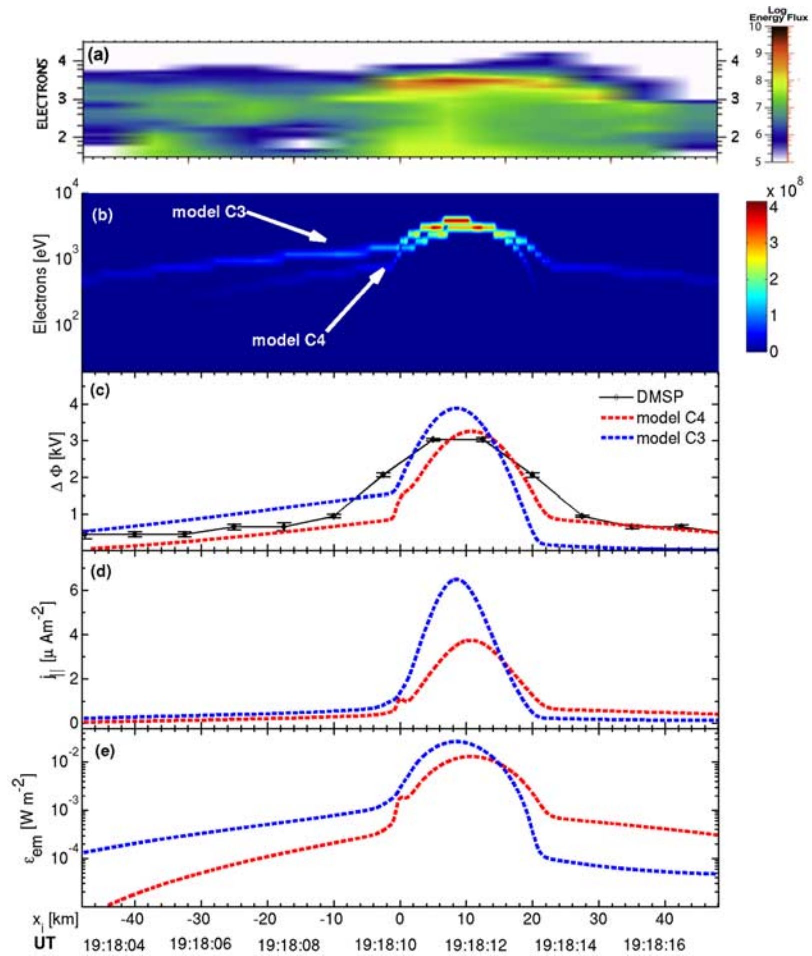


**Figure 2.** DMSP-F14 data and model results are plotted against $x_i$, the coordinate normal to the arc; corresponding DMSP time is also indicated. (a) Logarithm of the energy of precipitating electrons from DMSP-F14; (b) two model energy spectra obtained at DMSP altitude for Maxwellian electrons injected at 4.7 $R_E$ in the computed $\Delta\Phi$; (c) the field-aligned potential drop, $\Delta\Phi$, derived from DMSP F14 electron spectra (black symbols) and from current continuity for the two generator models C3 and C4 (dashed lines); (d) two corresponding solutions for the field-aligned current density; (e) two corresponding results for the flux of precipitating energy.

and the electromagnetic field inside the discontinuity. The current and charge density are analytical functions of the electric and magnetic vector potentials, $\Phi_m$, $a_y$ and $a_z$ [*Echim et al.*, 2007]. In addition to the populations whose dynamics is determined by the asymptotic conditions, the Vlasov equilibrium also includes so-called trapped particles, i.e. particles that are confined in the center of the transition. The model provides $\Phi_m$, $a_y$, $a_z$ as a function of $x_m$, the coordinate normal to the magnetospheric discontinuity. A detailed description of kinetic modeling of tangential discontinuities (TD) is given in the review paper by *Roth et al.* [1996].

[8] The ionospheric module of the M-I coupling model discussed in this paper is based on the current continuity equation [*Lyons*, 1980]. The adiabatic dynamics of particles between the magnetospheric generator and the auroral ionosphere determines a field-aligned current density, $j_{\|}$, and a flux of precipitating energy, $\epsilon_{em}$, as function of the field-aligned potential drop $\Delta\Phi = \Phi_i - \Phi_m$. Note that $j_{\|}$ also depends on the ratio between ionospheric and magnetospheric magnetic field, $b = B_i/B_m$, as well as on the density and temperature of magnetospheric and ionospheric auroral species [*Knight*, 1973; *Lemaire and Scherer*, 1973]. An ionospheric feedback is introduced by assuming that the height-integrated Pedersen conductivity, $\Sigma_P$, depends on $\epsilon_{em}$, carried mostly by the precipitating electrons [*Harel et al.*, 1977]. Thus the current continuity equation is solved for the ionospheric electrostatic potential, $\Phi_i$:

$$\sum_{\alpha} j_{\|}^{\alpha}(b, N^{\alpha}, T^{\alpha}, \Phi_i - \Phi_m) = \frac{d}{dx_i}\left[\Sigma_P(b, N^{-}, T^{-}, \Phi_i - \Phi_m)\frac{d\Phi_i}{dx_i}\right] \quad (1)$$

where $x_i$ is the coordinate normal to the arc in the ionosphere and the summation is over all, ionospheric and magnetospheric, species $\alpha$. In equation (1) the coupling with the magnetosphere is introduced via $\Phi_m$, the self-consistent electric potential provided by the TD model of the magnetospheric generator. With $\Phi_i(x_i)$ computed from equation (1) one then determines $\Delta\Phi$, $j_{\|}$, and $\epsilon_{em}$, and compares with observations at ionospheric altitudes.

**Table 1.** Density (n), Temperature (T), Drift Velocity ($V_\perp$) and Length Scale ($L$) of the Populations Considered by the TD Model C4[a]

| | $n^-$ [$cm^{-3}$] | $n^+$ [$cm^{-3}$] | $n^{O^+}$ [$cm^{-3}$] | $T^-$ [eV] | $T^+$ [eV] | $T^{O^+}$ [eV] | $V_\perp$ [km/s] | $L^-$ [$R_L^-$] | $L^+$ [$R_L^+$] | $L^{O+}$ [$R_L^{O+}$] |
|---|---|---|---|---|---|---|---|---|---|---|
| $x = x_1(t_1)$ | 0.12 | 0.12 | - | 75 | 580 | - | 4.50 | 64.28 | 1.50 | - |
| $x = x_2(t_2)$ | 0.31 | 0.31 | - | 200 | 3800 | - | −8.50 | 64.28 | 1.50 | - |
| $x = 0$ (center) | 0.90 | - | 0.5 | 230 | - | 2800 | 15.00 | 110 | - | 8 |

[a]Left hand side (given at $x_1$), right hand side (given at $x_2$), and trapped (given at the center); "−" and"+" stand for respectively electrons and protons, $R_L^\alpha$ denotes the Larmor radius of species $\alpha$, $L$ is defined by *Roth et al.* [1996].

[9] Kinetic solutions for the interface intersected by the Cluster spacecraft are obtained from the magnetospheric generator module by imposing boundary conditions (B-field, density, temperature) determined from Cluster data see Table 1. Thus, the model solutions C3 and C4 in Figures 1d–1f are obtained with boundary conditions corresponding to measurements made by Cluster 3 and 4 at $t_1$ = 19:15:00 UT and $t_2$ = 19:20:00 UT. The model electric potential $\Phi_m$ is in good agreement with the observations, as illustrated by Figure 1d; the model retrieves the deep minimum of $\Phi_m$ and the spatial scale revealed by data from Cluster 3 and 4. A good estimation is also obtained for the central peak of the plasma density and its spatial scale (Figure 1f). The model also reproduces the position and scale of the upward current, but overestimates the current density (Figure 1e). However, the computation of $j_{||}$ from B-field measurements is strongly affected by the uncertainties of the single-spacecraft method. The global agreement between models C3 and C4 and observations suggests that the Cluster spacecraft observe the convergent electric field of a magnetospheric TD-like interface. The structure is stable during hundreds of seconds at least. We associate this plasma interface with the generator of the auroral arc observed at lower altitudes by DMSP-F14.

[10] Figures 2b–2e show results obtained from equation (1) for input $\Phi_m$ provided by the two generator models, C3 and C4, discussed above. The ionospheric electric potential, $\Phi_i$, is computed at the altitude of DMSP, $z_i$ = 850 km, and gives a field-aligned potential drop with a maximum between 3.2 kV (model C4) and 3.9 kV (model C3). The flux of precipitation energy, $\epsilon_{em}$, estimated by the model has a maximum between 12 mW/m$^2$ (model C4) and 26 mW/m$^2$ (model C3), close to the precipitating energy flux measured by DMSP (20 mW/m$^2$ reported by *Vaivads et al.* [2003] at lower ionospheric altitude). The model also shows that the peak of $\Delta\Phi$ and $\epsilon_{em}$ coincide with the ionospheric projection of the center of the magnetospheric discontinuity, where the plasma density is maximum and $\Phi_m$ is minimum.

[11] A Maxwellian electron population with density and temperature similar to the trapped electrons included in the TD model (see Table 1) is "launched" at an altitude $z_m$ = 4.5 $R_E$ and a magnetic field $B_m$ = 480 nT, into the acceleration region and the parallel potential drop given by the model. The precipitating electron energy spectrum is computed by Liouville mapping of the initial VDF at an altitude $z_i$ = 850 km and a magnetic field $B_i$ = 40000 nT. The results are shown in Figure 2b and reveal a clear inverted-V signature with a characteristic spatial scale of 30 kilometers and a spectral width in good agreement with DMSP F14 observations.

## 3. Discussion and Conclusions

[12] We make, to the best of our knowledge, for the first time a direct qualitative and quantitative comparison between the results of a kinetic magnetosphere–ionosphere coupling model and in-situ data measured simultaneously above the acceleration region and below it by Cluster and DMSP. At high altitudes our model computes self-consistently the structure of the transition between the two magnetospheric states observed by Cluster. The model shows a good agreement with observations of the electrostatic potential and plasma density by Cluster 3 and 4 and describes an auroral generator with a convergent electric field. The latter has two main components: (1) thermoelectric due to kinetic pressure gradients and (2) convective due to shears of plasma bulk velocity. The dip of the magnetospheric electric potential is due to the plasma response to preserve charge quasi-neutrality and total pressure equilibrium when particles coming from both sides of the interface are interacting between them and with the trapped particles in the center. The central peak of plasma density is due to two competing kinetic processes: (a) superposition of electrons and ions gyrating from the left and right hand-side of the TD and cumulating their density and (b) confinement of trapped particles in the center of the TD. The electrostatic potential of the generator is coupled to the ionospheric load via a kinetic current-voltage relationship and the current continuity equation. The effects on the TD structure itself of the coupling with the conducting ionosphere have been discussed by *Roth et al.* [1993] who concluded that the TD structure is able to generate the electromotive force on time scales consistent with the life time of stable discrete arcs. The numerical solutions provide a field-aligned potential drop consistent with observations of precipitating electrons by DMSP and up-going Oxygen ions by Cluster. The maximum of the accelerating potential drop corresponds roughly to the height of the central dip of the magnetospheric potential. The model suggests that the spatial scale of the inverted-V structure depends on the spatial scale of the magnetospheric TD and also on the magnetic compression factor.

[13] The model results and experimental data evidence a quasi-stationary field-aligned potential drop established between the high-latitude ionosphere and the magnetospheric dusk flank. Due to the difficulty to trace magnetic field lines and lack of data at higher altitudes it is impossible to distinguish between two generator scenarios. The plasma interface observed by Cluster might be the generator of the auroral arc revealed by DMSP. In this case the generator would be located along the plasma sheet boundary layer (PSBL), at its interface with the lobe. In this scenario the generator is an elongated 3D structure extending to higher altitudes, as illustrated in Figure 3 (the magenta region).

[14] Another possible generator scenario might consider the interface between the LLBL and the outer plasma sheet. In Figure 3 we also illustrate this possible alternative. Velocity shears and kinetic pressure gradients exist in this region and may sustain strong convergent electric fields. If this is indeed the case, Cluster observes a low-altitude signature of this LLBL generator (the green region in Figure 3).

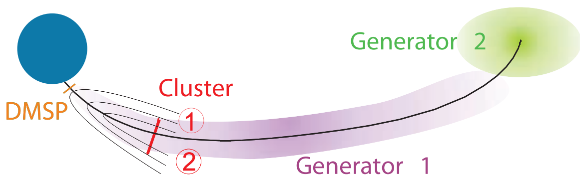


**Figure 3.** A section through GSE YOZ plane illustrating two possible generator scenarios supporting the satellite observations from April 28, 2001. In scenario 1 the generator extends along the PSBL and is marked with magenta; in scenario 2 the generator is confined at the inner edge of the LLBL, indicated in green. Cluster spacecraft cross the interface between two plasmas denoted 1 and 2; DMSP-F14 orbit, electric equipotentials and a magnetic field line (connecting the Earth with the inner edge of the LLBL) are also illustrated.

Interplanetary data from WIND and Geotail (not shown) suggest that on April 28, 2001 conditions were favorable for the formation of strong pressure gradients at the inner interface of the LLBL, sustaining an enhanced convergent electric field.

[15] In both scenarios a magnetospheric tangential discontinuity formed at the interface between plasmas with different macroscopic parameters plays the role of a generator for discrete auroral arcs. The spatial scale of the TD is a combination of the Larmor radii of all species contributing to the total pressure equilibrium. An increase of pressure gradient and/or velocity shear enhances the electromotive force generated across the TD, and thus increases the field-aligned potential drop and the flux of precipitating energy in the auroral ionosphere, producing visible auroral emissions. The arc fades away when the gradients and shears diminish across the TD and the generator cannot supply enough energy to sustain auroral activity above the visible threshold.

[16] The Cluster-DMSP-F14 conjunction on April 28, 2001 took place in a complex B-field geometry, at the dusk flank of the magnetosphere, during a substorm recovery phase. Experimental data and model results support a magnetosphere–ionosphere coupling configuration with a quasi-stationary field-aligned potential drop and field-aligned currents closing in the ionosphere through Pedersen currents. Future investigation of similar cases can bring more insight on TD generators of discrete arcs.

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