

## Cluster electron observations of the separatrix layer during traveling compression regions

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[1] We present Cluster 4-point observations of electrons during traveling compression regions (TCRs) on 19 September 2001. The electron and  $|B|$  signatures vary with distance from the plasma sheet, confirming that transient plasma sheet bulges propagate past Cluster. TCRs with  $|B|$  increases have either no electron signature, or unidirectional  $\sim 1$  keV electrons at the plasma sheet edge. However, spacecraft initially near the plasma sheet edge are engulfed within the bulge and observe a diamagnetic reduction in  $|B|$ . In cases where the underlying plasma sheet bulge moves earthward, electrons at the plasma sheet edge stream tailward. We suggest this represents either a remote observation of electrons closing the Hall current system in an ion diffusion region located farther tailward, or the outflow jets along the separatrix formed by a second neutral line located farther earthward of the spacecraft. The latter case implies the simultaneous action of multiple X-lines in the near-Earth tail.

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### 1. Introduction

[2] Traveling compression regions (TCRs) were first identified in the deep geomagnetic tail by *Slavin et al.* [1984], who suggested they are caused by tailward passage of a plasmoid or magnetic flux rope, which creates a localized bulge in the plasma sheet. The bulge compresses the magnetic flux between the edge of the plasma sheet and the tail magnetopause, giving a transient increase of  $|B_{\text{LOBE}}|$ . The draping of the lobe field over the bulge also creates a north-then-south (NS) deflection in the  $B_z$  component. *Moldwin and Hughes* [1994] first reported IMP-8 TCR signatures with south-then-north (SN)  $B_z$  perturbations, and inferred the underlying plasmoid/flux rope to be moving earthward. TCRs in the distant tail have subsequently been studied using ISEE 3, IMP 8 and Geotail data [see *Slavin et al.*, 2003a, and references therein].

[3] Magnetic flux ropes have also been reported in the nearer Earth plasma sheet. Most recently, *Slavin et al.* [2003a] found small ( $< 5 R_E$ ) flux rope structures are common at  $-20 R_E < X_{\text{GSE}} < -30 R_E$ . These show SN (NS)  $B_z$  deflections when they are embedded in earthward (tailward) flow, and were interpreted as evidence of magnetic reconnection occurring near-simultaneously at several

X-lines. Variations in the reconnection rates at these multiple X-lines mean the fastest will reach lobe field lines first, and thus cause a disconnection between the sections of plasma sheet earthward and tailward of this X-line [*Schindler*, 1974]. Owing to the high lobe Alfvén speed, flux rope structures and plasma sheet plasma lying earthward (tailward) of this X-line will subsequently be swept earthward (tailward), accounting for the SN (NS)  $B_z$  deflections.

[4] As first proposed by *Owen and Slavin* [1992], the signature of the passage of a plasmoid/flux rope is a function of distance from the neutral sheet. Classic TCR signatures may be observed by a spacecraft remaining within the lobe proper throughout the plasmoid passage. In this case there is no plasma signature. However, a spacecraft initially close to the edge of the plasma sheet, may be temporarily engulfed by the bulge, causing a strong increase in the observed plasma pressure. The associated diamagnetic effect results in a reduction of the observed magnetic field strength rather than a compression. The bipolar  $B_z$  signature can generally still be identified, however. Between these extremes, *Owen and Slavin* [1992] report a class of signature in which the spacecraft is far enough from the neutral sheet that the bulge is sufficient only to deflect the plasma sheet boundary layer (PSBL) over the spacecraft. In this case, a classic magnetic TCR signature is recorded, but there is also a clear plasma signature. During magnetic reconnection, the PSBL is synonymous with the separatrix layers, such that observations from these regions could be used to remotely sense processes occurring at the neutral line(s). For example, models and simulations of the reconnection region based on ideas first put forward by *Sonnerup* [1979] show that decoupling of ion and electron motion gives rise to Hall currents in the ion diffusion region. These currents are supported by an electron flow into the diffusion region along the separatrix layer, in the opposite sense to the broader plasma sheet outflow from a reconnection site. Observations consistent with this idea have been presented by, e.g., *Nagai et al.* [2001]. In this paper, we examine TCR signatures observed by Cluster on 19 September 2001 [*Slavin et al.*, 2003b], with emphasis on the electron plasma data returned by the PEACE instruments [*Johnstone et al.*, 1997]. We use the 4-point nature of these measurements to examine these processes in unprecedented detail.

### 2. Observations: 19 September 2001

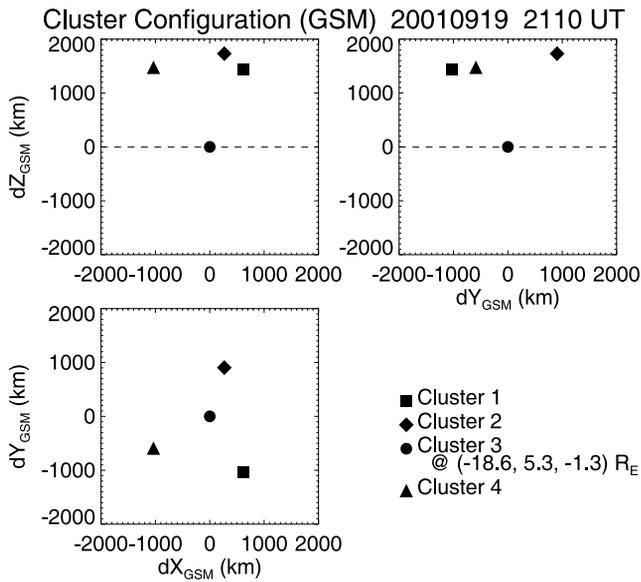
[5] The near-optimum configuration of the Cluster tetrahedron at 2110 UT on 19 September 2001 is shown in Figure 1, where the 3 panels show the relative locations of the 4 spacecraft projected on to the GSM X-Z, Y-Z and X-Y planes. Cluster 3 (C3), the reference spacecraft, is located at GSM coordinates  $(-18.6, 5.3, -1.3)R_E$  and 1400–1800 km southward of the other 3 spacecraft. The quartet was moving predominantly in the  $-Z_{\text{GSM}}$  direction at this time.

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**Figure 1.** Cluster configuration at 2110 UT, 19 September 2001. Note that C3 is located 1400–1800 km southward of C1, 2, and 4.

[6] A well-defined substorm onset occurred at 2039 UT, with several subsequent intensifications at 2109 UT, 2115 UT, and 2151 UT, before a recovery phase from  $\sim 2215$  UT (E. Boralv et al., Correlation between ground-based observations of substorm signatures and magnetotail dynamics, submitted to *Annales Geophysicae*, 2004). Cluster observed 6 TCR signatures associated with this activity [Slavin et al., 2003b], as evident in Figure 2, which shows an overview of the FGM [Balogh et al., 1997] and PEACE data for the period 2050–2205 UT. The top 2 panels show  $B_z$  and  $|B|$ , respectively, at each of the 4 spacecraft (C1-black, C2-red, C3-green, C4-magenta). Note  $B_x$  (not shown) remained negative at each spacecraft, indicating they all remained below the tail neutral sheet during this period. The lower 4 panels contain spectrograms of the direction-averaged differential energy flux for electrons in the energy range 30 eV–30 keV recorded by the PEACE instrument on each spacecraft. Note that intense fluxes below  $\sim 50$  eV in panels 3 and 4 are photoelectron artifacts on C1 and C2, where the spacecraft potential (solid trace) can not be held to  $<10$  V.

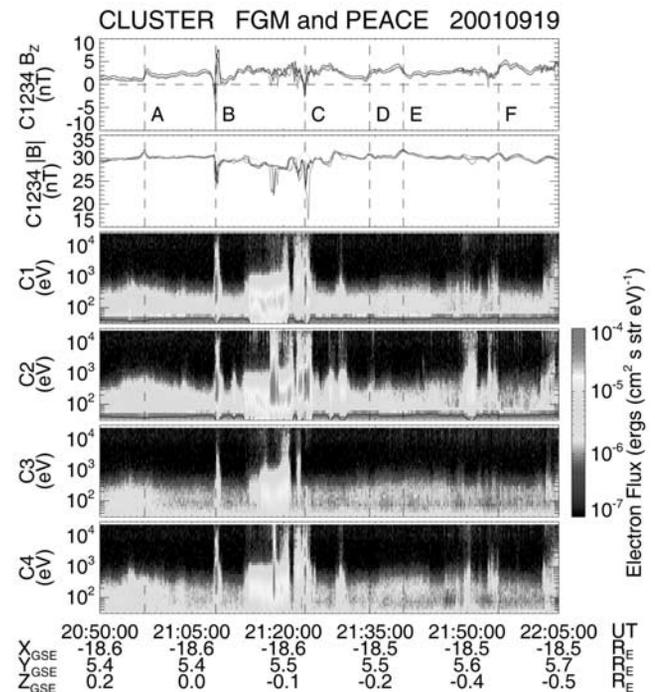
[7] The 6 TCR signatures identified by Slavin et al. [2003b] are marked by vertical dashed lines in Figure 2 and labeled A–F. Of these, 5 (A–D, F) were associated with a SN  $B_z$  variation. Analysis of time delays between spacecraft confirms that these TCRs are indeed moving earthward, as expected from the sense of this  $B_z$  variation, at speeds from  $\sim 380$  to  $\sim 600$  km s $^{-1}$ . The remaining TCR signature (E) exhibited a NS bipolar signature, and timing analysis confirmed this TCR moved tailward at 260 km s $^{-1}$ . At C3 (green trace), all events are associated with a transient increase of a few nT in  $|B|$ , such that C3 sees a series of “classic” TCR magnetic signatures. Similar magnetic signatures are seen at the other 3 spacecraft for events A, D, E, and F. However, for events B and C, the field strength at C1, 2, and 4 exhibits a significant transitory decrease.

[8] We note several types of response in the electron data for these events. Events A and E have no electron flux disturbance at any of the spacecraft. For D and F, weak flux

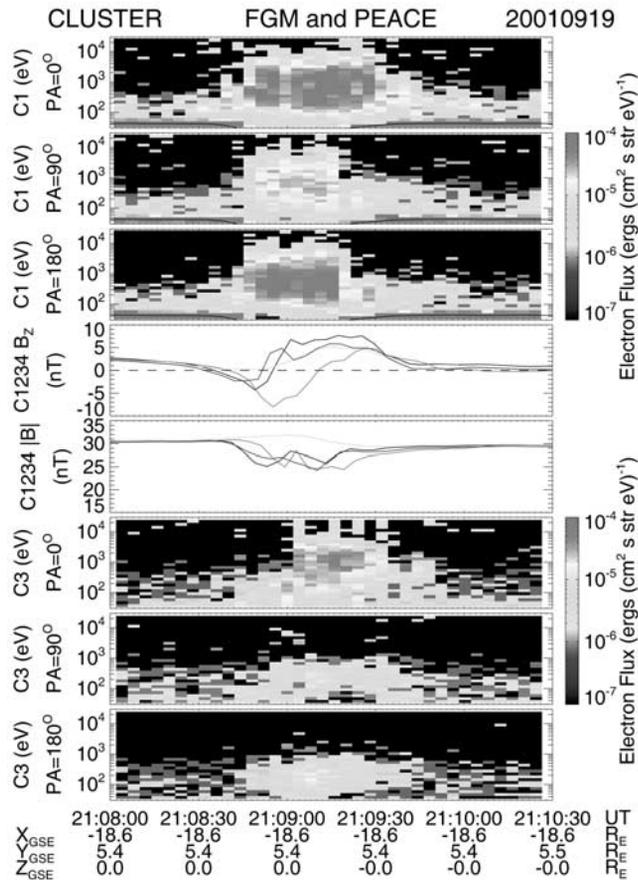
enhancements, extending to higher energies than the inter-event background, appear at 1 or more spacecraft. For event D, this appears at C2 (farthest north) only, while for event F this is evident in C1, 2 and 4 data. Events B and C, which have  $|B|$  reductions at C1, 2 and 4 show relatively strong flux enhancements at these spacecraft, while at C3 only weak (B) or no (C) enhancement is observed.

[9] Figure 3 shows 2.5 min of data centered about the TCR event labeled B in Figure 2. The top 3 panels each contain a spectrogram of PEACE electron data recorded by C1. The format is the same as the spectrograms shown in Figure 2, but now the 3 panels indicate the differential energy flux observed in the instrument look-directions most closely associated with particles of  $0^\circ$ ,  $90^\circ$  and  $180^\circ$  pitch angle, respectively. The data shown in these panels are largely representative, with the exception of a time shift, of those recorded by C2 and C4 for this period, so we show only one of these datasets here. The 4th and 5th panels again show the magnetic field  $B_z$  component and magnitude from all 4 spacecraft, in the same format as Figure 2. Finally the lower 3 panels are formatted as the top 3 panels, but show the data recorded by C3 during this interval.

[10] The magnetic field traces during this sub-interval clearly show a bipolar SN signature at all 4 spacecraft, consistent with an earthward moving TCR. Moreover, examination of the timing of the inflection points for the data recorded at C1, 2, and 4, which lie in a plane close to parallel to the GSM XY plane, implies that the underlying structure moved earthward and duskward past the spacecraft.



**Figure 2.** Cluster FGM and PEACE observations for 2050–2205 UT on 19 September 2001. The top 2 panels show  $B_z$  and  $|B|$  observed by C1 (black), C2 (red), C3 (green), and C4 (magenta). The lower 4 panels show E-t spectrograms of direction-averaged electron differential energy flux from each spacecraft. Occurrence of TCR signatures is marked by vertical dashed lines labeled A–F. See color version of this figure in the HTML.



**Figure 3.** Cluster FGM and PEACE observations for 2050–2205 UT on 19 September 2001 (Event B). The top 3 spectrograms show differential energy flux, observed by C1, of 0°, 90° and 180° pitch angle electrons, respectively. The middle 2 panels show  $B_z$  and  $|B|$  in the same format as Figure 2. The lower 3 panels, in the same format as the top 3 panels, show data recorded by C3. The outermost edge of the plasma sheet is characterized by a tailward (0° p.a.) beam of particles. See color version of this figure in the HTML.

More sophisticated analysis [Slavin *et al.*, 2003b] shows this earthward motion was at a speed of  $416 \text{ km s}^{-1}$ . Examination of the PEACE data from C1 in the top 3 panels indicates that the depression in the field strength observed by C1 (and C2 and C4) is associated with the appearance of strong fluxes of electrons with temperature  $\sim 1 \text{ keV}$ . These electrons show strong bi-directional streaming along the magnetic field direction (first and third panels), with a weaker enhancement in the perpendicular direction. Note however that the enhancement of fluxes of 0° pitch angle electrons begins prior to those of the 90° and 180° pitch angle electrons, and more obviously has a cessation some 10–12 seconds later than 90° and 180° particles. Similar behavior is exhibited in the data from C2 and C4 (not shown).

[11] In contrast, the magnetic field observed at C3 is observed to have a peak in the field strength during the passage of the TCR. Examination of the PEACE data in the lower three panels of Figure 3 indicates a weaker enhancement in the fluxes of  $\sim 1 \text{ keV}$  electrons, and this enhancement is almost entirely confined to those electrons with 0° pitch angles. The other 2 look-directions exhibit only very modest enhancements of lower energy electrons. Data (not shown)

from the CIS-HIA instrument at 12 s resolution show an ion flux enhancement at C1 from 2108:42 to 2109:18 UT (approximately the period of the 180° electron enhancement). These ions have earthward bulk velocity of  $100\text{--}200 \text{ km s}^{-1}$ , although velocities on either side (i.e., during the enhancement of 0° electrons) are  $\sim 0$  or slightly tailward. In fact, the ion flow is first southward then northward, consistent with a boundary moving temporarily over C1 in this manner. At C3, a brief increase in ion flux during the electron enhancement is peaked at 90° pitch angles, such that the ions make no contribution to the parallel current in this region.

[12] The TCR discussed in detail above is the only one of the 6 events in which C3 observed a flux enhancement. However, similar flux enhancements also occur at the locations of at least one of C1, 2, 4 in events C, D and F. In these cases, we see similar electron behavior, with the flux enhancement first or predominantly in the electrons with 0° pitch angles. Unfortunately, the solitary event (E) reported by Slavin *et al.* [2003b] to be moving tailward in this period does not exhibit a flux enhancement at any spacecraft.

### 3. Discussion

[13] The 4 Cluster spacecraft observe only negative  $B_x$  and thus remain south of the tail neutral sheet throughout this period. Thus, C3 is located furthest from this interface, while C2 is nominally the closest. For all the TCR events, except B, C3 remains within the south lobe of the magnetotail, and observes no significant change in the electron population. For events A and E, the other 3 spacecraft also remain entirely within the lobe. These observations thus represent the classic signature of the TCR resulting from a compression of the lobe, as first suggested by Slavin *et al.* [1984]. Observations of electron flux enhancements at one or more of the northernmost spacecraft during the other 4 events unambiguously confirm that this compression is caused by a bulge in the plasma sheet expanding over the Cluster tetrahedron. For events B and C, this bulge is of sufficient size that C1, 2 and 4 enter the plasma sheet itself, where the plasma pressure causes a diamagnetic reduction in the observed field strength. In event B, C3 grazes the edge of the PSBL, and observes a relatively weak flux enhancement, while for event C it remains within the lobe proper and sees no flux enhancement. These observations demonstrate that the variety of field and plasma signatures during the passage of these TCRs is indeed a function of the relative distance of the spacecraft from the edge of the plasma sheet. These 4-point observations thus directly confirm the conclusions of Owen and Slavin [1992], which were based on statistical analysis of single spacecraft data.

[14] The observations shown in Figure 3 allow a closer examination of plasma sheet dynamics surrounding the passage of TCRs than has hitherto been possible. As the plasma sheet is deflected southward over C1, 2, and 4, the enhancement in electron flux is observed first in particles of 0° pitch angle. As the plasma sheet recedes back northward over these 3 spacecraft, it is clear the enhancement in flux persists for 10–12 s longer in the 0° pitch angles than in the other look directions. We interpret these observations as consistent with the existence of a narrow layer of  $\sim 1 \text{ keV}$  electrons between the lobe and plasma sheet. These electrons beam uni-directionally along the magnetic field direction in this layer. Somewhat deeper into the plasma sheet, this

electron population intensifies and shows a more bidirectional motion along the field. The existence of this narrow layer of unidirectional electrons is confirmed by the observations of C3, which only observes an enhancement in  $0^\circ$  pitch angles. We thus infer that this spacecraft just scrapes the edge of the PSBL, sampling only this outermost layer, as it is pushed southward by the plasma sheet bulge.

[15] Since the Cluster spacecraft are located in the southern lobe during these events, particles with  $0^\circ$  pitch angles are moving tailward. Thus although the underlying TCR motion is earthward (from both the SN bipolar signature and the 4 spacecraft timing [Slavin *et al.*, 2003b]), electrons in the outermost PSBL are clearly strongly beaming in the opposite, tailward, direction. Flux enhancements observed by one or more of the spacecraft during the earthward moving events C, D, and F also show this characteristic. We suggest 2 possible explanations for these observations. Firstly, the earthward movement of the TCR implies that its motion is controlled by a reconnection neutral line tailward of Cluster. The length of this TCR, determined from signature duration ( $>60$  s) and inferred velocity ( $416 \text{ km s}^{-1}$ ), implies this neutral line probably lies  $\geq 4 R_E$  tailward of the spacecraft. If the electrons observed by C3 are associated with the magnetic separatrix related to this neutral line, then the electrons are clearly strongly beaming *towards* this reconnection site. Thus this may represent the separatrix current closing a Hall current system at the neutral line. It is then of significance that these can be so clearly observed at these relatively large inferred distances from the neutral line.

[16] A second possible explanation is that the observed tailward beaming electrons are part of the separatrix outflow jet formed by an active reconnection neutral line lying earthward of Cluster. If this is so, Cluster observes the simultaneous consequences of multiple neutral lines in the tail, since the earthward TCR motion implies that its motion is still driven by a neutral line lying tailward of the spacecraft. Such a situation may arise from relatively slow reconnection of plasma sheet field lines at the tailward neutral line which is “overtaken” by faster reconnection at the earthward neutral line. The latter rapidly proceeds to reconnect lobe magnetic flux, and thus creates the observed boundary layer of fast tailward-streaming electrons before the plasma sheet effects (which travel tailward from this neutral line at approximately the plasma sheet Alfvén speed) can modify the motion of the underlying plasmoid/flux rope. Distinguishing between these two explanations will be possible with a wider database of TCR events. All TCRs in this interval with electron flux enhancements have similar characteristics: They move earthward while the outermost electrons beam tailward. This lack of variety might lead to a preference for the former suggestion, since this does not invoke a particular timing between 2 independent neutral lines. Unfortunately, the single tailward moving TCR in this study has no electron flux enhancement and thus cannot be used as the deciding case.

#### 4. Summary

[17] We have presented Cluster 4 point observations of electron signatures associated with the passage of TCRs

past the spacecraft in the near-Earth tail. These TCRs were previously identified by their bipolar magnetic signature. The 4 Cluster spacecraft are at different distances from the edge of the plasma sheet. In particular, C3 is located deeper in the south lobe than the other 3 spacecraft. We have thus shown the observed electron and  $|B|$  signatures are functions of distance from the plasma sheet, confirming the picture of a transient plasma sheet bulge propagating past the spacecraft. This also directly confirms the statistical results of Owen and Slavin [1992], that bipolar signatures with  $|B|$  increases can be associated with either no signature, or with beaming electrons at the very edge of the PSBL. Spacecraft close enough to the edge of the plasma sheet to be engulfed within the bulge see a  $|B|$  reduction due to diamagnetic depression in the plasma sheet plasma.

[18] In the examples presented here, we see clear evidence that although the underlying plasma sheet bulge moves earthward, the electrons at the edge of the PSBL stream tailward. We suggest this may represent either remote observation of electrons acting to close the Hall currents mapping through an ion diffusion region located farther tailward, or outflow jets from a second neutral line located farther earthward of the spacecraft. The latter case thus represents the simultaneous action of multiple X-lines in the near-Earth tail.

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