SUBSTORM THEORIES AND CLUSTER MULTI-POINT MEASUREMENTS

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1. INTRODUCTION

There are basically two types of models for substorms:

- Substorms are triggered by the (spontaneous?) development of one (or several) X-line(s), in the mid-tail (20-30 R_E), which leads to fast flows. Earthward of the reconnection site (X- line) flow bursts are directed earthward. While approaching the dipolar region the speed of these flows is reduced ("flow braking"), which can result in a dipolarization, in the near Earth plasmasheet. Later the dipolarization eventually moves tailward.

- Substorms are triggered by current disruption/diffusion via an instability. In this scenario the dipolarization results from the development of an instability. The dipolarization expands radially, thereby causing the reduction/diffusion of the tail current. In this type of model the formation of X-line/point is the consequence of the dipolarization instead of being its cause.

These two models have extensively been discussed in several papers and during several conferences. Yet it seems that some of the basic theoretical results are not well known, therefore we start by giving a short review about modelling of magnetic reconnection. We focus on what mechanism could lead to the formation of X-line(s). Then we present Cluster data and try to see what model fits best with data.

2. CAN TEARING INSTABILITY PRODUCE SPONTANEOUS RECONNECTION IN A COLLISIONLESS PLASMAS?

A reversed magnetic field configuration is a source of free energy. In collision dominated plasmas such a configuration is unstable to tearing modes and does lead to the development of X-line(s). 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. Coppi, Laval&Pellat, 1966, [2] have suggested that 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 tearing instability. The presence of a finite Bz modifies electron motion. Electrons no longer move along straight lines; they undergo bounce motion. The stabilization of the electron tearing is therefore due to electron bounce motion and the associated electron compressibility (Galeev & Zelenyi, 1976 [4], Lembège, 1976 [6]).

Then it was realized that the current sheet can be very thin. Thus ions are likely to be non adiabatic and could therefore be unmagnetized. Then Schindler, 1974 [11] suggested that the ion Landau damping could provide the dissipation requested for tearing instability to develop. Schindler, however, assumed that electrons are cold. Lembège and Pellat, 1982 [7] have shown that once a finite Te is considered, the energy associated with electron compressibility is larger than the free energy available from reversed magnetic field configuration, hence ion tearing cannot develop over realistic distances. For our future discussion it is important to keep in mind that physically the stabilization is linked to bouncing electrons.

Pitch angle diffusion, or electron stochasticity can in principle take over the role normally played by collisions, at least if they involve small scale lengths. Then Coroniti, 1980 [3] and Buchner&Zelenyi, 1987 [1] proposed that the associated electron diffusion could remove the stabilization of ion tearings via electron compressibility. This idea turned out to be incorrect; a more general criterium was found by Pellat et al., 1991 [9], 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 Sitnov, 1998 [12] has suggested that the inclusion of an untrapped electrons population could reduce the stabilizing effect associated with bouncing trapped electrons, and therefore modify marginal stability con-

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dition, thereby leading to less unrealistic unstable wavelength. This is an interesting suggestion, but it is not clear that it changes the condition given above that the number of electrons in the flux tube should change fast enough to enable the tearing instability. Thus, in a collision-free plasma, spontaneous reconnection via tearing modes does not seem to be a viable mechanism to produce X-line(s). Of course the formation of X- line(s) can be forced via external conditions as it is often the case in numerical simulations.

3. 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 dissipation and therefore produce induced electric fields. 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 Hesse et al., 1999 [5]. 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 box are such that electron bounce motion cannot properly be described, at least for more or less realistic ion to electron mass ratios (100).

Given that the stabilization of the tearing instability is due to bouncing electrons, it is still unclear that X-line can develop and remain stable for quite a long time. Inclusion of Hall terms is clearly an important improvement. Yet it is not clear that kinetic effects are limited to a very small diffusion region (L$\sim$ few electron Larmor radii). Indeed the dissipation associated with electron bounces is not limited to such a small region; it occurs at the scale of the current sheet.

In order to identify the dissipation mechanism we need to run simulations, (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 $T_{be} \sim T_{H+}$. Notice that the ratio T_{be}/T_{H+} depends on the mass ratio M/m which is used in the simulation.

4. CURRENT DISRUPTION MODEL(S)

The so called current disruption models are much less developed than reconnection models. The basic idea is that once the current sheet gets very thin the current density, flowing in the azimuthal direction, can exceed the threshold for an instability; see for instance Lui et al., 2001 [8]. The enhanced current density can also be produced by a strong ion pressure gradient, as requested for the ballooning instability to develop (Roux et al, 1991 [10]). Current driven instabilites can interrupt, or rather diffuse spatially, the tail current locally; in other words the total current remains essentially constant, while the current density decreases. 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 tailward, 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; thus a tailward expansion is more likely to occurs but an earthward expansion is not necessarily ruled out. 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 distances. Indeed at large distances; say for instance $\sim 20R_E$, and beyond, Bdipole gets so small that the δB_z, associated with the instability, can reverse the sign of Bz and thus the sense of the flow. Similarly a disruption/reduction of the currents earthward of the spacecraft can produce a negative δB_z, or 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 ($E_y = -\partial A_y/\partial t$) associated with the dipolarization. Then the ion flow is simply given by the corresponding $\vec{E} \times \vec{B}/B^2$.

5. 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 a signature of magnetic reconnection. 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 ($k_y \gg k_x$).

- An azimuthally moving perturbation (k_y) should lead to an azymuthal modulation of J_y and hence, via $div\vec{J} = 0$, to localized filamentary field aligned current structures.

- The signature of the dissipation and the spatial extent of the dissipative region. For models based on the disruption/diffusion of the current, the spatial extension, along Z, should be the current sheet thickness. In the reconnection model the dissipation can only occurs in a (much smaller) diffusion region.

6. ANALYSIS OF CLUSTER DATA

6.1. Overview

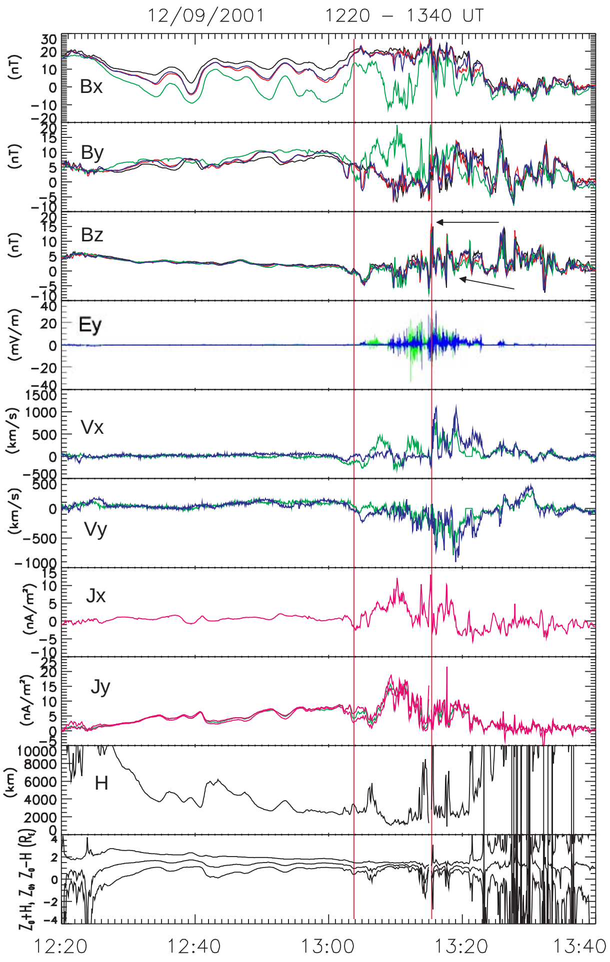

Figure 1. from top to bottom: the 3 components of the magnetic field , at the 4 s/c, the electric field Ey and the Vx and Vy components of the ion flow velocity at s/c2 and 4, the Jx and Jy components of the current density, computed via curlB, anf finally the two bottom panels show the thickness H of the current sheet and the location of its center, Z0, computed from a fit with a Harris sheet.

Figure 1 is a composite showing data for the September 12, 2001 event. The s/c are located near midnight LT, at about $19R_E$. The distance between the spacecraft (s/c) is of the order of 2000km. This event was selected because the 4 Cluster s/c remained inside a relatively thick ($\sim$ 4000km) current sheet (CS) for quite a long time ($\sim$ 45mn.), before the event. During the active phase (13:04-13:20) the CS gets thinner ($\sim$ 1000-2000km); some of the s/c get out of the CS, but at least one spacecraft (s/c3) remains located inside it. Large amplitude fluctuations are observed during the whole period. These oscillations are confined in the CS; as s/c1 leaves the CS, between 13:04 and 13:15 it hardly detects the fluctuations that show up very clearly on s/c3. Keep in mind that s/c3 is at a lower Z than the other s/c.

- Before 13:04 the CS is thick. Low frequency (T$\sim$ 5mn.) oscillations are observed in the CS, but E_y, and the ion velocity V_{xi} remain steady and very small. J_x is negligible while $J_y \sim 5nA/m^2$ corresponds to the current carried by ions ($V_y \sim$ 100km/sec).

- Between 13:04and 13:15 the CS gets thinner; only C3 remains inside it. Larger amplitude, shorter period (T$\sim$ 100sec) fluctuations, together with HF fluctuations (on $\partial E \& \partial B$), are observed. During this period the V_{xi} increases but remains relatively small (<500km/sec), V_{yi} becomes negative, hence the J_y current, which is positive and enhanced during this period, has to be carried by electrons (in the s/c frame). During this period, however, the distance between Cluster s/c is comparable or even larger than the CS thickness, thus J is likely to be underestimated, hence $J_x > 10nA/m^2$ and $J_y > 20nA/m^2$. 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 ($\sim$ 100sec) continue to modulate the B_x components. These large amplitude fluctuations are observed on the 3 components. The large fluctuations of B_y can be interpreted as field aligned current signatures. These signatures, however, do not correspond to sheets of parallel currents, as would be expected for Hall currents around an X-line (quasi-invariance by translation along Y). Indeed similar signatures are also found on B_z, which tells us that the parallel currents are filamented in the y direction, as expected for the development of an azimuthally propagating perturbation with a large k_y. These structures correspond to fast ion flow bursts ($\sim$ 1000km/sec), and to large amplitude HF fluctuations ($\delta B \sim$ 1-3nT, $\delta E \sim$ 5-20mV/m), 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 electrons at the 4s/c is about the same. This is to be expected because H the CS thickness is larger than D the distance between the s/c (D$\sim$ 2000km). Notice that low energy electrons are sporadically observed, together with a quasi steady energetic ($\sim$ 2keV) component. These low energy electrons, however, are only observed on the parallel and anti-parallel fluxes.

- Between 13:15 and 13:20 the CS thins; s/c1,2,4 are located close to the CS boundary (13:04-13:12), or

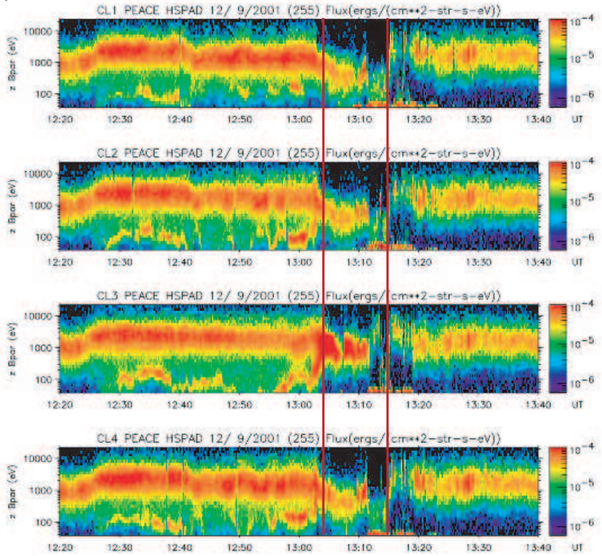

Figure 2. Electron energy fluxes versus energy and time observed by PEACE in the direction parallel to the magnetic field B onboard the 4 Cluster satellites

get out of the CS 13/12-13:15), hence the flux and the energy decreases. A completely different behaviour is observed at s/c3, which remains inside the CS. The low energy electron flux largely intensifies, and their energy increases up to ∼ 1keV, while the energetic component disappears or merge with the enhanced, initially low energy component. This is better seen in figure 3.

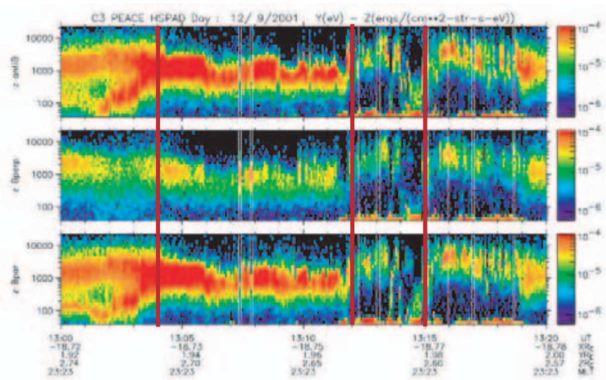

Figure 3. Electron energy fluxes versus energy and time observed by PEACE onboard Cluster-3 in 3 directions : opposite to B (first panel), perpendicular to B (second panel) and parallel to B (bottom panel)

6.2. Active period: Electron dynamics

Figure 3 is an expanded view showing electron fluxes, from 13:00 to 13:20, in antiparallel (top panel), perpendicular (middle) and parallel direction (lowermost).

- Between 13:04 and 13:12 the enhanced flux electron component is only seen in the parallel and antiparallel directions. The flux in the perpendicular direction is much weaker. The enhanced flux electron population is only seen on s/c3; it is therefore highly confined near the magnetic equator. Yet it is field aligned! How can these properties be reconciled? We suggest that this enhanced, initially low energy, component corresponds to passing electrons accelerated by a parallel electric field confined near the equator.

- Between ∼ 13:12 and 13:15 the electron energy suddenly increases at s/c3, while the energy and fluxes at s/c1,2,4 are consistent with being in the lobes; the CS is even thinner than during the previous period. We observe a bursty electron acceleration, together with bursts of accelerated ion flow (see figure 4).

- Between 13:15 and 13 :19 the bursty electron acceleration continues to be observed, but now on all 4 s/c, thereby suggesting that the CS has expanded. This is confirmed on the lowermost panel of figure 1.

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

6.3. Active period: fields.

Figure 4 is essentially a zoom of figure 1. During the thinning of the CS (13:04-13-12) the B_z component, on s/c3, is weak and changes sign, for instance at ∼ 13:10 and at ∼ 13:11:30. Notice that the modulus of $\vec{B}$ is small for these two times. The sign of the V_x component changes accordingly, but the flow velocity remains small; only after 13:12 do we see very fast flows (∼ 1000km/sec). On the other hand the B_y component at s/c3 increases and becomes very different from B_y(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 B_z are smaller than that of the other components; the variation of the current density is essentially laminar along Z. Conversely, after 13:13 (in particular at ∼ 13:15 and ∼ 13:18) the variations of B_z and B_y are comparable in amplitude and simultaneous; they correspond to filamentary field aligned current structures. Notice that the current density in the structures is essentially radial (along X), and the structures move eastward. This suggests that these filamentary structures correspond to the disruption, locally, of the J_y current. In line with this suggestion we observe that the CS thickens, after the passage of each structure, as evidenced by a large decrease in B_x components. For instance, the large amplitude structure observed on B_y and B_z, just after 13:15, precedes a decrease in the B_x component (and hence a decrease in the current density J_y) at the 4s/c.

Full resolution data from EFW (figure 4, panel 4) and STAFF (not shown) give evidence for large amplitude (5-20mV/m, 2-5nT) HF fluctuations. These fluctuations are confined in the CS, but they are not localized near the nulls in the magnetic field (around 13:13); we do not see evidence for particular enhancement in a small region that could correspond to a diffusion region.

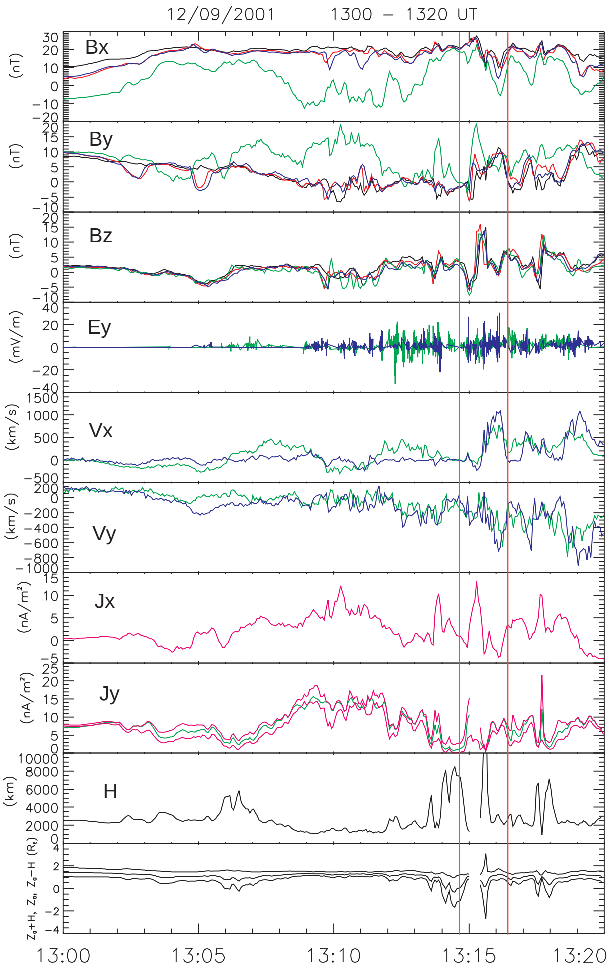

Figure 4. same parameters as figure 1, with an enlarged scale. The two vertical lines bracket the filamentary magnetic structure at ∼13:15 and the associated local dipolarization.

6.4. Active period: flows

Short lasting bursts of flowing ions are observed when the current density decreases and the CS thickness increases. This sequence of events suggests the filamentary structures correspond to a local reduction of J_y (via field aligned currents) which produces an enhanced E_y that accelerates ions earthward. The induced electric field E_y, and hence the ion flow V_x, are indeed linked to the variation of J_y via a simple relation: $\mu_0 \partial J_y/\partial t \approx \partial^2 E_y/\partial z^2$, which is valid as long as $\partial/\partial z \gg \partial/\partial y$, $\partial/\partial x$, and $\nabla \cdot E = 0$. These conditions are fulfilled for a thin CS, in the low frequency limit. For $\Delta J_y \approx$ 25nA/m^2, $H \approx$ 2000km, and $E_y \approx$ 4mV/m (measured by EFW), we get a rise time (for E_y or V_x): $\Delta t \approx$ 25sec, which is consistent with the observed fast increase of V_x and E_y (around 13:15). 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.

7. SUMMARY AND CONCLUSIONS

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

- The key question is to produce a large $\partial Ay/\partial t$ (an inductive E_y). Since the tearing instability is unlikely to be a viable mechanism in a collisionless plasma, $\partial Ay/\partial t$ has to be achieved by (fast) changes in external conditions, or by local interruption of J_y over 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 field aligned currents structures that can result from the development of an azimuthally propagating (k_y) modulation, such as a ballooning mode.

- In addition to, or in support of, this low frequency (T∼ 100sec) modulation we observe large amplitude (2-5nT, 5-20mV/m), higher frequency fluctuations. These fluctuations are confined in the thin active CS, but we do not see evidence for a localised enhancement that could be interpreted as a diffusion region. The nature and the role of these fluctuations will be discussed elsewhere.

- 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 dipolarization in the whole plasma sheet would then result from the overall effect of local events corresponding to interruption/diffusion of J_y. This resemble to a ”chain reaction“.

- THEMIS, and associated ground-based measurements well suited to give evidence for such a ”chain reaction“.

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