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Cluster/rapid energetic electron observations at the dayside magnetospheric boundary

K. Mursula [a,*], R. Kerttula [a], T. Asikainen [a], R. Friedel [b], A. Vaivads [c], F. Søraas [d], M. Grande [e], M. Carter [e], P.W. Daly [f], T.A. Fritz [g], J.F. Fennell [h], A. Balogh [i]

[a] *Department of Physical Sciences, P.O. Box 3000, FIN-90014 University of Oulu, Finland*
[b] *LANL, Los Alamos, NM, USA*
[c] *IRF-U, Uppsala, Sweden*
[d] *University of Bergen, Bergen, Norway*
[e] *RAL, Chilton, Didcot, UK*
[f] *MPAE, Katlenburg-Lindau, Germany*
[g] *Boston University, Boston, MA, USA*
[h] *Aerospace Co., Los Angeles, CA, USA*
[i] *Blackett Lab, Imperial College, London, UK*

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Abstract

We study the energetic electrons by the Cluster-II Rapid instrument on a dayside high-latitude pass on the night between March 21/22, 2001. The Cluster satellites were flying outward in the pre-noon sector, passing a cusp/cleft type region roughly at midnight. Contrary to earlier observations of high fluxes of energetic particles in the high-latitude cusp, we found a very low flux of energetic particles in this region. Soon thereafter the satellites entered the closed field line region of high-altitude magnetosphere with high fluxes of energetic particles and a low plasma density. While still in the region of downward oriented field lines, satellites observed surface waves propagating along magnetopause (MP) and modulating strongly the energetic particle fluxes. In the dayside sector satellites, observed several MP crossings, as well as periods when MP was quite stable and close to the satellites, even between them. We derive the speed and direction of the moving dayside magnetopause using observations of energetic electrons and plasma density. We also note that the moving magnetopause was often found to be connected with an increase of energetic electron flux while the stagnant MP was effectively a sink to energetic particles.

Keywords: Cluster-II; Energetic electrons; Magnetospheric boundary

1. Introduction

We will study the energetic (20–400 keV) electrons observed by the Rapid/IES (Imaging Electron Spectrometer) instrument (for a review of instrument properties and performance, see e.g., Wilken et al., 1997, 2001) during the night between March 21, 2001, about 2200 UT and March 22, 0300 UT. We also use measurements by the electric field EFW instrument and magnetic field FGM instrument. (For reviews of the two instruments, see Gustafsson et al., 2001 and Balogh et al., 2001). Cluster armada was on an outbound pass in the pre-noon (about 10 MLT) sector from the nightside magnetosphere via dayside magnetosphere to the magnetosheath. The satellite configuration at this time was such that s/c1 had the largest (positive) Z-component, s/c3 was the leading satellite (with the largest X-component), s/c4

* Corresponding author. Tel.: +358 8 5531302; fax: +358 8 5441575. *E-mail address:* kalevi.mursula@oulu.fi (K. Mursula).

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was trailing (the smallest X-component) while s/c2 was in the middle and had the smallest Y-component.

The time interval studied was in the recovery phase of an intense magnetic storm which had its main phase on March 20, 2001, with D_{st} minimum of -165 nT. During this time the D_{st} index was systematically rising from -52 to -40 nT. The time was geomagnetically very quiet as indicated by very low K_p values of 1 and -1. However, as evidenced by Cluster observations, the dayside magnetosphere was quite dynamic. The low geomagnetic activity reflects the conditions in the solar wind and IMF: the SW speed was typically about 300 km/s and IMF Bz(GSM) was positive (4–8 nT) all the time. Also the two other IMF components were positive throughout, Bx(GSM) about 0–8 nT and By(GSM) about 3–9 nT.

2. Overall timeline of observations

At the start of the interval studied the Cluster satellites were in the Earth's northern night-side polar cap, in a low-density plasma with no energetic particles. When flying towards dayside between 22 and 24 UT, the satellites observed a continuously increasing plasma density which, according to CIS and PEACE instrument observations (not shown here) consisted of bursts of magnetosheath type plasma. These bursts occurred intermittently and had a typical duration of 5–10 min. It seems likely that they are due to magnetosheath plasma convecting tailwards after reconnection at the dayside.

At about 00–0015 UT plasma density reached its local maximum (see Fig. 1(a)). Simultaneously, the magnetic field intensity was decreased (not shown). This is the expected location of the cusp/cleft region. Note that no significant fluxes of energetic particles were found at this time. After 0015 UT plasma density decreased significantly and the flux of energetic electrons started increasing rapidly (see Fig. 1(b)) until reaching typical magnetospheric fluxes after 0030 UT. It is probable that the interval from 0015 to 0030 UT corresponds to a transit from a region of open field lines to closed field lines. From 0030 UT until about 0245 UT the energetic electron fluxes remained roughly at the same level, despite the dropouts corresponding to the magnetopause (MP) crossings to be discussed later.

We can divide the region of energetic particles to two sectors: the tailside (or cusp-side) sector from 0030 UT to about 0120 UT and the dayside sector from 0120 to 0245 UT. This division is motivated by three facts. First, at 0120 UT the magnetic Z-component (not shown) turned from negative to positive, indicating that at this time the satellites were on the top of a closed field line in the dayside magnetosphere, moving from downward oriented field (tailside) sector to the upward oriented

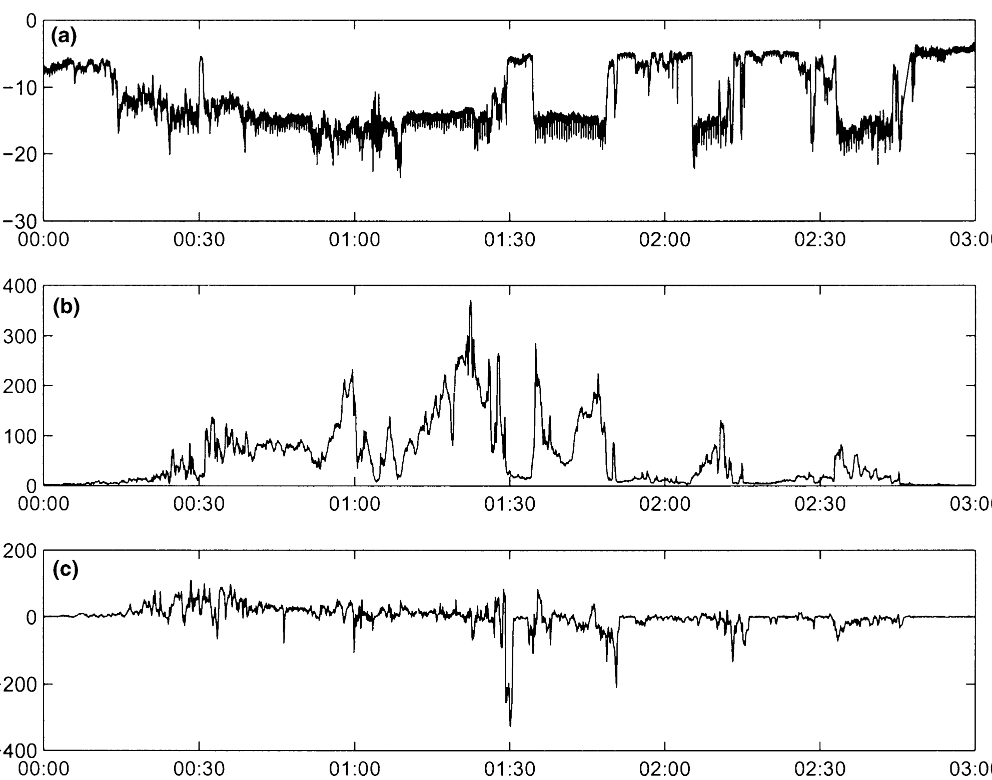

Fig. 1. Overview plot for March 22, 2001, 00-03 UT. (a) The (negative of) s/c1 potential as a quasi-logarithmic measure of plasma density. Small (large) negative potential values correspond to high (low) plasma densities. The regular small negative excursions are due to the WHISPER instrument. (b) Total Rapid/IES flux of s/c1 in units of counts*s^{-1} $cm^{-2}sr^{-1}keV^{-1}$. (c) IES flux difference between s/c3 and s/c4.

field (dayside) sector. Second, the energetic electron flux maximum was observed roughly at this time (see Fig. 1(b)). Third, it is interesting to note that the leading satellite (s/c3) observed slightly higher overall fluxes than the trailing satellite (s/c4) in the tailside sector from 0015 until about 0120 UT, but the situation was reversed in the dayside sector after 0120 UT (see Fig. 1(c)). These facts indicate that the satellites indeed were in a region of closed field lines, and that the deeper inside the magnetosphere they were the higher were the fluxes on an average.

Note also the outstanding overall anticorrelation between plasma density and IES flux variations over the whole 3-h period. In particular, the anticorrelation is overwhelming in the dayside sector after 0120 UT when the three main MP crossings at about 0130 UT, 0150–0205 UT and 0215–0235 UT greatly increased plasma density and decreased the IES fluxes.

3. Detailed events: tailside sector

At 0030 UT, in the early phase of the tailside sector, an abrupt peak of plasma density is observed (see Fig. 1(a)). This is coincided by a simultaneous temporary IES flux dropout (see Fig. 1(b)). It is interesting to note that the plasma density peak is observed by all satellites except for the leading s/c3 and that the strongest changes in both variables are seen in s/c1 which is located highest in the Z-direction. It is likely that these changes are due to a temporary equatorward extension of the open/closed field line boundary, leading to brief recovery of the cusp/cleft region at those three satellites that are closest to the boundary. Curiously, this extension seems to have proceeded close to the satellites, probably between s/c3 and the rest of the Cluster fleet.

At about 0050-0110 UT, while the satellites were still in the tailside sector, plasma density (see Fig. 1(a) and 2(d)) and, in particular, IES fluxes depict large fluctuations (see Fig. 1(b) and 2(a)). At the same time the magnetic field intensity shows fluctuations of about 4 min period and a few nT amplitude (see Fig. 2(c)). Note that there is a fair anticorrelation between the magnetic field intensity and IES fluctuations. Ultimately, these fluctuations are most likely caused by a sharp solar wind pressure (mainly density) pulse observed by the Wind satellite (not shown) which increased the pressure by roughly a factor of two for the same 20 min time interval. It is likely that the pressure pulse initiated fluctuations of the dayside magnetopause, so called surface waves, which then propagated even to the tailside sector, as observed by the Cluster satellites.

The magnetic field fluctuations of the surface wave are fairly modest (a few percent) but they can be responsible for the large fluctuations in the IES flux (roughly a factor of 1–2; see Fig. 2(a)) and plasma density (see Fig.

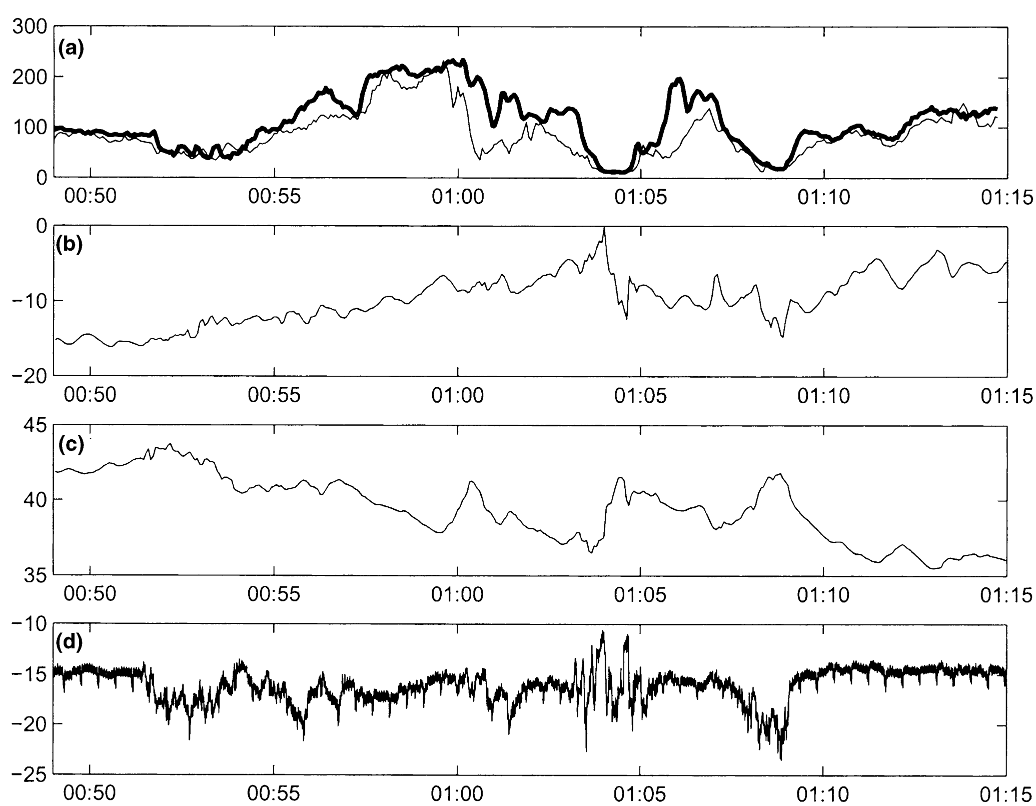

Fig. 2. Observations during solar wind pressure pulse at 0050–0115 UT. (a) Total Rapid/IES fluxes of s/c1 (thin line) and s/c2 (thick line). (b) Magnetic Z-component in GSM coordinate system. (c) Total magnetic field intensity. (d) S/c1 potential as a measure of plasma density.

2(d)) since the surface wave riding on MP can move the effective location of the satellites with respect to the open/closed field boundary. E.g., at 0104 UT the surface wave shifts the boundary inwards so that the satellites were taken out of the magnetosphere for a while, as evidenced by the depleted IES flux and increased plasma density. Note that there is a clear time difference in the IES dropout between s/c2 and other spacecraft (e.g., s/c1, see Fig. 2(a)). The dropout in s/c2 starts last and ends first, indicating that the boundary extended eastwards at a finite velocity and then returned back. Other types of waves, e.g., field line resonances, would not be able to cause such delays between the satellites.

Note also that the average plasma density in all satellites was slightly reduced during the 20 min pressure pulse (see Fig. 2(d)). This may indicate that the pressure pulse, in addition to causing the above discussed fluctuations, also pushed the whole dayside magnetosphere slightly tailwards, thereby changing the effective geomagnetic location of the satellites slightly deeper into the magnetosphere, further away from the high density cusp/cleft region.

4. Detailed events: dayside sector

Soon after the satellites entered the dayside sector of the magnetosphere at about 0120 UT they experienced the first of the three main dayside MP crossings at around 0130 UT. As seen in Fig. 1(a), the plasma density is increased at this time to values typical also later for the magnetosheath. IES fluxes also decrease but remain even at their minimum at a reasonable level, clearly above typical magnetosheath values. This is partly because the satellites are still very close to their innermost location in the magnetosphere (close to the overall IES maxima) and stay in the magnetosheath only a few minutes.

Moreover, since the MP boundary does not move very far inside beyond the location of the satellites, sizable amounts of energetic particles can leak through the boundary to be detected by Cluster. This can be concluded from the detailed analysis of the IES fluxes and plasma density depicted in Fig. 3. Note first the different behaviour of the IES flux in s/c1 from that observed in other satellites. The IES flux at s/c1 experienced the first dropout already at 0127 UT, simultaneous to a first peak in plasma density. At this time, no significant changes were seen in the other satellites. This corresponds to the first brief visit of the MP boundary close to s/c1. This is understandable since s/c1 was located highest in the Z-direction and the satellites were quite close to the top of the field line. Therefore, the inward MP motion would be first registered by s/c1. (s/c1 did, however, not yet go into the magnetosheath, as evidenced by the fairly low value of the density peak and a considerable IES flux at the minimum).

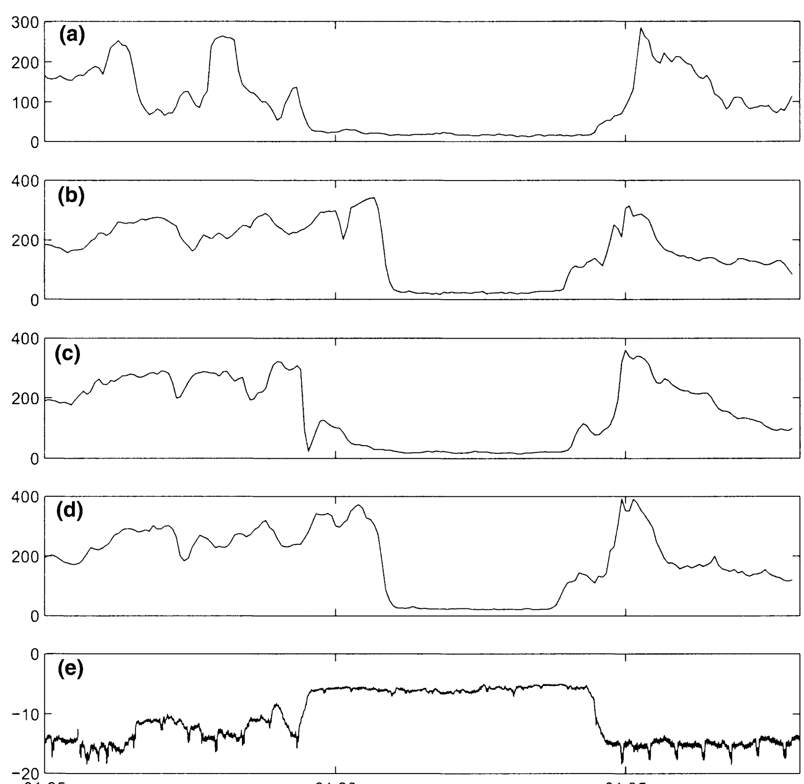

Fig. 3. Observations during dayside magnetopause crossing at 0125–0140 UT. Total Rapid/IES fluxes of: (a) s/c1; (b) s/c2; (c) s/c3; (d) s/c4; (e) s/c1 potential as a measure of plasma density.

Very soon after the s/c1 IES flux recovered at about 0128 UT, it started decreasing again, simultaneously with density increase. Accordingly, MP moved again closer to (but still not inside) s/c1. The IES fluxes (and densities) remained nearly constant at the other satellites until at about 0129 UT also the s/c3 IES flux (plasma density) experienced a dropout (increase, correspondingly) and both the two satellites entered the magnetosheath. Subsequently, at about 0131 UT MP moves further inwards, beyond the location of s/c2 and 4. Accordingly, the MP boundary was moving very slowly close and between the Cluster satellites for about 4 min from 0127 to 0131 UT. Note also that the IES fluxes at satellites 2 and 4 are slightly enhanced just prior to the fast MP crossing.

Satellites stay in the magnetosheath for about 3–5 min until MP starts retreating outwards, as evidenced by the increasing IES fluxes. The fluxes rise first at the three innermost satellites 2–4 at about 0134 UT. The outward MP motion is now considerably fast, leading to a nearly simultaneous rise of IES fluxes. Assuming a planar MP and using the time differences between the four satellites we can derive the MP speed of about 30 km/s during this outward crossing. It is interesting to note also that the direction of the motion was almost purely in the $+Z$-direction.

5. Discussion and conclusions

The Cluster/Rapid observations verify that there is a considerable population of energetic particles in the closed field line region of the very high-latitude dayside magnetosphere up to the magnetopause. Here, we have studied observations of energetic electrons on one orbit only but the same is true for ions, as well as for similar orbits more generally. In particular, this seems to be the case irrespective of the prior storm development or magnetic activity in the tail. (A paper including a larger statistics is under preparation.)

Contrary to earlier results (for a review and references, see Fritz, 2001) we have found a very low flux of energetic particles in the cusp/cleft region. (Although shown here only for electrons the same is true also for ions.) In fact, we found (see, e.g., Fig. 1(b)) that the flux levels of energetic electrons within the cusp/cleft region can be understood in terms of leakage from the near-by closed field line regions including large fluxes.

We have evidenced an excellent anticorrelation between the fluctuations of plasma density and energetic electron fluxes. Accordingly, both parameters can, e.g., be used to trace the MP motion. The data verify the very dynamic nature of the dayside boundary even in a situation where the solar wind and IMF conditions are quite stable. We have shown that a rather minor increase in SW pressure can cause sizable changes in the whole dayside magnetosphere, pushing it tailwards and launching surface waves. As seen here, such waves can propagate even to the shadow side of the dayside magnetosphere (region of downward directed field lines), and cause large fluctuations in the energetic particle fluxes and plasma density by moving the magnetospheric boundary.

During the several MP crossings during 3-h interval studied, we have seen both very slowly moving, nearly stagnant MP, as well as fast MP velocities up to about 50 km/s. Similar velocities have been derived in earlier MP studies using, e.g., magnetic field changes (see, e.g., Dunlop et al., 2001). In the present study, magnetopause was found to be quite thin, much thinner than the typical s/c separation of 600 km. This may be related to the strongly positive IMF Z-component which denies extensive reconnection in the subsolar region.

We have also noted that the magnetopause crossings are often related to flux maxima of energetic particles (see Fig. 3). This is particularly true for when magnetopause is moving fast. Accordingly, this gives evidence for particle acceleration inside a moving magnetopause (see also Sauvaud et al., 2001). Instead, a stagnant MP is effectively a slow sink to energetic particles.

Acknowledgement

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References

Balogh, A., Carr, C.M., Acuña, M.H., et al. The Cluster magnetic field investigation: overview of in-flight performance and initial results. Ann. Geophys. 19, 1207–1218, 2001.

Dunlop, M.W., Balogh, A., Cargill, P.J., et al. Cluster observes the Earths magnetopause: coordinated four-point magnetic field measurements. Ann. Geophys. 19, 1449–1460, 2001.

Fritz, T.A. The cusp as a source of magnetospheric energetic particles, currents, and electric fields: A new paradigm. Space Sci. Rev. 95, 469–488, 2001.

Gustafsson, G., André, M., Carozzi, T., et al. First results of electric field and density observations by Cluster EFW based on initial months of operation. Ann. Geophys. 19, 1219–1240, 2001.

Sauvaud, J.-A., Lundin, R., Réme, H., et al. Intermittent thermal plasma acceleration linked to sporadic motions of the magnetopause, first Cluster results. Ann. Geophys. 19, 1523–1532, 2001.

Wilken, B., Axford, W.I., Daglis, I., et al. RAPID: the imaging energetic particle spectrometer on Cluster. Space Sci. Rev. 79, 399–473, 1997.

Wilken, B., Daly, P.W., Mall, U., et al. First results from the RAPID imaging energetic particle spectrometer on board Cluster. Ann. Geophys. 19, 1355–1366, 2001.