GEOPHYSICAL RESEARCH LETTERS, VOL. 30, NO. 15, 1799, doi:10.1029/2003GL017095, 2003

Sharp boundary between the inner magnetosphere and active outer plasma sheet

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Received 10 February 2003; revised 20 May 2003; accepted 5 June 2003; published 6 August 2003.

[1] We report observations of a sharp spatial boundary between the outer plasma sheet and the inner magnetosphere. It was successively crossed by the Cluster spacecraft in their pearl-on-string configuration near the perigee ($\sim$4 Re) at midnight during a substorm expansion phase. Being mapped presumably to 8–10 Re in the equatorial tail, this boundary was extremely thin, comparable to a gyroradius of plasma sheet proton. Substantial changes on this spatial scale were observed coherently in (1) the fluxes of radiation belt energetic electrons (exceeding a factor 10 at $E \geq 100$ keV), (2) the plasma pressure (by a factor of 2), (3) the density and outflow of the cold ionospheric plasma. Strong diverging electric field (azimuthal shear flow) coincides with this boundary and is accompanied by a strong downward field-aligned current. While this boundary was staying at nearly the same location during the $\sim$5 min time scale, we also found indications of its dynamical origin. We suppose it could be generated by a sudden braking and azimuthal deflection of localized bursty fast flows produced by the magnetic reconnection which was going on at this time in the near tail. *INDEX TERMS:* 2740 Magnetospheric Physics: Magnetospheric configuration and dynamics; 2764 Magnetospheric Physics: Plasma sheet; 2730 Magnetospheric Physics: Magnetosphere—inner; 2712 Magnetospheric Physics: Electric fields (2411); 2720 Magnetospheric Physics: Energetic particles, trapped. **Citation:** Sergeev, V. A., J.-A. Sauvaud, H. Reme, A. Balogh, P. Daly, Q.-G. Zong, V. Angelopoulos, M. Andre, and A. Vaivads, Sharp boundary between the inner magnetosphere and active outer plasma sheet, *Geophys. Res. Lett.*, *30*(15), 1799, doi:10.1029/2003GL017095, 2003.

1. Introduction

[2] There exist a number of particle boundaries separating the innermost trapped plasma population from the population of the outer regions, these boundaries are formed by different mechanisms depending on the energy range considered (*Kivelson and Russell* [1995]). The basic (keV energy range) plasma sheet population has a well-known Alfven boundary between closed and open drift trajectories which results from a competition of magnetic and electric drifts. For the cold plasma of ionospheric origin the corotation effects replace the magnetic drifts and form a similar pattern with a separatrix between open and closed trajectories, known as the plasmapause. Quite different processes (mostly the losses due to precipitation and drift losses) are responsible for the formation of the outer boundary of the most energetic particle population, the outer radiation belt (energies higher than some tens keV). At times these boundaries can be quite sharp, in the nightside sector they are all typically observed in the distance range 5 to 10 Re. However because of different physical processes leading to their formation, they have different shapes, stay at different distances (being often dispersed in energy) and are formed on the different time scales.

[3] In this paper we report the observation of a sharp (comparable to the ion gyrodadius) boundary between the inner and outer regions at which energetic, plasma sheet and ionospheric plasma populations change substantially.

2. Observations

[4] Here we use data from the ion spectrometer CIS (on spacecraft C1 and C4), magnetic field (FGM) and double probe (EFW) instruments, and energetic particle spectrometers (RAPID) (see the special issue of Annales Geophys. 2001, N 10–12 for detailed descriptions of these instruments). The observations have been obtained on February 14, 2001 when the Cluster spacecraft crossed the nightside auroral zone near midnight close to its perigee, Figure 1. The T89 model (Kp = 4) model was selected for mappings since it gave the best agreement with the external (IGRF subtracted) part of magnetic field observed by the Cluster spacecraft at that time. As seen from Figure 1 the spacecraft crossed inbound the auroral zone flux tubes at middle magnetic latitudes and $r \sim 4$ Re near midnight in the southern hemisphere. The Cluster spacecraft C1, C3 and C4 were in a pearl-on-string configuration (spacecraft C1 leading), they followed nearly the same trajectory, and had 3 to 5 minute difference between the crossing of the same L-shell. Spacecraft C2 was slightly ($\sim$0.05 h MLT) westward. As the magnetic field was strong ($B \sim 500$ nT), the natural coordinate system for analyzing electromagnetic disturbances is the mean-field-aligned (MFA) local coordinates (see Figure 1), in which **b1** is along the mean magnetic field (obtained with 300-s running average), **b2** (positive to the east) is perpendicular to both the radius from the Earth center and **b1**, and **b3** is directed inward completing the triad.

[5] This crossing of the southern auroral zone occurred during the maximum phase of a $\sim$400 nT (AE) substorm, beginning on 0026 UT on February 14, 2001 (a detailed analysis of this event will be published elsewhere). The

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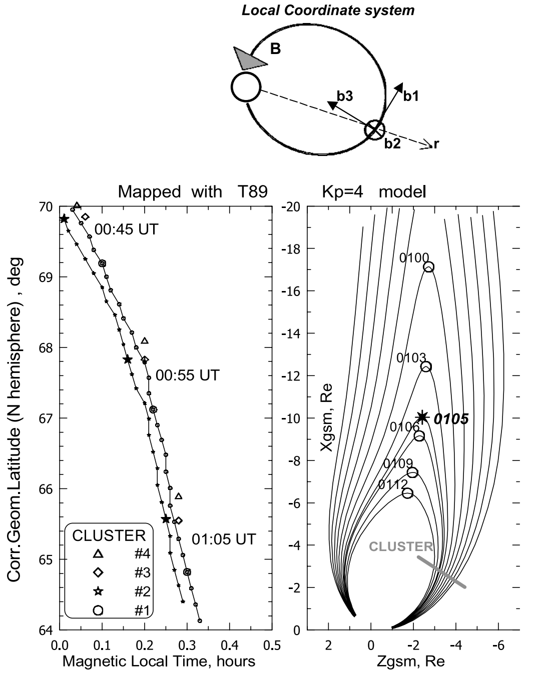

Figure 1. Cluster trajectory, local coordinate system used (top panel), and the mappings to the magnetosphere (right panel) and to the ionosphere (left panel). Ionospheric footpoints are shown every 5 min for all four spacecraft whereas the points show the C1 and C2 projections with a 1 min time step. Time marks in the magnetospheric mappings correspond to the spacecraft C1.

Geotail spacecraft at [−23; 6; 2] Re in the plasma sheet observed a sequence of earthward and tailward flow bursts between 0030 UT and 0115 UT.

[6] The spacecraft C1 crossed the poleward oval boundary at $\sim$0043 UT (I1 in Figure 2) as signaled by the appearance of energetic particle fluxes and variations of the electromagnetic field. Then it observed the intense Alfvenic wave activity (note the absence of compressional component, dB1) with a predominant energy flow directed towards the ionosphere, and also strong outflows of cold ionospheric ions (not shown) and variable fluxes of plasma sheet particles. They are observed while the spacecraft crossed the outer plasma sheet until 0105 UT when, according to the orbit mapping, the spacecraft passed inward through $r \sim 10$ Re (if mapped to the magnetic equator). While the energetic electron flux shows a few increases, its variation at 0104:54 UT is especially sharp, has the largest flux increment and a strong counterpart in the electric field and other parameters as well. This sharp boundary (Energetic Electron Wall, EEW) is the subject of our interest in this paper.

[7] We have strong arguments in favor of the spatial origin of this sharp variation. First, most of the sharp variations observed in different parameters are successively detected by all spacecraft (see the superimposed epoch plot in Figure 4). The time delays of its registration at the spacecraft C3 (being in the middle of the spacecraft array) and other spacecraft (i) were estimated as $DT_{i3} = s_{i3}/V_3$ (based on their separation along the axis **b3** in our local reference system and the spacecraft C3 velocity component in this direction, which is the largest component in this case of inward moving spacecraft). The predicted (observed) time delays were 161s (148s) between spacecraft C3 and C1, 143s (158s) between C4 and C3, −64s (−71s) between C3 and C2 and 303s (306s) between C4 and C1. Here the observed time delays are given based on the sharp energetic electron flux increase which started at 0104:54 UT(spacecraft C1), 0108:33 UT(C2), 0107:22 UT (C3) and 0110:00 UT (C4) correspondingly. The largest delay between C4 and C1, $\sim$5 min, gives us the time scale on which this boundary was observed at the same spatial location. The next argument comes from the finite ion gyroradius effects seen in the 3D distribution function. This effect is expected when the boundary is very thin, with a thickness comparable to the ion gyroradius. The 3D distribution at 0104:51 UT in Figure 3 confirms this, showing a halfspace with low counts (upper part, corresponding to the gyrocenters located outward from spacecraft and having the same low flux as observed on the previous scans in the outer plasma sheet) and a halfspace with large counts (with inward gyrocenters and fluxes like those observed at later times, when spacecraft passed through the innermost magnetosphere). Therefore, the observed flux increase is really due to the crossing a sharp spatial boundary. Note that the 32 keV ion gyroradius in the local 500 nT B-field is about 50 km, such thickness is

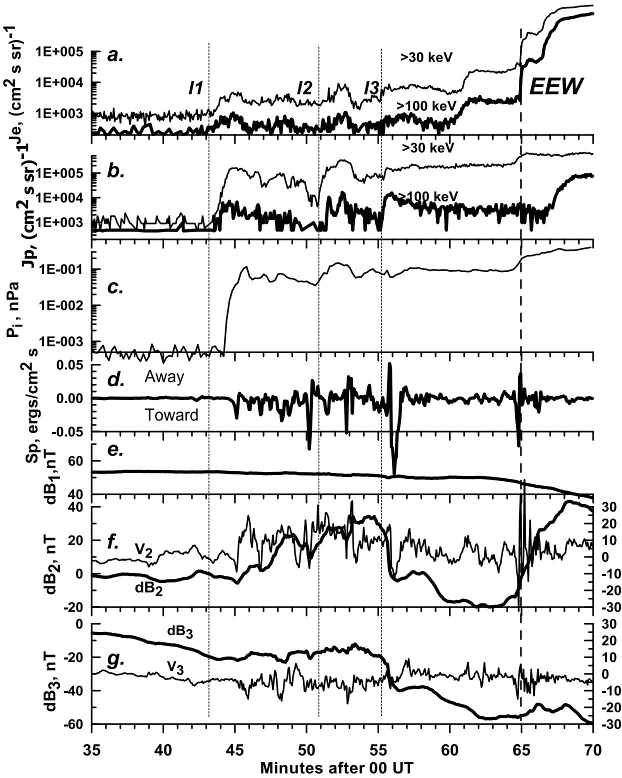

Figure 2. :Survey of observations by Cluster C1: (a), (b)-differential fluxes of energetic electrons and protons (from RAPID); (c)- proton pressure (from CIS-2); -variations of parallel Poynting flux (d), (e)–(g) -magnetic field (dB, with IGRF field subtracted) and convection velocity (V = [E × B], from observations by FGM and EFW instruments). Local coordinate system is used for presentation of B and V variations. Vertical lines mark the sharp time variations corresponding to the particle injections (I1–I3) and to the crossing of spatial boundary (EEW).

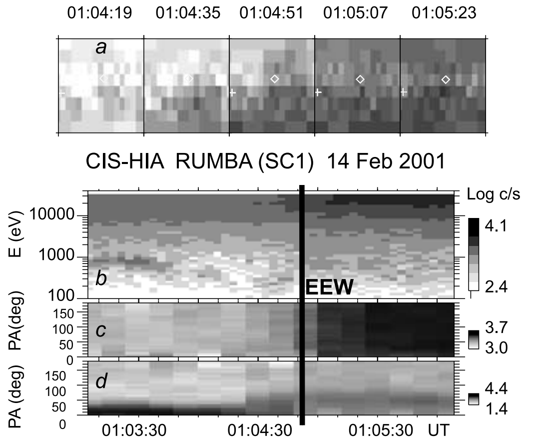

Figure 3. Details of the ion distributions at the spacecraft C1 (from CIS-2 spectrometer). From top to the bottom: *a* -3D distributions of 32 kev proton count rate in polar angle (vertical) versus azimuthal angle (horizontal) coordinates, directions parallel (antiparallel) to the local magnetic field are shown by circles (crosses); *b*)- Energy-time spectrogram of the ion fluxes; - pitch-angle distributions of the energetic ions (9–32 keV, *c*) and low energy ions (0.01–1 keV, *d*).

consistent with the ~8 sec (2 spins) duration of the energetic electron flux increase, see Figure 4, top (4.5 km/s spacecraft inward velocity along **b3** multiplied by 8 sec gives 36 km).

[8] There are sharp variations in other plasma and field characteristics coinciding with the EEW appearance. At plasma sheet energies (keV to tens keV), the most spectacular feature is a ~2-fold increase of the ion pressure (Figure 4, bottom, including contributions of both protons and heavy ions) of isotropic plasma sheet component (Figure 3c). This increase occupies a somewhat broader region, about 250 km across the boundary, corresponding to ~50 s duration (Figure 4, bottom). The cold plasma also undergoes significant changes: the strong ion outflow terminates (Figure 3, bottom) whereas the density strongly increases in the inner region as evidenced by the sharp increase of the negative of the spacecraft electric potential shown in Figure 4. A very distinct EEW signature is a sharp variation of the electric field. It has a largest component in the radial direction ($|E2|$ does not exceed 20–30% of $|E3|$ during this variation) and has a bipolar character with the electric field vectors diverging from the EEW boundary. Its magnitude is very large at all four spacecraft, ranging between 50 and 200 mV/m. Another repeatable feature is the associated magnetic variation with azimuthal polarization (the eastward dB2 increasing) which corresponds to a downward field-aligned current. This current starts to increase some 30–50s before the EEW crossing reaching the peak close to the EEW (Figure 4). Its peak value (~1 nT/s in dB2/dt under the inward spacecraft velocity of 4.5 km/s) appears to be rather large, about 3.6 $\mu A/m^2$. This intense downward FAC is a part of a more broad (and less intense) downward FAC (crossing duration about 4 min, scale-size across B ~1000 km) which is clearly seen in Figure 2 (dB2) and was registered with appropriate time-shift by spacecraft C2,C3,C4.

[9] From crossing to crossing of the EEW by the Cluster satellites important temporal variations do occur. (*1*) There is an indication of progressive plasma compression: in Figure 4, bottom the ion pressure at spacecraft C4 is 0.2 nPa higher than that at C1. Also, comparing the flux variations of high energy ($\geq$95 keV) protons and He^{++} ions (Figure 5) we find them steadily increasing at all spacecraft starting after 0104 UT (this was sometimes interrupted by flux decreases just following the crossing of EEW boundary). (*2*) The bipolar electric field variation amplitude (tip-to-tip, 1s averaged data) is 64 mV/m (spacecraft C1), 48 mV/m (C2, not shown), 65 mV/m (C3) and approaches 220 mV/m (C4, out of scale in Figure 4). The sign and the overall shape of this variation is conserved. The electric field also displays ~20s oscillations at the spacecraft C1 which are not seen by the other spacecraft). (*3*) Peak density of the field-aligned current is also increasing (see Figure 4), being 2.4 $\mu A/m^2$ (at C1), 3.2 (at C3) and 4.5 $\mu\ A/m^2$ (at C4). (*4*) The energetic electron flux increment was also increasing, being enhanced at the EEW (in 2 spins) by a factor ~10 (C1), ~20 (C3) and ~50 (C4). Being combined they give evidence that this sharp boundary was time-evolving (sharpened) during the 5 min long time window of Cluster observations.

3. Discussion

[10] We report a spectacular sharp boundary (scale-size ~50 km in the direction across B, i.e. a few gyroradii of plasma sheet protons). It was characterized by an intense

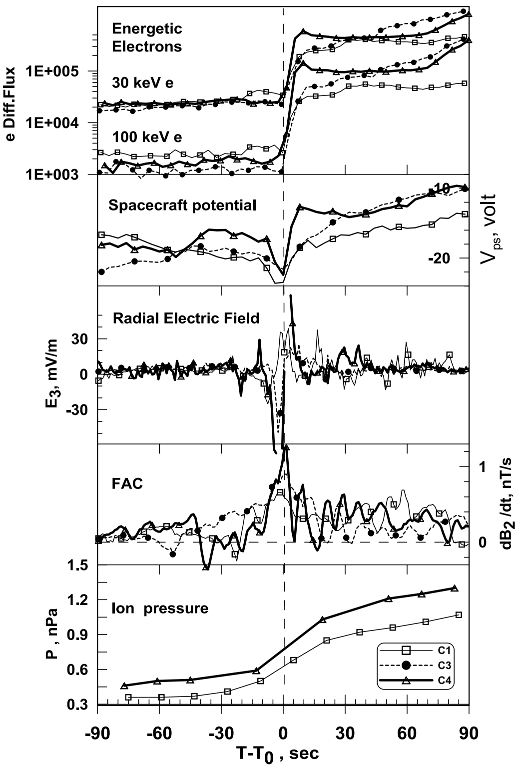

Figure 4. Superposed epoch analysis of observations at Cluster spacecraft C1, 3, 4 closely following each other along the same orbit. The zero epoch times T0 are 010454 UT (C1), 010722 UT (C3) and 011000 UT(C4). The ion pressure (from CIS-1 spectrometer) includes contributions of all ions.

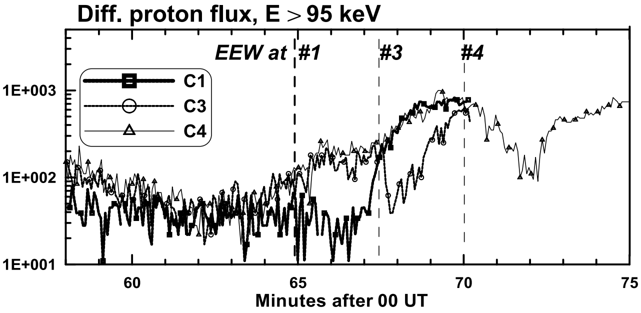

Figure 5. Temporal variations of the high-energy proton fluxes; crossings of the EEW are shown by vertical lines.

energetic electron flux increase (a factor 10–50 at E $\geq$ 100 keV) and very strong ($\sim$30–100 mV/m) diverging radial electric fields. On somewhat broader spatial scale it has associated very strong downward field-aligned current ($\geq 10^{-5} A/m^2$ if mapped to the ionosphere), $\sim$2-fold ion pressure increase, as well as by a sharp electron density increase and by the end of the cold plasma outflow from the ionosphere (on the inward side of this boundary).

[11] This spectacular sharp boundary delineates a transition between the active outer plasma sheet and the more stable inner magnetosphere. However, the observations have been done at midlatitudes (see the trajectory in Figure 1), far from the equatorial region where this sharp boundary could be created. The mapping with T89 Kp = 4 model places this boundary at 10 Re at the neutral sheet (Figure 1). The observed ion pressure value $\sim$1nPa is typical for the plasma sheet distances r $\sim$ 8 Re (±1 Re) in the equatorial nearmidnight magnetosphere (*De Michelis et al.* [1999]).

[12] A key to interpret this boundary could be the energetic electrons which display the most remarkable and repeatable signature. Indeed at these distances they are expected to behave adiabatically, and their intensity distribution should be formed by the redistribution of preexisting population, or by their acceleration or losses, which are all controlled by the magnetic field. The adiabatic redistribution of existing radiation belt particles will promptly form a sharp radial flux gradient in some limited longitudinal sector if a sharp magnetic wall (region of sharply increasing equatorial magnetic field B_{eq}) is formed in this sector at the contact between the quasi-neutral (weak B_{eq}) current sheet and the inner strong quasi-dipole field. If the acceleration is more important, the fast inward transport in the rapidly increasing magnetic field is the natural way to form a sharp flux increase. Losses hardly play any role to deplete the fluxes in the weak-B region since here the energetic electron lifetime in the strong diffusion limit exceeds several tens minutes. In spite of apparent similarity of the sharp flux increases, our case is different from the well-known 'substorm injection boundary' [e.g., *Baker et al.*, 2002] which has the enhanced (accelerated) particle fluxes behind (tailward of) it, whereas the enhanced (radiation belt) flux stays earthward of the sharp EEW in our case.

[13] Kinetic 3D simulations made by *Pritchett and Coroniti* [2000] suggest that such magnetic wall with associated density and pressure gradients can be formed by a localized plasma jet impinging on the near-Earth plasma region. The jet interaction included the formation of a local B_{eq} minimum ahead of the plasma jet as well as the narrow regions where the plasma diverts azimuthally. This resembles the situation we had in the case presented here, where the Geotail spacecraft registered the flow bursts at X = -23 Re. The last burst observed between 0105 and 0112 UT reached a peak amplitude Vx = -650 km/s by 0107 UT, just during the time interval of EEW observation. Although this was observed $\sim$2 hours MLT westward of the meridian where the Cluster crossed the EEW boundary, it seems quite probable that intense pulse of magnetic reconnection could develop at that time in the midtail plasma sheet somewhere between the 10 and 20 Re distances. Such situation is rare, which could explain the rare appearance of so sharp boundaries like the EEW which, to our knowledge, have been never reported before.

[14] Spectacular electromagnetic signatures (bipolar diverging electric fields implying azimuthal velocity shear (and toroidal magnetic field disturbance) combined with a downward field-aligned current (as required by the quasistatic current closure in the ionosphere) could be formed by either a kind of resonance phenomena at the sharp discontinuity (like the Alfven field-line resonance), or as a result of the those transient processes which form dynamically the magnetic wall. The magnetosphere feeds the energy for these phenomenon as follows from the Poynting flux toward the ionosphere (see Figure 2). Such electromagnetic events could be more frequent, a Cluster event (during a substorm recovery phase at 03 h MLT) has been already reported by *Marklund et al.* [2001] but it had not so stable and sharp energetic particle boundary associated as we had in our case. More observational studies are required to understand the physics of such sharp boundaries.

[15] **Acknowledgments.** We thank Prof. T. Mukai for the Geotail data. V.S. thanks CESR for the financial support during his stays in Toulouse, his work was also supported by RFBR grant 03-02-17533 and Intergeophysics program.

References

Baker, D. N., et al., A telescopic microscopic view of a magnetospheric substorm on March 31, 2001, *Geophys. Res. Lett.*, *29*, 10.1029/2001GL014491, 2002.

De Michelis, P., I. A. Daglis, and G. Consolini, An average image of proton plasma pressure and os current systems in the equatorial plane derived from AMPTE/CCE-CHEM measurements, *J. Geophys. Res.*, *104*, 28,615, 1999.

Kivelson, M., and C. T. Russell (eds), Introduction to Space Physics, UCLA, 1995.

Marklund, G. T., et al., Temporal evolution of the electric field accelerating electrons away from the auroral ionosphere, *Nature*, *414*, 724–727, 2001.

Pritchett, P. L., and F. V. Coroniti, Localized convection flows and field-aligned current generation in a kinetic model of the near-Earth plasma sheet, *Geophys. Res. Lett.*, *27*, 3161, 2000.

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