

Substorm theories and Cluster multi-point measurements

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Abstract: The development of the collisionless tearing instability is often considered as the trigger for substorms and magnetic reconnection in the tail current sheet (CS). Yet it was demonstrated, in a series of papers, that unless the number of particles in a flux tube drastically changes, via strong spatial diffusion across B, tearing modes are stable. We briefly review this long lasting controversy and conclude that the collisionless ion and electron tearings are indeed stable, or weakly unstable, at least at low frequencies and therefore at the large scale where neutral lines are expected to form. When a positive growth rate is obtained, it turns out to be too small for reconnection to develop over the short time scale implied by observations. Meanwhile tearing modes correspond to $K_x \gg K_y$, but Cluster observations indicate that large amplitude perturbations are essentially travelling azimuthally and therefore correspond to a different kind of instability with $K_y \gg K_x$. In the current disruption model the dipolarization is due to current disruption/diffusion. The corresponding temporal variation induces an electric field that accelerates the flow and leads to field aligned currents structures distributed in azimuth.

In order to identify the signature of the instability developing at substorm breakup we analyze Cluster data corresponding to a substorm event that occurred while Cluster was in the current sheet before and during the early phase. At the end of the growth phase (1304-1312), enhanced fluxes of field aligned (parallel and antiparallel) electrons (~ 1 keV) are observed, together with a decrease, by about 1keV, in the energy of the original plasma sheet population. This field aligned component corresponds to ionospheric electrons accelerated by an (induced) parallel electric fields, associated with the thinning of the current sheet, at the end of the growth phase. These electrons are bouncing across the equatorial region. At the end of this preparatory phase (1309) two types of fluctuations are observed, (i) transient fluctuations with quasi periods of the order of 60 sec propagating azimuthally, and higher frequency wide band electromagnetic fluctuations. The active phase starts at about 1312, as the waves intensify, reaching 2nT and 20mV/m for HF, and 10nT for LF. From 1312 to 1315 the CS gets even thinner; only C3 is inside it. Yet electrons, at C3, are heated; and their flux is highly variable. We suggest that electron heating is due to HF waves that bounce resonate with them. Between 1315 and 1320 a series of short lasting (about 60 sec) magnetic structures are observed on B_y and B_z . They correspond to field aligned currents and partial dipolarizations. These field aligned structures move azimuthally. They are associated with fast ion flows (1000km/sec), and with bursts in the amplitude of HF waves. In summary data analysis suggest that HF waves produced by bouncing electrons, in an increasingly thin current sheet, interrupt the current, thereby producing a local dipolarization and the corresponding ion flow bursts. This is consistent with the CD model.

1. Introduction

Prior to substorm breakup, during the growth phase, the tail current sheet becomes very thin. While the growth phase is a slow process, with a characteristic time ~ 30 mn, the breakup occurs over a short time scale; a minute or even less. This sharp contrast between a slow growth phase and a sudden breakup suggests that a plasma instability breaks down the quasi-equilibrium and plays a major role in substorm dynamics, namely the role of a trigger. There are basically two types of models for substorms.

- In the Near Earth Neutral Line (NENL) model the thinning of the Current Sheet (CS) and the subsequent formation of neutral line(s) is often attributed to the development of the

tearing instability. According to this model the filamentation of the tail CS, associated with the development of the tearing instability, leads to the formation of neutral line(s), in the mid-tail (20-30 Re), and to the subsequent fast flows. Earthward of the reconnection site (X-line) the flow is directed earthward. While approaching the dipolar region the speed of these flows is reduced; the "flow braking", can result in a dipolarization, in the near Earth plasmasheet. Later the dipolarization eventually moves tailward.

- In the current disruption/diffusion model(s), the dipolarization results directly from the development of an instability that reduces/diffuses spatially the tail current (J_y). Later the dipolarization may expand radially, thereby causing the reduction/spatial diffusion of the current in a broad region. In this type of model the formation of X-line/point can be the consequence of the dipolarization instead of being its cause.

In section 2, and 3, we briefly review the two kinds of instabilities, on the basis of theoretical arguments, and of existing data. The two models have many similarities. For instances field aligned currents are expected to develop in both cases. Yet there are also distinctive characteristics that can be sorted out by data analysis. For instance the tearing instability has

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to produce a spatial modulation in the radial direction (K_x), while instabilities involved in tail current disruption/diffusion, should produce an azimuthal modulation (K_y). Another constraint stems from the short duration of substorm breakup; we stress the importance of identifying an instability mechanism that develops fast enough to account for the sudden explosion observed at breakup. In section 4 we present data taken by most of Cluster instruments, during a substorm that occurred while Cluster spacecraft (s/c) were located inside a CS, and try to determine what model fits best with the data.

2. Can tearing instability produce spontaneous reconnection in a collisionless plasmas?

2.1. Theory

Most of the recent literature concentrates on the consequence of an X-line, once it formed. It is assumed that the X-line(s) structure(s) can be formed, either via tearing instability, or by suitably controlling external conditions (forced reconnection). A particular emphasis has been put on the potential role of Hall currents, in a situation where the current sheet is very thin, so that ions are demagnetized. Yet in a real situation, how external constraints could lead to the formation of an X-line remains unclear and we do not know how this X-line could remain quasi-stable for quite a long time. On the other hand the tearing instability is known to be a viable mechanism to form X-line(s). A reversed magnetic field configuration is indeed a source of free energy; tearing modes have a negative energy and can therefore be destabilized via some form of dissipative process. In collision dominated plasmas, collisions ensure the requested dissipation; the tearing modes are therefore unstable, and their development leads to the formation of X-lines and O-type islands. When the effect of binary collisions becomes negligible, as it is the case in the Earth's plasmasheet, some form of collisionless dissipation is needed to take over the role usually played by collisions. [1] have suggested that the electron Landau damping produces the requested dissipation. This is true as long as there is no normal component. It was soon realized, however, that even a small B_z stabilizes the electron tearings. Indeed the presence of a finite B_z modifies electron motion. Electrons no longer move along straight lines; they are magnetized; which removes the Landau resonance and the corresponding collisionless dissipation (e.g. [2], [3]).

Then it was realized that ions can be non adiabatic and unmagnetized. [4] suggested that the ion Landau damping (associated with unmagnetized ions) could provide the dissipation requested for tearing instability to develop. Schindler, however, assumed that electrons were cold ($T_e=0$). [5] have shown that once a finite T_e is considered, the energy associated with electron compressibility is larger than the free energy available from the reversed magnetic field configuration. Hence ion tearing cannot develop over realistic distances. [5] showed that $L_T < (\pi^2 B_0 H / 2 B_n)$ is a sufficient condition for stability. Here L_T is the wave length of the tearing mode, H the CS thickness, and B_0 and B_n the lobe and normal magnetic fields. For an already thin CS ($L \sim 2000\text{km}$), and $B_0/B_n \sim 20$ we get $L_T > 30R_e$, which is still much too large. Furthermore the WKB domain is limited by $k > (B_n / H B_0)$, and hence $L_T < (2\pi B_0 H / B_n)$. Combining the two inequalities we find that there is no parameter space for ion tearing instability to

develop. This stabilizing effect, called the electron compressibility, is linked to the strong magnetization of electrons in the CS. In order to preserve charge neutrality ions should follow electrons, which requires more energy than available in the reversed field configuration. Hence ion tearing instability is unlikely to develop.

Pitch angle diffusion, or electron stochasticity can in principle take over the role normally played by collisions. Then [6], and [7] suggested that electron scattering could restore the ion tearing, by removing the stabilization associated with electron compressibility. This idea turned out to be incorrect; a more general criteria was found by [8] who showed that what really matters is the conservation of the number of electrons on a flux tube. Neither pitch angle diffusion nor electron stochasticity change significantly the number of electrons in the flux tube. Only spatial diffusion at Bohm rate could change that number fast enough.

More recently [9] have suggested that the inclusion of an untrapped electrons population (transient electrons) could reduce the stabilizing effect associated with trapped electrons. [9] showed that transient/untrapped electrons do modify the sufficient condition for stability given above. More precisely they showed that inclusion of untrapped electrons introduces a factor $(3T_e/T_i)^2$ in Lembege and Pellat sufficient condition for stability. Thus it seems that there is still a window: $(\pi^2 B_0 L / 2 B_n)(3T_e/T_i)^2 < L_T < \pi B_0 L / B_n$ where ion tearings could develop (keep in mind that the latter inequalities are only a necessary condition for instability). For $T_i/T_e \sim 7$, and the same parameters as above, we get $L_T > 6R_e$, implying that the tail CS should be homogeneous over at least $6R_e$, which is still quite large. More recently [10] carried out an analysis of the marginal stability threshold for collisionless tearing instability. They found that tearing instability is much less sensitive to the ratio T_i/T_e than expected from the criterion quoted above (see figure 4 in [10]). They also evaluated the growth rate and found that when tearing modes are unstable they grow over a typical time scale of $\sim 5\text{mn}$, which is longer than the duration of substorm breakup.

Thus, in a collision-free plasma, spontaneous reconnection via tearing modes does not seem to be a viable mechanism to trigger substorms via the formation of X-line(s), at early breakup. Of course the formation of X-line(s) can be forced via external conditions as it is often the case in numerical simulations.

2.2. Modelling of magnetic reconnection via numerical simulations

In MHD simulations the resistivity, be it artificially applied or produced by numerical effects, determines the formation of X-line(s). Then MHD simulations cannot be used to investigate the possible formation of spontaneously generated tearing modes. Most of recent simulations take into account Hall effects in the Ohm's law. Hall effects can indeed provide some form of collisionless dissipation. Fully kinetic 2.5 and 3D simulations are now available, and are currently used to try to identify the nature of the collisionless dissipation process; see for instance [11] The constraints on the computing time, however, introduce serious limitations, namely: (i) the formation of X-lines is forced by external conditions, or (ii) simulations start with an Harris sheet, and thus with no B_z (and therefore no

electron bounces), and even in the cases where the modes are allowed to grow spontaneously, (iii) the constraints on the computing time, and on the dimensions of the 2 or 3D simulation boxes are such that electron bounce motion cannot properly be described, at least for realistic ion to electron mass ratios.

Thus, depending upon the particular parameter domain and boundary conditions used for the simulations, different results about the development of the tearing instability are found. For instance while [12] concluded, from kinetic simulations, that ion tearings are unstable, [13] concluded to stability, irrespective of T_i/T_e .

Inclusion of Hall terms is clearly an important improvement with respect to MHD, but they are not sufficient to describe very important kinetic effects. Furthermore it is not clear that kinetic effects are limited to a very small diffusion region at the electron scale ($L_e \sim \text{few km}$). In the present paper we discuss the possible role of electron bounce resonance. The associated dissipation is not limited to such a small diffusion region; it occurs at the scale of the current sheet. The electron bounce period (T_{be}) is comparable to the proton gyroperiod in the lobes (T_{H+}).

In order to identify the dissipation mechanism simulations runs, (i) with closed field lines, as initial conditions, (ii) carried out in a regime where electrons can undergo several bounces, and (iii) in a parameter regime such that $T_{be} \sim T_{H+}$, are needed. Notice that the ratio T_{be}/T_{H+} depends on the mass ratio M/m which is used in the simulation. Thus it is still unclear that X-line can develop in a realistic collision-free plasma and remain stable for quite a long time.

3. Current disruption model(s)

The so called current disruption models are much less developed than reconnection models. Unlike tearing modes, the modes that disrupt the J_y current correspond to a modulation in the azimuthal direction. The basic idea is that once the current sheet gets very thin, the current density, flowing in the azimuthal direction, can exceed the instability threshold; see for instance [14]. The enhanced current density can also be produced by a strong ion pressure gradient, as requested for the ballooning instability to develop (e.g. [15]). Current driven instabilities can interrupt, or diffuse spatially, the tail current. In the latter case the total current remains essentially constant, while the current density decreases in the equatorial region. This decrease in the current density leads to a change in the magnetic configuration: a local dipolarization. For a fully fledged substorm the current disruption/diffusion is likely to expand, step by step, thereby leading to a more dipolar configuration over the whole plasma sheet. The dynamics of this expansion depends on the non-linear evolution of the instability and on the spatial distribution of the currents. For a large substorm the instability is likely to start developing in the near Earth plasma sheet, in magnetic conjunction with the southernmost arcs appearing at early breakup, and to expand azimuthally and radially outward. Yet an earthward expansion is not necessarily ruled out, in particular in the case of weak substorms/pseudo substorms corresponding to arcs starting at high latitudes. While the basic mechanism of the instability seems to be essentially the same, whatever the radial distance, the non linear evolution does produce different effects at small and at large dis-

tances. Indeed at large distances; say for instance $\sim 20R_e$, and beyond, B_{dipole} gets so small that the B_z , associated with the instability, can reverse the sign of B_z , and thus the sense of the flow. Similarly a disruption/reduction of the currents earthward of the spacecraft (or an increase of the current tailward of the spacecraft) can produce a negative B_z , which can lead to a magnetic null. Therefore an X-line/X-point can be the consequence of current disruption. In the current disruption models the ion flow is produced by an inductive electric field: $E_y = -\partial A_y / \partial t$, where the characteristic time is given by the time variation of the magnetic field associated with the dipolarization. Then the ion flow is simply given by the corresponding $\vec{E} \times \vec{B} / B^2$.

As alluded to above, current disruption/diffusion can be produced by different instabilities. In the model proposed by T. Lui, current disruption is achieved via lower hybrid drift or ion Weibel instability. The ballooning instability proposed by Roux et al. was investigated in a series of papers, based upon MHD, multi-fluid, and kinetic approach. [16] concluded that ballooning modes are generally stable, while [17] drew a different conclusion: ballooning modes are unstable for $\beta \sim 1$. From a kinetic description carried out in a regime where both ions and electrons are not adiabatic, [18] concluded that ballooning modes are weakly unstable; essentially like for in the MHD approach.

Given the short time scale of current disruption (and substorm breakup), [19] suggested that the “high frequency” (~ 1 Hz and beyond) waves, that they observe together with lower frequency ($T \sim 60$ sec.) ballooning modes, can disrupt the parallel current associated with the modulation of the perpendicular current (J_y) by the ballooning modes. If the current sheet becomes very thin the current J_y has to be carried by electrons (see next section). Then high frequency waves can act directly on the perpendicular current and disrupt J_y , as will be discussed later.

4. Comparisons with observations

4.1. Possible tests of models

It is not necessarily easy to find tests that could be applied to determine which model fits best observations. For instance the existence of a quadrupolar signature on B_y is often considered as the characteristic signature of a nearby diffusion region, associated with an X-line. In fact this kind of signature can also be produced by the field aligned current associated with the development of the ballooning instability. Here we discuss tests that can be applied to Cluster data to discriminate the two types of theories, namely:

- The direction of the spatial perturbation. Tearing like perturbations correspond to radial modulation and therefore are characterized by $k_x (k_x \gg k_y)$. On the other hand ballooning modes and current driven instabilities are characterized by large $k_y (k_y \gg k_x)$.
- Thus a Hall structure should be essentially invariant by translation along the Y , and its magnetic signature should be observed on B_y . On the other hand an azimuthally moving perturbation (k_y) should lead to an azimuthal modulation of J_y and hence, via $\text{div} J = 0$, to localized filamentary field aligned current structures. The passage of a filamentary structure should produce simultaneous perturbations on the B_y and B_z .

4.2. Analysis of Cluster data

4.2.1. Overview

We investigate a substorm that developed on September 12th, 2001, while the 4 Cluster s/c were inside a relatively thick current sheet (CS) for quite a long time (~ 45 mn.). A negative bay was observed at Tixi, at 13:10, followed by a positive bay at 13:15. Weak Pi2, observed at Kakioka, intensify after 13:10. Figure 1 is a composite showing data for this event. The s/c were located near midnight LT, at about 19Re. The distance between the s/c was of the order of 2000km. Keep in mind that s/c3 is at a lower Z than the other s/c. An estimate of H, the CS thickness, and of Z_0 , the location of CS center, is given in the lowermost panels of Figure 1; it is based on a fit with a Harris sheet. The estimate is good when the 4 s/c are located inside the CS and the values of magnetic components are significantly different, at different s/c locations, as it is the case for instance from 12:30 to 13:00. On the contrary the fit is not good when the magnetic components are the same at the 4s/c, and $B_x \sim B_{lobe}$; then the s/c are outside the CS (for instance at $\sim 12:20$). However, when the magnetic components are the same at the 4s/c, and $B_x \ll B_{lobe}$ (for instance after 13:25) the CS thickness $H \gg D$ (D being the distance between the s/c). Finally, when only one s/c is inside the CS and the others outside, the fit overestimates the CS thickness and underestimates the current, as it is often the case between 13:09 and 13:15. With these restrictions in mind we can try to investigate a possible relation between CS dynamics and CS thickness.

- Before 13:04 the CS is thick, but its thickness decreases from ~ 10000 km to ~ 3000 km. Low frequency ($T \sim 5$ mn.) oscillations are observed in the CS, but E_y and V_x remain steady and very small. J_x is negligible while J_y increases from 3 to 8 nA/m^2 . The ion velocity, $V_{yi} \sim 100$ km/sec, is sufficient to carry the westward current.

- Between 13:04 and 13:15 the CS gets very thin; $H \sim 1000$ - 2000 km, or less, since only s/c3 remains inside it (see discussion above). Hence $H \sim \rho_i$, the ion Larmor radius in the lobes. Larger amplitude, shorter period ($T \sim 100$ sec) fluctuations, together with HF fluctuations (on δE and δB), are observed. Panel 4 shows electric fluctuations. During this period V_{xi} (panel 5) seems to increase, but this enhancement can be due to the finite radii effects in a very thin CS, as pointed out by [20]. In any case the estimated V_{xi} remains relatively small. V_{yi} (panel 6) becomes negative, thus the J_y current, which is positive and enhanced during this period, has to be carried by electrons. The large negative values of V_{yi} can be due to an electric field E_z , pointing towards CS center (e.g. [21]), or to a finite radius effect (e.g. [20]), or both. During this period, the distance between Cluster s/c being comparable to, or even larger than the CS thickness, J is likely to be underestimated, hence $J_x > 10 \text{ nA/m}^2$ (panel 7) and $J_y > 20 \text{ nA/m}^2$ (panels 8). The increase in the current density J_y and the decrease in the CS thickness are approximately consistent with the conservation of the total current.

- Between 13:15 and 13:20 large amplitude fluctuations (~ 100 sec) continue to modulate the B_x components, but now the amplitudes at the 4 s/c are similar, and B_x decreases, which indicates that the CS is now thick. These structures correspond to fast ion flow bursts (~ 1000 km/sec) around 13:15:30; the examination of the ion distributions indicates that we are really observing ion flow bursts during this period. Large amplitude

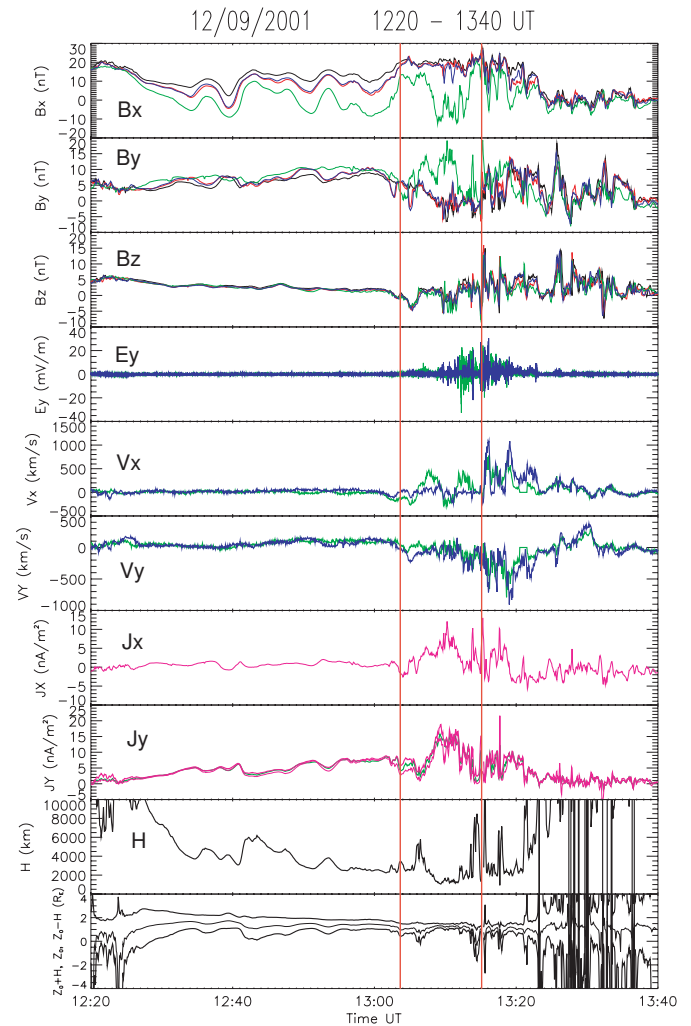


Fig. 1. Field parameters. H is the CS thickness and Z_0 its center.

high frequency (HF) fluctuations ($B \sim 0.5$ - 2 nT, $E \sim 5$ - 20 mV/m) are simultaneously observed (see panel 4), as will be discussed later.

Figure 2 displays data from PEACE; it shows the electron flux versus energy and time, in the parallel direction, over the same time period as figure 1.

- Before 13:04 the flux of energetic electrons (few keV) is about the same, at the 4s/c. This is to be expected because the CS thickness H is larger than D the distance between the s/c ($D \sim 1500$ - 2000 km). Notice that low energy, quasi-monoenergetic, electrons (up to a few 100eV) are sporadically observed, together with the quasi steady energetic ($\sim$ few keV) component, typical of the plasma sheet. This low energy component, however, is only observed on parallel and anti-parallel electron fluxes. The variations in the energies of these two components are in antiphase. When the energy of the low energy component is maximum, the energy of the plasma sheet electron is minimum.

- After 13:04 the energy of plasma sheet electrons decreases at all s/c, but a component, with a very low initial energy is clearly observed on s/c3. Its energy increases up to 1keV, as it merges with plasma sheet electrons. This is better visualized in

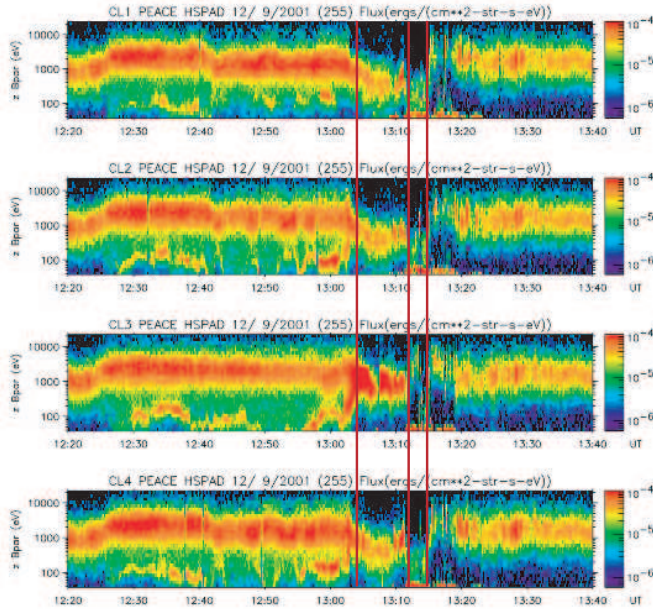


Fig. 2. Electron energy fluxes versus energy and time observed by PEACE in the direction parallel to the magnetic field B onboard the 4 Cluster satellites

figure 3 and described in the next subsection.

4.2.2. Active period: Electron dynamics

Figure 3 is an expanded view showing electron fluxes at s/c3, from 13:00 to 13:20, in antiparallel (top), perpendicular (middle) and parallel directions (bottom).

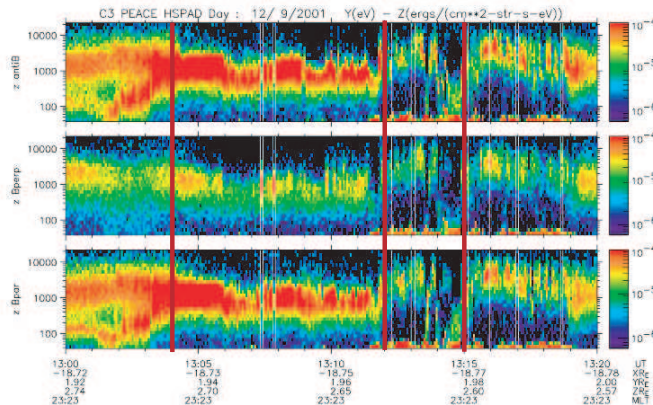


Fig. 3. Electron energy fluxes versus energy and time observed by PEACE onboard Cluster-3 in 3 directions : opposite to B (first panel), perpendicular to B (second panel) and parallel to B (bottom panel)

- Around 13:04 (first vertical red line) we observe an accelerated electron component. The energy increases from $< 100\text{eV}$ to $\sim 1\text{keV}$, where this component merges with the pre-existing plasma sheet population. This electron structure is observed only on s/c3. The enhanced flux around 1keV lasts $\sim 7\text{mn}$, but its energy and its intensity fluctuate. This initially very low energy population, presumably ionospheric electrons,

gains about 1keV .

- Between $\sim 13:12$ and $13:15$ the electron energy suddenly increases at s/c3, but the flux is highly sporadic. Simultaneously the energy and the flux decrease at s/c1,2,4, which suggests that these s/c are now in the BL. Hence, the CS is probably even thinner than during the previous period. The energetic electrons observed on s/c3 correspond to a bursty electron population accelerated in the near equatorial region.

- Between 13:15 and 13:19 the bursty electron acceleration continues, but now on all 4 s/c, thereby suggesting that the CS has expanded in a very irregular fashion. This is confirmed by the lowermost panels of figure 1 (H increases).

- After 13:19 the electron flux, on the 4 s/c, is more steady, less energetic, and tends to be isotropic; it corresponds again to a typical electron plasma sheet.

In summary, as the CS thins, we observe first an accelerated ionospheric electron population, merged with a decelerated plasma sheet population, and then, as the CS gets even thinner, we observe bursty accelerated electrons.

4.2.3. Active period: fields.

Figure 4 is essentially a zoom of figure 1.

- During the thinning of the CS (13:04-13:12) the Bz component, at s/c3, is weak and often changes sign. The By component at s/c3 increases and becomes very different from By(1,2,4). Hence the By component does not correspond to a uniformly applied guide field; it strongly depends on how deep in the CS, is the s/c. During this early period the variations of Bz are smaller than the variations of the other components; thus the current density is essentially invariant along Y.

- Between $\sim 13:12$ and $13:15$ the modulus of B (not shown) is very small around 13:12:25, 13:13:00, and 13:14:15. This near cancellation does not correspond to a particular ion acceleration. Indeed the electric component Ey changes sign simultaneously, which indicates that electric and magnetic fluctuations correspond to low frequency fluctuations propagating essentially eastward (they are seen first at C2 which is located to the west of the other s/c). After 13:13 (in particular $\sim 13:15:30$) the variations of Bz and By are comparable in amplitude and simultaneous; they correspond to filamentary currents.

- Full resolution data from EFW (figure 4, panel 4) and STAFF (not shown) give evidence for large amplitude (5-20 mV/m, 0.5-2nT) “HF” fluctuations ($< 10\text{Hz}$). These fluctuations are confined in the CS, but they are not localized near the quasi-nulls in the magnetic field.

4.3. Discussion

On September 12, 2001, Cluster spacecraft were in a suitable position to monitor the thinning of the CS.

Parallel acceleration of electrons

From 13:04 to 13:12, as the CS thickness decreases and $H \sim \rho_i$, an initially very low energy electron population shows up. These electrons are accelerated up to 1keV ; their flux is very large, at least at C3, which is closer to the equator. The signature is hardly seen at C2 and does not show up at C1 and C4. Therefore this accelerated electron population is highly confined near the magnetic equator. Yet electrons are field aligned, parallel and anti-parallel. If these electrons were accelerated in a diffusion region, near a neutral line, the By signature should change sign as Bx changes sign (at least as long as Bz does not

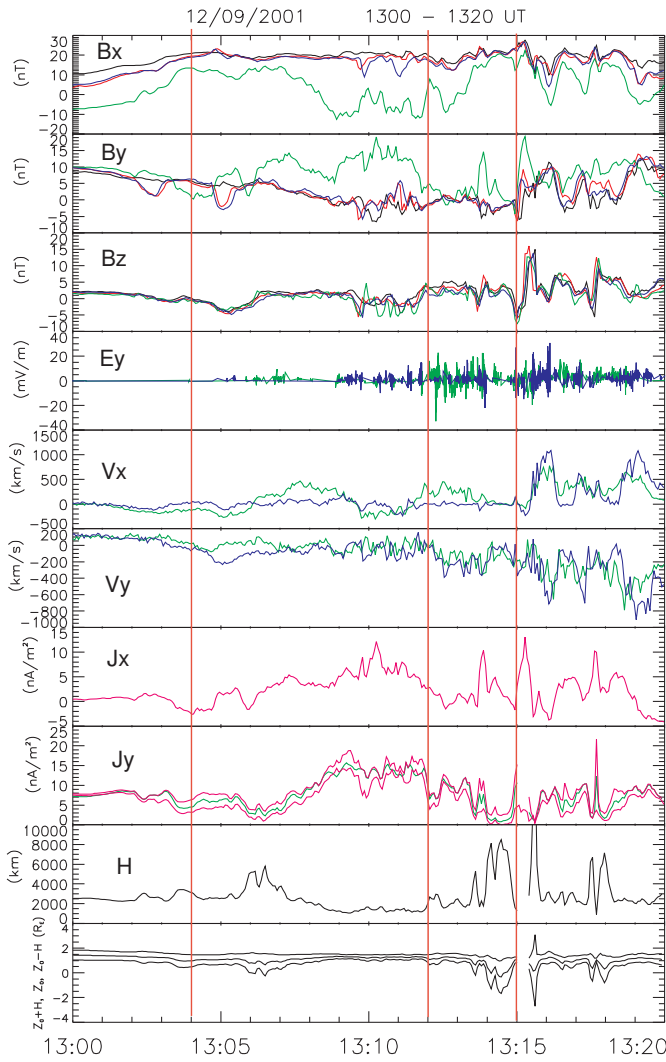


Fig. 4. same parameters as figure 1, with an enlarged scale. The two vertical lines bracket the filamentary magnetic structure at $\sim 13:15$ and the associated local dipolarization.

change sign). A large B_y component is indeed observed at C3, until 13:12 (Figure 4, panel 2), but B_y remains positive, as B_x changes sign, around 1308:30, and B_z remains small but positive. Another interpretation should be sought. We suggest that this large flux, initially low energy component, corresponds to low energy passing electrons, coming from the ionosphere or from adjacent regions, which are accelerated by a parallel electric field, directed towards the equator on both sides (of the equator), and confined in the near equatorial region. This interpretation could also account for the arch-shaped structures observed at various s/c, before 13:04. The arch-shaped acceleration structures observed before 13:04, however, have much smaller fluxes and reach lower energies (few 100eV). They should therefore correspond with much smaller parallel electric fields. In both cases trapped electrons (plasma sheet) loose energy while passing electrons (ionospheric) gain energy, in the near equatorial region. This is consistent with the conservation of the total energy and of the first and second invariant for electrons. Data displayed in Figures 1 and 2 indicate that the energy reached by accelerated electrons is controlled by two

factors: the distance from the equator, normalized to the CS thickness, and the modulation by LF waves. Hence the parallel electric field is not static; it is associated with the fluctuations of the CS; it is an induced electric field. A mechanism for the formation of parallel electric fields, via fluctuations in the current density, is discussed by [22]. Scattering by HF fluctuations

Between 13:12 and 13:14 the amplitude of HF fluctuations increases at s/c3 (see Figure 4, panel 4), while it decreases at the other s/c. When the s/c leave the CS, as it is the case between 13:14:30 and 13:15 (for all s/c) the level of the fluctuations decreases by a large factor. This indicates that waves are confined in the CS, and that their intensities are maximum near the equator. Figure 5 illustrates the relation between HF fluctuations and electron acceleration. It shows the electron flux, integrated over all pitch angles, versus time and energy. δE_y , the electric component of the HF fluctuations ($< 10\text{Hz}$) is plotted at the same time scale. Bursts of energetic electrons (typically above 1keV) correspond to bursts in the amplitude of HF fluctuations for the electric and magnetic components. During these bursts the amplitude of the waves is very large; typically 0.5- 2nT, 5-20 mV/m. The largest bursts occur between 13:12 and 13:14:30, for s/c3, and around 13:15 and 13:16, for all s/c. The good correspondence between electron and wave bursts suggests that waves heat the electrons. Given the frequency range we expect that acceleration occurs via bounce resonance. Indeed $T_{be} \sim 2\text{sec}$, for 4keV, which is comparable to the period of the waves. It is suggested that HF/small scale fluctuations accelerate and isotropize electrons.

Structure of the currents

During the early period (13:04-13:12) $B_y > 0$ and large at s/c3, while B_z is small. Hence the J_x current corresponds to a plane sheet more or less invariant along Y. Yet, as pointed out above, the B_y signature does not correspond to that of an Hall current structure. At $\sim 13:15:40$, and 1317:40, large amplitude fluctuations are observed simultaneously on B_y and B_z ; their signatures correspond to filamentary currents. The most prominent structure is at $\sim 13:15:40$. It corresponds to a filament with the current along the X direction; not to a flux rope extended along Y. The structure is observed first at s/c2, hence it moves eastward. The same remark is true for the other structure; it propagates essentially eastward. As pointed out in section 4.1, a simultaneous signature on B_y and B_z , and an azimuthal propagation are expected for an instability developing in the azimuthal direction, and leading to a cancellation of the tail current. In line with this suggestion we observe that the CS thickens, after the passage of each structure, as evidenced by large decreases in the B_x components. For instance, the large amplitude structure observed on B_y and B_z , between 13:15 and 13:16, precedes a decrease in the B_x component at all s/c, and hence a decrease in the current density J_y . Current density perturbations move azimuthally eastward as expected from current disruption model.

Flow velocity

The flow velocity remains small until 13:15. Between 13:15 and 13:16 a fast ion flow burst takes place ($\sim 1000\text{km/sec}$) while the CS thickness increases. This sequence of events suggests that the filamentary field aligned current structures produces a local reduction of J_y (via $\text{div} J = 0$), which leads to an enhanced E_y , thereby accelerating ions earthward. The induced electric field E_y , and hence the ion flow V_x , are linked to the

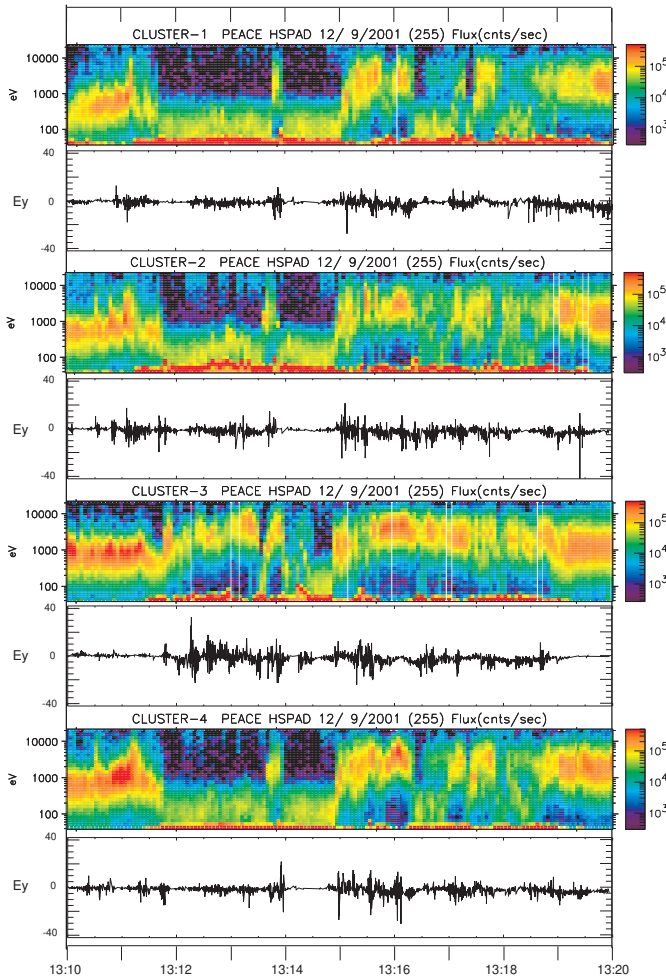


Fig. 5. Figure 5 shows the electron flux, integrated over pitch angle, together with the electric field E_y . Largest E_y fluctuations generally correspond to bursts of energetic electrons.

variation of J_y via a simple relation: $\partial J_y / \partial t \approx \partial^2 E_y / \partial z^2$, which is valid as long as $\partial / \partial z \gg \partial / \partial y, \partial / \partial x$, and $\nabla \cdot \mathbf{E} = 0$. These conditions are fulfilled for a thin CS, in the low frequency limit. For J_y 25nT, H 2000km, and a rise time (for E_y or V_x): t 25sec, we get E_y 4mV/m which is consistent with the value measured by EFW. For $E_y \sim 4$ mV/m, and $B_z \sim 5$ nT we get $V_x \sim 800$ km/sec., also in agreement with observations. Thus the short lasting fast flow bursts observed during the thickening of the CS can be interpreted as a consequence of the reduction in J_y .

5. Conclusions

- In a collisionless plasma, spontaneous reconnection, via tearing instability, does not seem to be a viable mechanism to form X-lines.

- In order to initiate magnetic reconnection the key question is to produce a large $\partial A_y / \partial t$ (an inductive E_y). Since the tearing instability is unlikely to develop in a collisionless plasma, $\partial A_y / \partial t$ has to be achieved by (fast) changes in external conditions, or by local interruption of J_y over a short time scale, via an instability. We have shown here an example of how a

large electric field E_y can be induced by a fast reduction in the J_y current. This reduction is associated with the development of filamentary current structures that can result from the development of an azimuthally propagating (k_y) modulation, such as a ballooning mode; or from a smaller scale instability that reduces the currents.

- Large amplitude (0.5-2nT, 5-20 mV/m), high frequency fluctuations are observed in association with the eastward travelling low frequency current structures. These HF electromagnetic fluctuations are confined in the thin active CS. Their close association with bursts of energetic electrons suggest that HF fluctuations accelerate and isotropize the electrons. When the J_y current is carried by bouncing electrons, as it is the case for the event discussed here, HF fluctuations can directly reduce J_y by scattering field aligned electrons, and/or reducing field aligned currents J_x .

- In summary we suggest that the reduction in the tail current is achieved via a series of local "dipolarization" events, such as the ones described here. Then the dipolarization in the whole plasma sheet would result from the overall summation of local events corresponding to interruption/diffusion of J_y . This resembles to a "chain reaction".

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