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Energetic electron signatures in an active magnetotail plasma sheet

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Abstract

Particles with energies of tens to hundreds of keV provide a powerful diagnostic of the acceleration processes that characterise the Earth's magnetosphere, in particular the highly dynamic nightside plasma sheet. Such energetic particles can be detected by the RAPID experiment, onboard the quartet of Cluster spacecraft. We present results from the study of a series of quasi-periodic, intense energetic electron signatures in the magnetotail revealed by RAPID Imaging Electron Spectrometer (IES) observations some 19 Earth radii (R_E) downtail, associated with the passage of a highly geoeffective, high-speed solar wind stream. The RAPID-IES signatures – interpreted in combination with magnetic field and lower-energy electron measurements from the FGM and PEACE experiments on Cluster, respectively, and with reference to energetic electron observations from the CEPPAD-IES instrument on Polar – are understood in terms of repeated encounters of the Cluster spacecraft with the tail plasma sheet in response to the resultant tail reconfiguration in each of a series of substorms. We consider the Cluster response for two of these substorms (identified according to the conventional expansion phase onset indicators of particle injection at geosynchronous orbit and Pi2 pulsations at Earth) in terms of two possible tail configurations in which a Near-Earth Neutral Line forms either antisunward or sunward of the Cluster spacecraft. The latter scenario, in which the reconnection X-line is assumed to form sunward of Cluster and subsequently migrate downtail such that the spacecraft become engulfed in a tailward expanding plasma sheet, is shown to be more consistent with the observations.

Keywords: Cluster; Substorm; Energetic particles

1. Introduction

In many regions of the Earth's magnetosphere, the energetic tail of the plasma distribution can contribute significantly to the total plasma energy density. Although the specific mechanisms whereby particles achieve energies that can exceed hundreds of keV are not fully understood (Friedel et al., 2002), the behaviour of energetic plasma provides a powerful diagnostic of geospace acceleration processes, in particular in the magnetotail associated with the substorm phenomenon. The RAPID – Research with Adaptive Particle Imaging Detectors – experiment (Wilken et al., 2001) on each of the four spacecraft of the Cluster mission (Escoubet et al., 2001) was designed to probe the Earth's energetic plasma environment. The Cluster spacecraft are in a polar orbit, with an orbital period of some 57 hours, and with perigee and apogee at 4 and 19.6 Earth radii (R_E), respectively. Energetic plasma observations are also made by the CEPPAD – Comprehensive Energetic Particle and Pitch Angle Distribution – experiment (Blake

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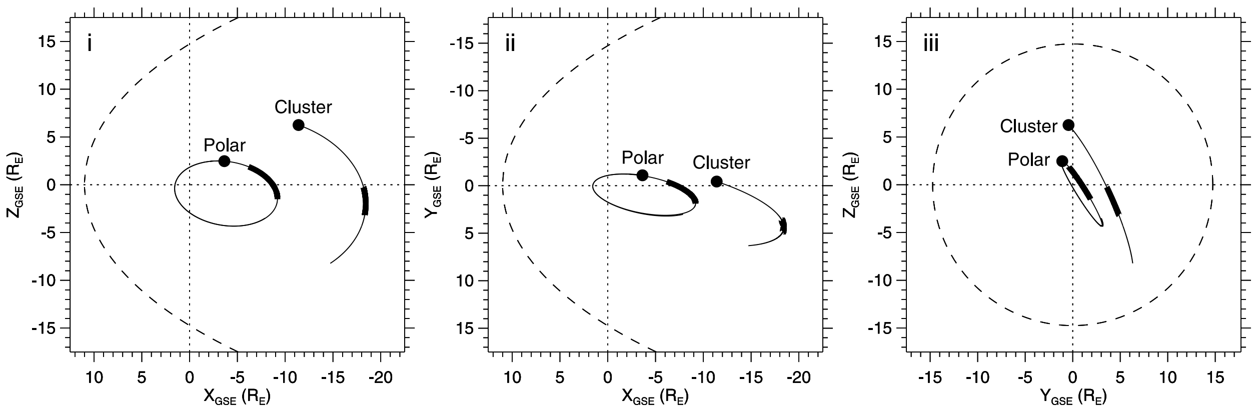

Fig. 1. Orbital track of Cluster spacecraft 2 and Polar in the $X–Z_{GSE}$ (panel *i*), $X–Y_{GSE}$ (panel *ii*), and $Y–Z_{GSE}$ planes (panel *iii*), during the interval extending from 05:00 UT on 17 September to 08:00 UT on 18 September, 2003; highlighted is that part of the orbit covered by each spacecraft between 17:00 and 22:00 UT on 17 September. Marked on the figure, as a dashed line, is the predicted magnetopause location (Sibeck et al., 1991).

et al., 1995) onboard the Polar spacecraft (Acuña et al., 1995), launched into a $1.8 \times 9\ R_E$ polar orbit.

Fig. 1 presents the orbital tracks of Cluster spacecraft 2 and the Polar spacecraft in the *X–Z* (panel *i*), *X–Y* (panel *ii*) and *Y–Z* (panel *iii*) planes, in the Geocentric Solar Ecliptic (GSE) coordinate system, for the interval that extends from 05:00 Universal Time (UT) on 17 September until 08:00 UT on 18 September, 2003. A filled circle marks the location of each spacecraft at start of this interval, and also highlighted, with a thick line, is that part of their orbit sampled by the spacecraft between 17:00 and 22:00 UT on 17 September, 2003. Marked on the figure for guidance is the predicted position of the magnetopause (dashed line), derived from the model of Sibeck et al. (1991). This interval corresponds to a southbound magnetotail crossing by Cluster, with apogee near 23 Magnetic Local Time (MLT) at 23:30 UT on 17 September. The orbital plane of Polar is fortuitously well aligned with that of Cluster, lying within an hour in local time, although Polar has a much shorter period of 18 h such that over the full interval of interest the spacecraft covers almost two full orbits. In contrast to Cluster, the Polar spacecraft moves northward through apogee.

The interval studied here is characterised by significant substorm activity, associated with conditions of variable interplanetary magnetic field (IMF) within a high-speed solar wind stream. We consider the resultant series of intense energetic electron signatures in the magnetotail, observed by the RAPID experiment on Cluster, in combination with magnetic field and lower-energy electron measurements, from the Cluster/FGM and PEACE experiments, respectively, and energetic electron observations from the CEPPAD instrument on the Polar spacecraft.

2. Instrumentation

The Cluster/RAPID experiment comprises both an Imaging Electron Spectrometer (IES) and an Imaging Ion Mass Spectrometer (IIMS). The RAPID-IES observes electrons with energies in the range of 40 to some 400 keV. For the interval that forms the basis for the current study, the RAPID-IES on Cluster spacecraft 2 was operating in a high data-rate mode, termed normal mode 3 (NM3). By taking advantage of the telemetry released due to the non-functionality of the CIS – Cluster Ion Spectrometry – experiment (Rème et al., 2001) on this spacecraft, the NM3 mode provides the full three-dimensional electron distribution from the RAPID-IES instrument over its entire energy range during each 4-s spin. The CEPPAD instrument on Polar includes an IES that is virtually identical to that on Cluster, providing spin-resolution (6-s) three-dimensional electron distributions.

The RAPID-IES energetic electron observations are interpreted in combination with magnetic field measurements, from the Cluster/FGM – FluxGate Magnetometer – instrument (Balogh et al., 2001), and lower-energy electron observations from Cluster/PEACE. The PEACE – Plasma Electron And Current Experiment – experiment (Johnstone et al., 1997) comprises two sensors, LEEA (Low-Energy Electron Analyzer) and HEEA (High-Energy Electron Analyzer), which cover a combined energy range of 1 eV to 25 keV. We present only measurements from the HEEA sensor, which was operating with its lower energy threshold set to 40 eV during the interval of interest. By combining the Cluster/RAPID-IES observations with those from the PEACE-HEEA sensor we are availed of electron observations over an extensive range of energies, from near 40 eV to over 400 keV, albeit with a small gap in coverage between the upper energy limit detectable by PEACE and the lower limit observed by RAPID.

3. Observations

3.1. Interplanetary conditions

Solar wind conditions during the interval that extends from 05:00 UT on 17 September until 08:00 UT on 18

September, 2003 were diagnosed by the ACE – Advanced Composition Explorer – spacecraft (Stone et al., 1998) as being characteristic of the passage of a high-speed solar wind stream, which was preceded, as is typical, by a region of compression termed a co-rotating interaction region (e.g., Feldman et al., 1978). The solar wind velocity, provided by the SWEPAM – Solar Wind Electron Proton Alpha Monitor – instrument (McComas et al., 1998) onboard ACE, exceeded 700 km/s over the majority of the interval. Such high prevailing solar wind speeds, in combination with episodes of southward-orientated magnetic field of up to 10 nT in magnitude in what was revealed by the ACE/MAG instrument (Smith et al., 1998) to be an extremely variable IMF, resulted in the solar wind being particularly geoeffective (see, for example, Baker et al., 2002). The response observed within the magnetosphere is commensurate with such highly geoeffective solar wind conditions, both on the ground – where the auroral electrojet indices derived from ground-based magnetometer observations showed significant substorm activity, with AE approaching 2000 nT – and at geosynchronous orbit, where a particular preponderance of substorms is confirmed by energetic particle observations from the Los Alamos National Laboratory (LANL) satellites (e.g., Belian et al., 1978).

3.2. Overview of polar and Cluster observations

Panel *i* of Fig. 2 presents a spectrogram of the spin-averaged differential energy flux of energetic electrons, over the full interval of interest, from the CEPPAD-IES instrument onboard the Polar satellite. Panel *ii* presents the equivalent energetic electron flux measurements from the RAPID-IES on Cluster spacecraft 2, but in combination with corresponding observations of lower-energy electrons from the HEEA sensor of the Cluster/PEACE instrument. The large flux of electrons observed by PEACE below about 100 eV corresponds to photoelectron contamination resulting from spacecraft charging effects, which, as is confirmed by the figure, is particularly problematic in regions of tenuous plasma such as the tail lobes (Szita et al., 2001). Panels *iii* and *iv* of Fig. 2 present magnetic field observations from Cluster/FGM, with the upper panel of the pair illustrating the X, Y, and Z components of the magnetic field – B_X, B_Y, and B_Z, respectively – in Geocentric Solar Magnetic (GSM) coordinates, and the lower panel, the field magnitude. For presentational purposes, all data in this plot are averaged to a temporal resolution of 60 s.

We consider initially the Cluster observations, from the southbound magnetotail crossing to which this interval corresponds. Fig. 2, panel *ii*, reveals that the RAPID-IES instrument on Cluster observed a series of intense bursts of electrons, throughout its entire operational energy range, and with fluxes enhanced by many orders of magnitude over those prior to and after each burst. These energetic particle signatures are understood to be the result of repeated encounters of the central tail plasma sheet/ plasma sheet boundary layer (PSBL) by the Cluster spacecraft, from an initial location in the lobe (subsequently, we will refer to the combined central plasma sheet/PSBL as the "plasma sheet"). Particles with energies approaching several hundreds of keV are characteristic of the plasma sheet, although after prolonged periods of northward IMF the plasma sheet has been seen to become cold and devoid of its high-energy component (Terasawa et al., 1997). The figure further reveals that the electron population of the plasma sheet, the energetic tail of which is detected by RAPID, extends far down into the energy range covered by the HEEA sensor of PEACE. Corresponding signatures of multiple plasma sheet encounters are also evident in the high and thermal energy ion observations from Cluster, from the RAPID-IIMS and CIS instruments, respectively (not shown).

It is noted that there is a good qualitative agreement between the electron energy flux observed in the upper energy channels of PEACE and that from RAPID-IES. This is confirmed by the examination of individual spectra. It should also be pointed out, however, that the RAPID energy fluxes appear consistently low relative to the expectation from an extrapolation of the PEACE fluxes to higher energies; this seems to be the case throughout the interval under study. To compensate for this apparent mismatch, the PEACE differential energy flux has been reduced by a factor of 5, a value estimated from fitting to a kappa distribution, although it is not yet clear to which instrument the discrepancy should be attributed.

The magnetic field at Cluster, from the FGM instrument (Fig. 2, panels *iii* and *iv*), shows an overall reversal in the magnetic field X component after around 11 UT on 17 September, from positive (Earthward) to negative values, denoting a crossing through the current (neutral) sheet as the spacecraft travels from north to south. The fact that there are multiple current sheet crossings before B_X becomes consistently tailward near 13 UT is indicative of the highly active conditions prevalent in the tail. On timescales of several hours, the magnetic field undergoes what could be described as a series of slow increases in magnitude, each followed by a more rapid, but by no means instantaneous, decrease. This behaviour, reflective mainly of variations in the dominant X component of the magnetic field, is clearest after the current sheet crossing and somewhat masked in the vicinity of the current sheet itself. Each of these reductions in the magnetic field magnitude, when considered in conjunction with the associated field reorientation characterised by a decrease in B_X and simultaneous increase in B_Z, provides a signature characteristic of tail dipolarization in response to substorm expansion phase onset. As the current sheet is not, in general, aligned to the GSM XY plane, a non-zero B_Z component does not necessarily indicate magnetic field threading the current sheet. Nevertheless, we note from Fig. 2 that consistently during the dipolarizations the Z component of the field at Cluster reverses, with brief intervals of weakly negative B_Z preceding intervals of positive B_Z. The subsequent

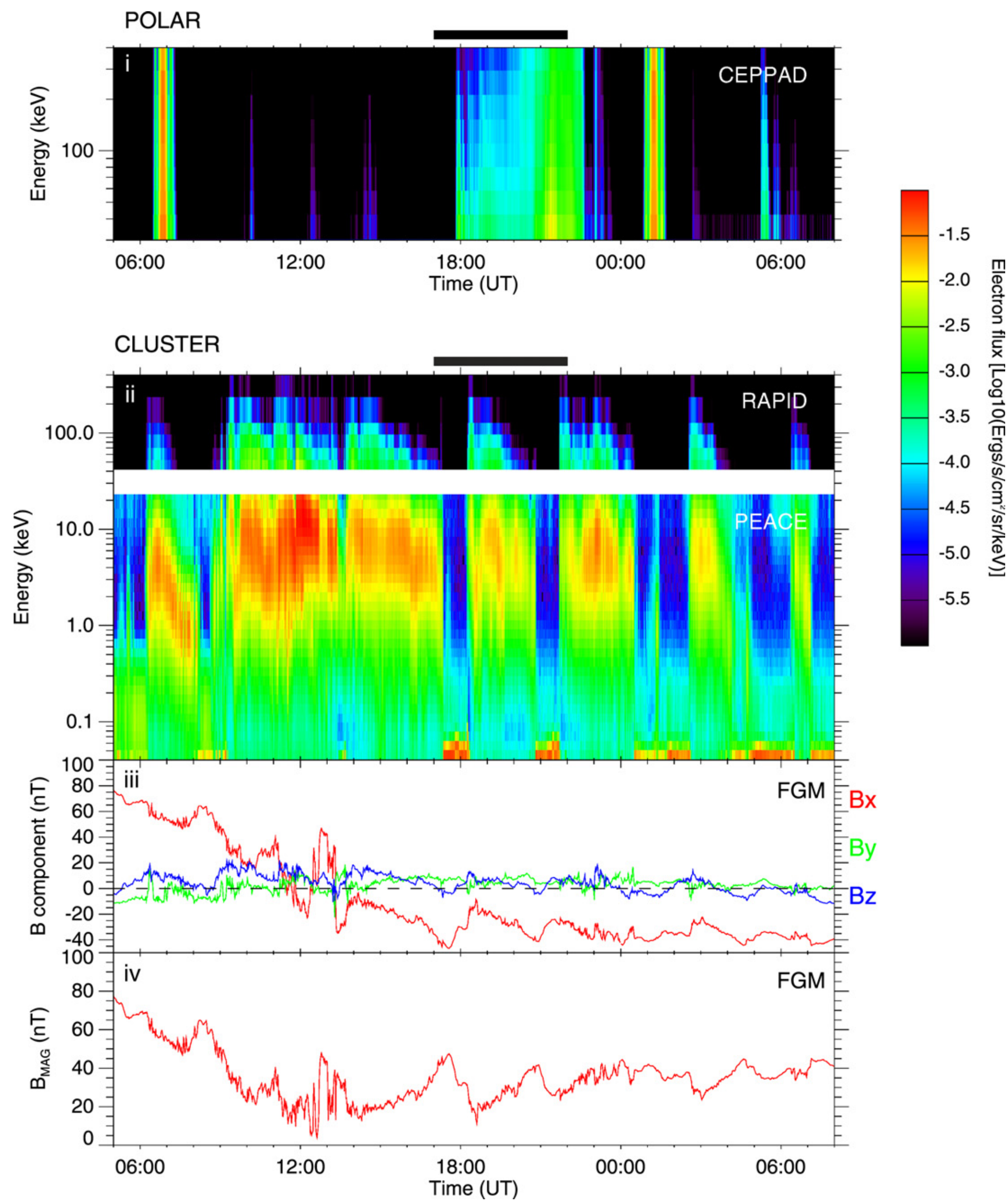

Fig. 2. Spectrogram of spin-averaged differential electron energy flux from the CEPPAD-IES instrument on Polar (panel *i*), combined Cluster/PEACE and RAPID-IES electron energy spectrogram (panel *ii*), magnetic field *X*, *Y*, and *Z* components, in GSM coordinates, from Cluster/FGM (panel *iii*), and field magnitude from FGM (panel *iv*), during the interval from 05:00 UT on 17 September to 08:00 UT on 18 September, 2003. Marked with a horizontal bar is that section of the plot from 17:00 and 22:00 UT on 17 September.

increase in the magnitude of B_X, and corresponding reduction in B_Z, is explained in terms of the thinning of the tail in the growth phase prior to the next substorm onset. The observations are consistent with a repeated sequence of dipolarizations and subsequent stretching of the tail over a number of substorm cycles. Given such a scenario, we interpret the observations as a series of incursions into the plasma sheet, evidenced by the intense energetic electron signatures, which is related to the ongoing substorm activity, itself associated with the prevailing highly geoeffective solar wind conditions.

To support this interpretation we turn our attention to the corresponding energetic electron observations from the Polar spacecraft during the period of the Cluster tail crossing, as depicted in panel *i* of Fig. 2. As noted previously the orbital planes of Cluster and Polar are well aligned. The intense fluxes seen by CEPPAD-IES centred at 06:50 UT on the 17 September and 01:15 UT on the 18 September correspond to Polar's passage at perigee through the ring current on the dayside and any correlation with the signatures seen by Cluster in the tail are purely coincidental. When Polar has emerged from perigee into the nightside segment of each orbit covered by the period under study, it too detects episodes of enhanced energetic electron flux, consistent with substorm-associated incursions into the plasma sheet from the lobe. That many of these are comparatively short lived and of low intensity is symptomatic of the orbital period being such that the spacecraft samples a much larger range of magnetic latitudes during this interval than does Cluster. The detection of an enhanced flux of energetic particles by CEPPAD-IES, shortly prior to 18:00 UT on 17 September when Polar is near the magnetic equator, heralds the onset of a more sustained plasma sheet encounter by the spacecraft.

3.3. Detailed observations

We now focus on a specific interval in order to examine in more detail the signatures observed by both the Cluster and Polar spacecraft, with the spacecraft being close to magnetic conjugacy, which we also relate to other indicators of substorm activity. To this end, Fig. 3 presents Polar and Cluster observations in the same format as Fig. 2, except covering the reduced time interval from 17:00 to 22:00 UT on 17 September; this interval corresponds to that section of Fig. 2 delimited by a horizontal bar, and the part of the orbits marked in Fig. 1 with thick lines. Observations are at the spin-resolution of the appropriate

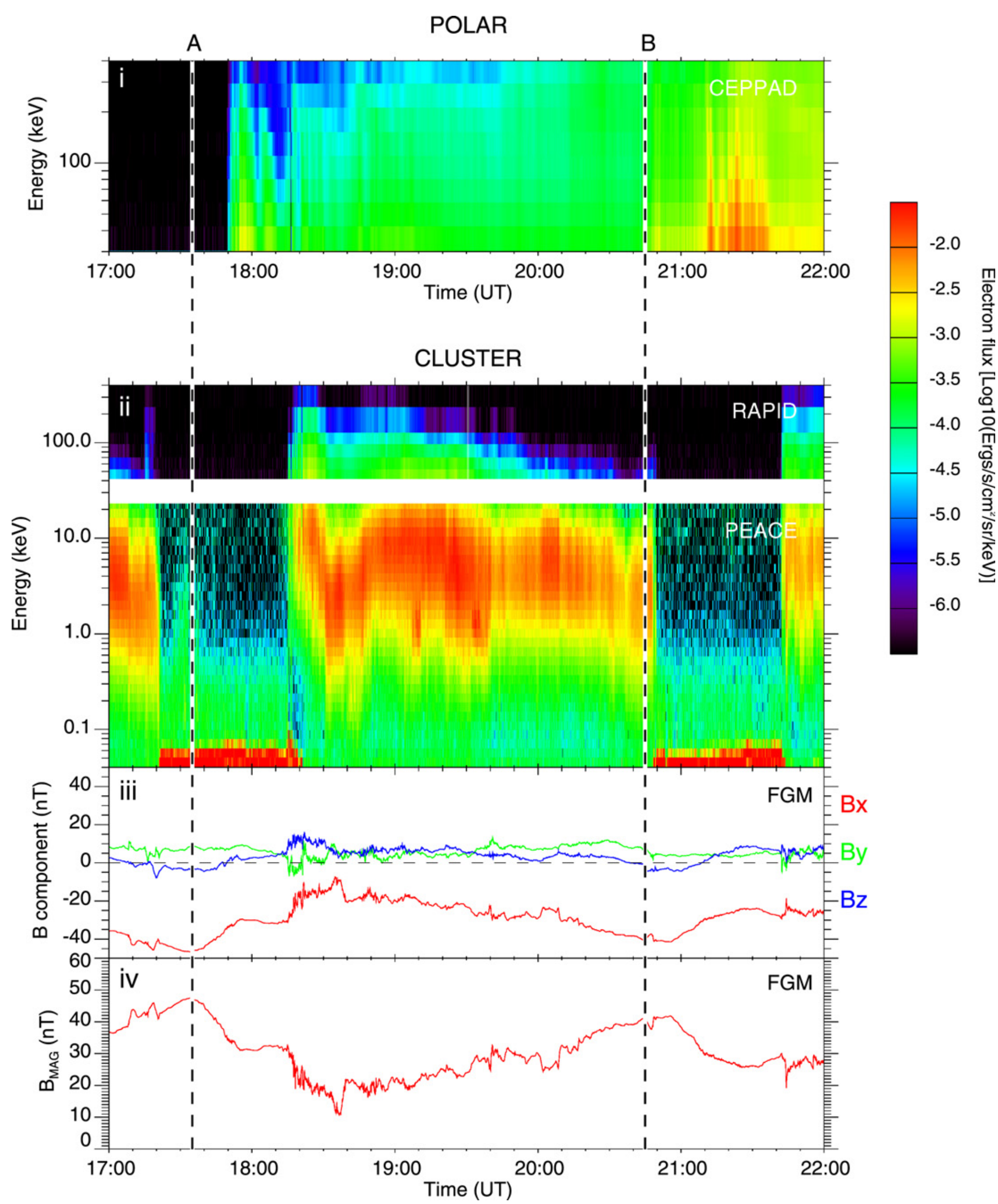

Fig. 3. As for Fig. 2, for the interval from 17:00 to 22:00 UT on 17 September 2003. A and B Indicate identified substorm expansion phase onsets.

spacecraft. During this interval, Cluster was south of the current sheet, which it had passed through some six hours previously. The Polar spacecraft was on a northbound passage through the current sheet which, based on MFE (Magnetic Field Experiment: Russell et al., 1995) observations (not shown), it crossed near 21:00 UT.

During this interval, we have identified two substorm expansion phase onsets, using the conventional onset identifiers of energetic particle injection at geosynchronous altitudes (Baker et al., 1981) and mid-latitude Pi2 pulsations at Earth (Yeoman et al., 1994). Observations from the LANL-02A geosynchronous satellite, the closest of the LANL spacecraft to midnight during the interval, reveal energetic particle injections at 17:35 and 20:45 UT, marked A and B on Fig. 3. Confirmation of these as being indicative of the times of expansion phase onsets is provided by the presence of Pi2 pulsations in the midnight sector, in mid-latitude ground magnetometer observations from the European SAMNET (Sub-Auroral Magnetometer Network) chain (Yeoman et al., 1990).

At the start of this interval, Cluster was located in the southern plasma sheet whilst Polar was in the southern tail lobe, as diagnosed by the particle instruments onboard the two spacecraft (Fig. 3, panels *i* and *ii*). Some 20 min later, at 17:20 UT, Cluster is seen to emerge from the plasma sheet and itself enter the southern lobe. It is concluded that this is a result of the thinning of the plasma sheet – under the enhanced magnetic pressure in the lobes – in the substorm growth phase, a conclusion supported by the Cluster/FGM magnetic field measurements (panels *iii* and *iv*) that are consistent with the development over a number of hours of a stretched tail configuration. The growth phase, as inferred from the FGM observations, continues until 17:35 UT at which time the magnetic field starts to relax into a more dipolar configuration. That this is indicative of substorm expansion phase onset, and not just a localized phenomenon, is confirmed by the close correspondence of the start of dipolarization to the substorm onset timed from the conventional onset indicators (marked A on Fig. 3). Some 15 and 40 min after onset, respectively, the Polar and Cluster spacecraft encountered the plasma sheet. Polar's encounter with the plasma sheet could be interpreted simply as the result of the spacecraft's northbound trajectory toward a nominal plasma sheet location. However, we can conclude that the plasma sheet must be expanding in order for it to engulf the southward-moving Cluster spacecraft. Cluster remains in the plasma sheet until 20:50 UT, much of which time is interpreted from the FGM observations as the growth phase of the subsequent substorm. A surprising feature is that, despite there being an expansion phase onset identified at 20:45 UT (marked B) – after which time one might expect Cluster to remain contained within the again expanding plasma sheet, Cluster exits into the lobe several minutes later.

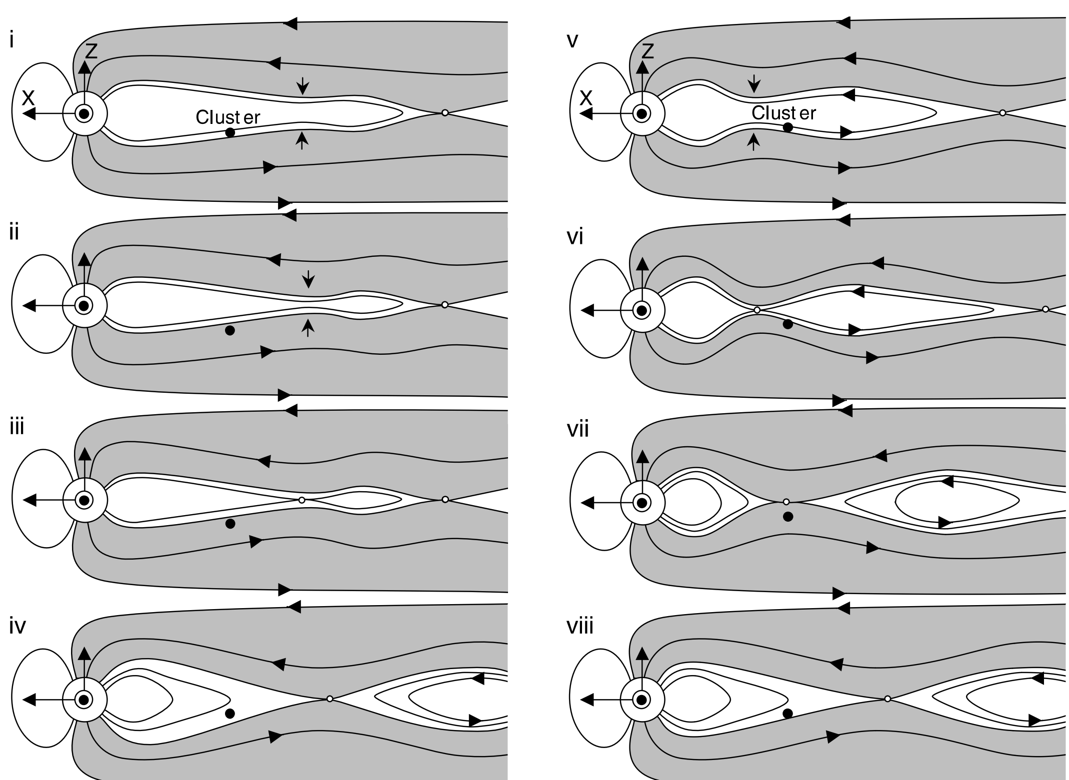

Fig. 4. Two possible scenarios considered to account for the Cluster observations, scenario 1 (panels *i* to *iv*) in which the NENL is assumed to form sunward of the spacecraft and, scenario 2 (panels *v*–*viii*) in which the NENL forms antisunward of Cluster. Grey shaded areas represent the tail lobes, open circles are active reconnection neutral lines in the cross-tail current sheet, and the filled circle is the location of the Cluster craft.

Unlike Cluster, the Polar spacecraft, which is close to the magnetic equator at this time, does remain within the confines of the plasma sheet.

In order to explain this unexpected aspect of the Cluster observations we consider the observations in terms of two possible scenarios of substorm expansion and recovery, in which the Near-Earth Neutral Line (NENL) formed either antisunward (scenario 1) or sunward (scenario 2) of Cluster. Scenarios 1 and 2 are represented schematically by panels *i* to *iv* and panels *v* to *viii*, respectively, of Fig. 4; Cluster is represented by a filled circle, and the tail lobes are shaded in grey.

In scenario 1, Cluster entered the lobe between *i* and *ii* during the growth phase of the substorm, because of plasma sheet thinning. Near the time of expansion phase onset (panel *iii*), the NENL had formed antisunward of Cluster such that subsequent dipolarization of the mid- and near-tail returns Cluster into the plasma sheet (*iv*). In scenario 2, Cluster entered the lobe between *v* and *vi*. This lobe entry could have occurred either before or after the formation of the NENL sunward of the spacecraft because it can be caused either by the plasma sheet thinning, as in scenario 1, or by the NENL forming and migrating tailward. By *vii*, the NENL had reached the X coordinate of the satellites and the previously negative B_Z field deflection turned to positive. In *viii*, the tailward retreat of the NENL brought Cluster back into the plasma sheet. In scenario 1, Cluster must have entered the lobe while the plasma sheet was thinning, i.e., during the growth phase before substorm onset. In scenario 2, onset may have occurred while Cluster was still within the proto-plasmoid plasma sheet and the satellites then moved into the lobe as the NENL migrated tailwards. Thus the Cluster observations of lobe entry after onset (in substorm A presented above), are inconsistent with scenario 1 but are consistent with scenario 2, thereby providing evidence that the NENL formed at or before the time of onset and sunward of the Cluster spacecraft at X near -15 R_E. Note also that scenario 2 predicts the observed bipolar signatures in the northward field threading the current sheet.

4. Conclusions

Results have been presented from the study of a series of intense energetic electron signatures in the magnetotail based principally on observations made by the RAPID-IES and PEACE instruments onboard Cluster, during an extended interval of intense substorm activity related to the passage of a highly geoeffective, high-speed solar wind stream. The energetic electron signatures are considered to be the result of repeated incursions of the Cluster spacecraft into the tail plasma sheet, in response to the tail reconfiguration in each of a series of substorms. From those substorms examined in detail, we consider that the particle and field observations are most consistent with a scenario in which the plasma sheet expands tailward over the spacecraft in the wake of a tailward-moving reconnection NENL, with the latter first formed sunward of Cluster. Tail thinning in the growth phase of the subsequent substorm contracts the plasma sheet such that it recedes back over Cluster, and spacecraft return to the tenuous plasma environment of the lobe.

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