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 published results show that unless the number of particles in a flux tube drastically changes via strong spatial diffusion across B, tearing modes are stable. We review this long lasting controversy and conclude that the collisionless ion and electron tearings are stable, or weakly unstable, at least at low frequencies and therefore at the large scale where neutral lines are expected to form. As well, tearing modes have $K_x \gg K_y$, but Cluster observations show large amplitude perturbations have $K_y \gg K_x$ (mostly azimuthal propagation). To identify the signature of the breakup instability we analyze Cluster data from a substorm that occurred while Cluster was in the CS. At the end of the growth phase, enhanced fluxes of field aligned electrons (∼1keV) are observed together with a ∼1keV decrease in the energy of the original plasma sheet population. This field aligned component corresponds to ionospheric electrons accelerated by an (induced) parallel electric field. Both azimuthally propagating fluctuations with quasi periods of ∼60 sec, and higher frequency wide band electromagnetic fluctuations are observed. As the active phase starts, the waves intensify, reaching 2nT and 20mV/m for HF, and 10nT for LF. The CS gets even thinner leaving only one satellite inside it, which observes that electrons are heated and have variable fluxes. We suggest that electron heating is due to bounce resonance with HF waves. This is followed by a series of short lasting (∼60 sec) magnetic structures in By and Bz. These correspond to field aligned currents and partial dipolarizations and are observed to move azimuthally. They are associated with fast ion flows (1000km/sec), and with bursts in the amplitude of HF waves. This data analysis suggests 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

During substorm growth phase, the tail current sheet (CS) becomes thin. The contrast between a slow (∼30mn) growth phase and a sudden breakup (∼1mn) suggests that a plasma instability plays the major role of a trigger in substorm dynamics. The two primary and competing paradigms are the Near-Earth Neutral Line (NENL) and Current Disruption (CD) models. In the NENL model the filamentation of the CS is associated with the development of the tearing instability, leading to the formation of neutral line(s) in the mid-tail (20-30 Re) and to subsequent fast flows. Earthward of the reconnection site (X-line) the flow is directed earthward. Braking of these fast flows as they approach the dipolar region can result in a dipolarization, in the near Earth plasmasheet. This dipolarization in turn propagates tailward. In the CD (also called diffusion) model(s), the dipolarization results directly from the development of an instability that reduces/diffuses spatially the tail current (Jy). 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 sections 2 and 3 we review theory and observations relevant to the two kinds of instabilities. The two models have similarities. For instance field aligned currents are expected to develop in both cases. Yet their characteristics also differ. For instance, the tearing instability has to produce a spatial modulation in the radial direction (Kx), while instabilities involved in CD/diffusion should produce an azimuthal modulation (Ky). As well, the instability mechanism must develop on a time scale consistent with that of breakup. In section 4 we present Cluster data from a substorm that occurred while Cluster spacecraft (s/c) were located in the CS, and try to determine what model fits best with the data.

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

In most recent literature, 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 a dissipative process. In collision dominated plasmas, collisions ensure this dissipation: the tearing modes are therefore unstable, and their development leads to the formation of X-lines and O-type islands. In the Earth's plasmasheet, some form of collisionless dissipation must play the role of collisions. [4] suggested that electron Landau damping for this, which can work provided there is no normal component. It was soon realized that even a small Bz stabilizes the electron tearings. Indeed the presence of a finite Bz modifies electron motion (they are magnetized) which removes the Landau resonance and the corresponding collisionless dissipation (e.g. [6], [9]).

Schindler [18] suggested that ion Landau damping (associated with unmagnetized non-adiabatic ions) could provide the dissipation required for tearing instability to develop. However, he assumed that electrons were cold (Te=0). [10] have shown that with finite Te, 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. [10] showed that $L_T < (\pi^2 B_0 H/2B_n)$ is a sufficient condition for stability. Here L_T is the wave length of the tearing mode, H the CS thickness, and B_o and B_n the lobe and normal magnetic fields. For an already thin CS (L∼2000km), and B_o/B_n ∼20 we get $L_T > 30R_e$, which is still much too large. Furthermore the WKB domain is limited by $k > (B_n/HB_o)$, and hence $L_T < (2\pi B_o H/B_n)$. 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 CS electrons. 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 could replace the role normally played by collisions. It was thus suggested that electron scattering could restore the ion tearing by removing the stabilization due to electron compressibility [5, 2]. This idea was incorrect: it was found that what really matters is the conservation of the number of electrons on a flux tube [14]. Neither pitch angle diffusion nor electron stochasticity change significantly the number of electrons in the flux tube.

More recently [19] suggested that an untrapped electron population could reduce the stabilizing effect associated with trapped electrons. [19] showed that transient/untrapped electrons do modify the stability condition (above). They showed that inclusion of untrapped electrons introduces a factor $(3T_e/Ti)^2$ in the Lembege and Pellat sufficient condition for stability. Thus it seems there is still a window where ion tearings could develop $((\pi^2 B_o L/2B_n)(3T_e/T_i)^2 < L_T < \pi B_o L/B_n)$. For $T_i/T_e \sim 7$, and the same parameters as above, we get $L_T > 6R_e$, implying that the CS should be homogeneous over at least 6Re, which is still large. Marginal stability threshold analysis showed that collisionless tearing instability is much less sensitive to the ratio T_i/T_e than expected from the criterion quoted above [20]. That study also evaluated the growth rate and found that when tearing modes are unstable they grow over a typical time scale of ∼5mn, which is too long for breakup.

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

Artificially applied or numerical resistivity determines the formation of X-line(s) in MHD simulations, which therefore cannot be used to investigate spontaneous tearing modes. Most recent simulations take into account Hall effects, which can provide collisionless dissipation, in the Ohm' s law. Fully kinetic 2.5 and 3D simulations are now used to explore the nature of collisionless dissipation process (e.g. see [7]). Computing time constraints, however, introduce serious limitations. The formation of X-lines is forced by external conditions, or simulations start with a Harris sheet (with Bz=0 and thus no electron bounces). Even in the cases where the modes are allowed to grow spontaneously, constraints on computing time and the dimensions of the 2 or 3D simulation boxes are such that electron bounce motion cannot properly be described for realistic ion to electron mass ratios. Thus, different simulation parameter domain and boundary conditions lead to differences in the predicted development of the tearing instability. For instance while [22] concluded, from kinetic simulations, that ion tearings are unstable, [16] concluded to stability irrespective of Ti/Te.

Inclusion of Hall terms is an important improvement, but they are not sufficient to describe important kinetic effects. Furthermore it is not clear that kinetic effects are limited to a small diffusion region at the electron scale (Le∼few km). In this paper, we discuss the possible role of electron bounce resonance, which has associated dissipation that occurs at the larger scale of the CS. 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 with initially closed field lines, where electrons can undergo several bounces, and carried out in a parameter regime such that $T_{be} \sim T_{H+}$, are needed. Note 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-lines can develop in a realistic collision-free plasma and remain stable for a long time.

3. Current disruption model(s)

The CD models are much less developed than reconnection models. Unlike tearing, the modes that disrupt Jy lead to azimuthal modulation. The premise is that once the CS gets very thin, Jy can exceed the instability threshold [12]. The enhanced Jy can be produced by a strong ion pressure gradient, as required for the ballooning instability (e.g. [17]). Current driven instabilities can interrupt or spatially diffuse the tail current. In the latter case the total current remains the same, but Jy decreases in the equatorial region. This decrease in Jy leads to a local dipolarization. For a full substorm the current disruption/diffusion expands, 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 distribution of the currents. For a large substorm the instability is likely to develop in the near Earth plasma sheet, magnetically conjugate to the equatorward most (breakup) arcs, and then expand azimuthally and radially outward.

An earthward expansion is not ruled out in weak and/or pseudo substorms with onset arcs at higher latitudes. Although the instability mechanism is essentially the same, whatever the radial distance, the non linear evolution does produce different effects at small and large distances. Indeed at large distances (∼20Re and beyond), B is in general small enough that the instability can reverse the sign of Bz, and thus the sense of the flow. Similarly changes in the currents can produce a negative Bz and 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: $Ey = -\partial A_y/\partial t$, 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, CD/diffusion can be produced by different instabilities. *T. Lui* proposed that CD 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. [13] concluded that ballooning modes are generally stable, while [11] concluded that ballooning modes are unstable for $\beta \sim 1$. From a kinetic description carried out in a regime where both ions and electrons are non-adiabatic, [8] concluded that ballooning modes are weakly unstable.

Given the short time scale of CD (and substorm breakup), [15] suggested that the "high frequency" (≥1 Hz) waves they observe together with lower frequency (T∼60s) ballooning modes can disrupt the parallel current associated with the modulation of the perpendicular current (Jy) by the ballooning modes. If the current sheet becomes very thin Jy has to be carried by electrons (see next section). Then high frequency waves can act directly, disrupting Jy, as will be discussed later.

4. Comparisons with observations

It is not easy to find tests that could be applied to determine which model fits best observations. For example, the existence of a quadrupolar By is a candidate 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. In particular, the direction of the spatial perturbation. Tearing like perturbations correspond to radial modulation and therefore are characterized by kx ($kx \gg ky$). On the other hand ballooning modes and current driven instabilities are characterized by large ky ($ky \gg kx$). Thus a Hall structure should be essentially invariant by translation along the Y, and its magnetic signature should be observed on By. On the other hand an azimuthally moving perturbation (ky) should lead to an azimuthal modulation of Jy and hence, via divJ=0, to localized filamentary field aligned current structures. The passage of a filamentary structure should produce simultaneous perturbations on the By and Bz. We investigate a substorm that developed on September 12, 2001, while the 4 Cluster s/c were inside a relatively thick current sheet (CS) for ∼45mn. 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.

Fields: Figure 1 shows relevant Cluster data. The s/c were located near midnight LT, at ∼19Re. The distance between the s/c was of order 2000km, with s/c3 at a lower Z than the others. Estimates of CS thickness (H) and the location of CS center (Zo) based on fits to a Harris sheet are also included. The fits are good when the magnetic components are different at the 4s/c, and Bx different from Blobe (the s/c are inside the CS). As well, between 13:09 and 13:15, only one s/c is inside the CS and the fit overestimates the CS thickness and underestimates the current. With these restrictions in mind we can try to investigate a possible relation between CS dynamics and CS thickness.

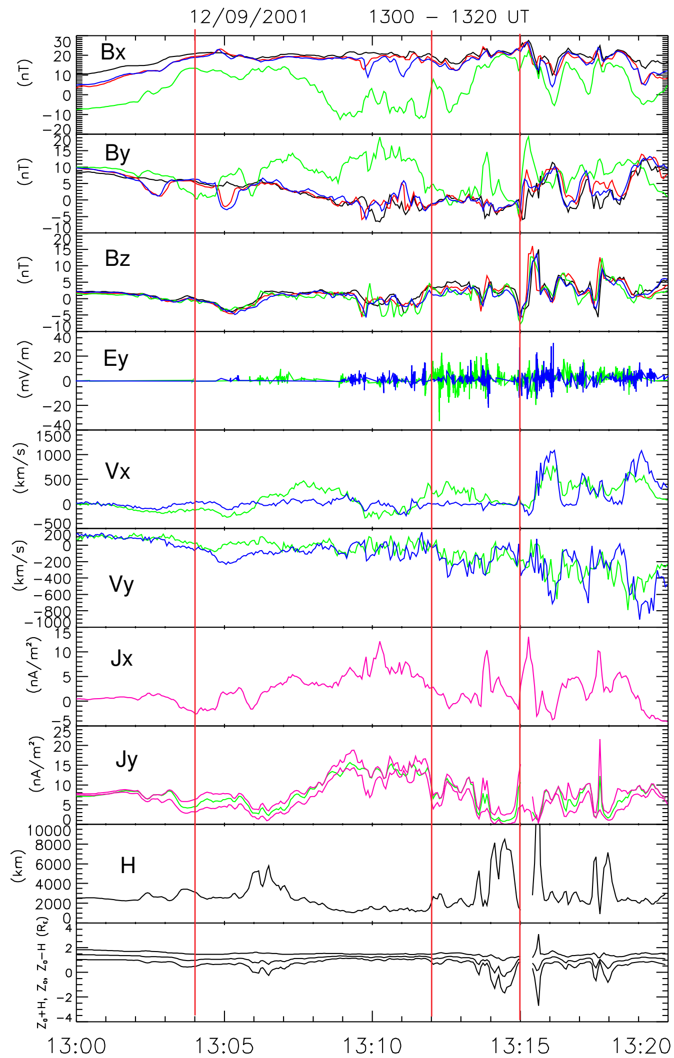

Fig. 1. Cluster filed parameters for this event. H and Zo are the CS thickness and center, respectively. The two vertical lines bracket the filamentary magnetic structure at ∼13:15 and the associated local dipolarization (see end of section 4).

Before 13:04 (not shown) the CS thickness decreases from ∼10000km to ∼3000km. Low frequency (T∼5mn.) oscillations are observed in the CS, but Ey and Vx remain steady and very small. Jx is negligible while Jy increases from 3 to 8 nA/m^2. The ion velocity, Vyi ∼100km/sec, is sufficient to carry the westward current. In Figure 1, between 13:04 and 13:15 the CS gets very thin $H \sim$2000km or less, since only s/c3 remains inside it. Hence $H \sim \rho_i$, the ion Larmor radius in the lobes. Larger amplitude, shorter period ($T \sim$100sec) fluctuations, together with HF fluctuations (on δE and δB), are observed. Panel 4 shows electric fluctuations. During this period Vxi (panel 5) seems to increases, but this enhancement can be due to the finite radii effects in a very thin CS, as pointed out by [21]. In any case the estimated Vxi remains relatively small.

Vyi (panel 6) becomes negative, thus the Jy current, which is positive and enhanced during this period, has to be carried by electrons. The large negative values of Vyi can be due to an electric field Ez, pointing towards CS center (e.g. [1]), or to a finite radius effect (e.g. [21]), or both. During this period, the interspacecraft distance is at least the CS thickness so J is likely underestimated, hence $J_x > 10nA/m^2$ (panel 7) and $J_y > 20nA/m^2$ (panels 8). The increase in the current density Jy and the decrease in the CS thickness are approximately consistent with conservation of total current.

Between 13:15 and 13:20 large amplitude fluctuations ($\sim$ 100 sec) continue to modulate Bx, but the amplitudes at the 4 s/c are similar and Bx decreases, indicating the CS is thick. These structures correspond to fast ion flow bursts ($\sim$1000km/sec) around 13:15:30. Examination of the ion distributions indicates that we are observing ion flow bursts (see below). Large amplitude high frequency (HF) fluctuations (B$\sim$0.5-2nT, E$\sim$5-20mV/m) are simultaneously observed (see panel 4).

During the thinning of the CS (13:04-13:12) the s/c3 Bz component is weak and often changes sign. The s/c3 By component increases and becomes very different from By at the other three s/c. Thus By depends on how deep the s/c is in the CS and so does not does not correspond to a uniformly applied guide field. 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 13:12 and 13:15 |B| is very small around 13:12:25, 13:13:00, and 13:14:15. This near cancelation 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 1, panel 4) and STAFF (not shown) give evidence for large amplitude (5-20 mV/m, 0.5-2nT) "HF" fluctuations (<10Hz). These fluctuations are confined in the CS, but they are not localized near the quasi-nulls in the magnetic field.

Electron Dynamics: Figure 2 displays PEACE parallel electron fluxes over a longer time period. Before 13:04, the energetic electron (few keV) flux is about the same at the 4 s/c, consistent with the CS thickness being larger than the interspacecraft distance. Low energy, quasi- monoenergetic electrons (up to a few 100eV) are sporadically observed along with the quasi steady energetic ($\sim$few keV) plasma sheet component. This low energy component is only observed in parallel and anti-parallel fluxes and the variations in the energies of these two components are in antiphase. After 13:04 the energy of plasma sheet electrons decreases at all s/c, but a component with a very low initial energy is observed on s/c3. Its energy increases up to 1keV as it merges with plasma sheet electrons.

Figure 3 shows s/c3 antiparallel, perpendicular, and parallel electron fluxes from 13:00 to 13:20. Around 13:04 (first vertical red line) we observe an accelerated electron component. The energy increases from $< 100eV$ to $\sim 1keV$, when 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$7mn, but its energy and its

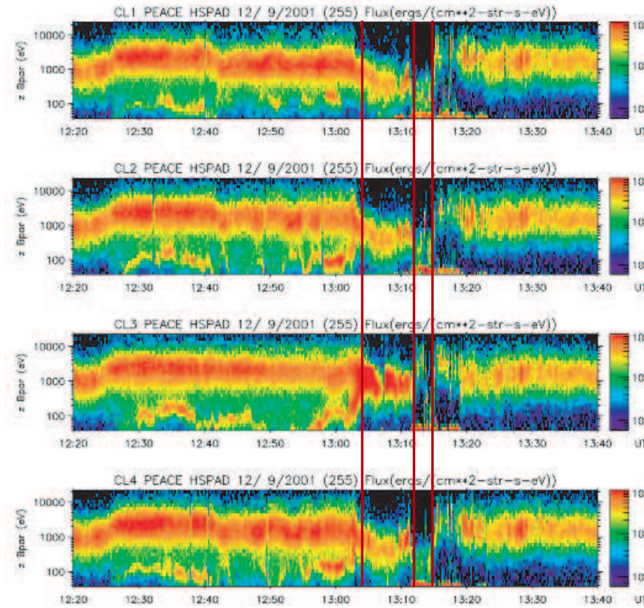

Fig. 2. PEACE parallel electron energy fluxes from the four s/c

intensity fluctuate. This initially very low energy population of (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 flux decrease at s/c 1,2, and 4, suggesting they are in the BL. Hence, the CS is likely 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, suggesting that the CS has expanded irregularly. This is confirmed by an increase in H just after 13:20 (not shown in Figure 1). After 13:19 the electron flux on the 4 s/c is more steady, less energetic, and isotropic, again indicating 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, bursty accelerated electrons.

5. Discussion

On September 12, 2001, Cluster monitored the thinning of the CS. From 13:04 to 13:12, as the CS thickness decreases and $H \sim \rho_i$, an initially low energy electron population shows up. These electrons are accelerated up to 1 keV and their flux is very large, at least at s/c3, which is closer to the equator. The lack of significant signature at s/c 1, 2, and 4 indicates that this accelerated electron population is highly confined near the magnetic equator. Electrons are, however, field aligned. If they 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 change sign). A large By component is indeed observed at s/c3 until 13:12 (Figure 1, panel 2), but By remains positive as Bx changes sign around 1308:30, and Bz remains small but positive. Another interpretation should be sought. We suggest that this initially low energy component

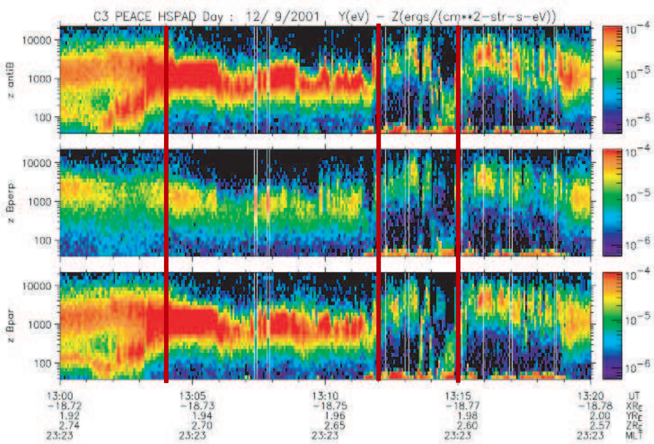

Fig. 3. s/c3 PEACE Electron energy fluxes in 3 directions: opposite (top), perpendicular (middle), and parallel (bottom) to B.

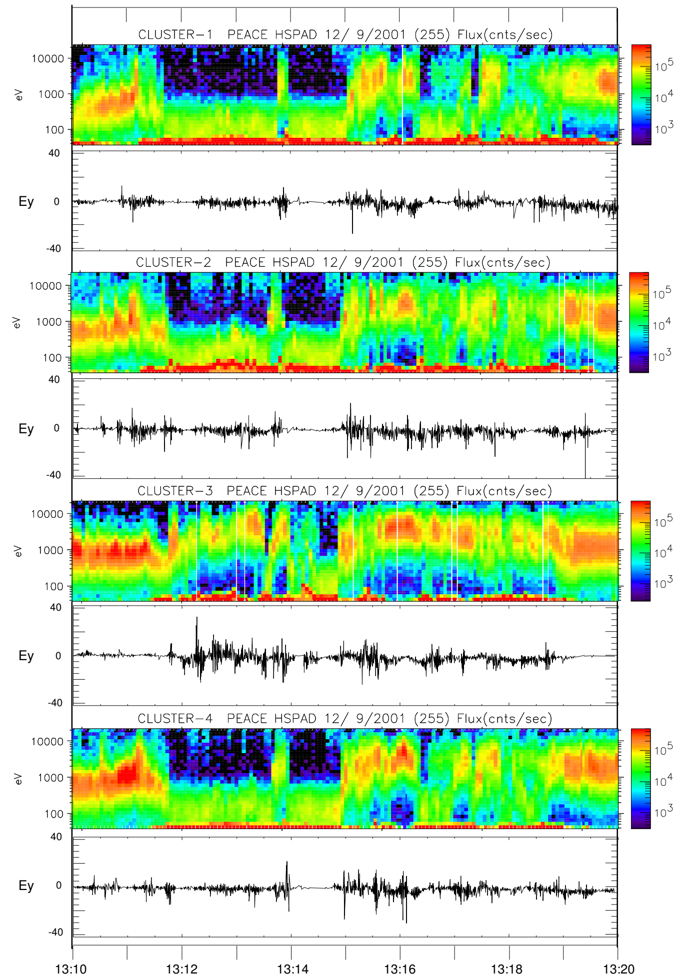

Fig. 4. Figure 5 shows the electron flux, integrated over pitch angle, together with the electric field Ey. Largest Ey fluctuations generally correspond to bursts of energetic electrons.

is low energy electrons coming from the ionosphere or from adjacent regions, and 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 could also account for the arch- shaped structures observed 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 ionospheric electrons 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 induced (not static) and is associated with the CS fluctuations. A mechanism for the formation of parallel electric fields, via fluctuations in the current density, is discussed by [3].

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

During the early period (13:04-13:12) By$>$0 and large at s/c3, while Bz is small. Hence the Jx current corresponds to a plane sheet more or less invariant along Y. Yet, as pointed out above, the By signature does not correspond to that of a Hall current structure. At $\sim$13:15:40, and 13:17:40, large amplitude fluctuations are observed simultaneously on By and Bz; 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. As the structure is observed first at s/c2, it is moving eastward. The same is true for the other structure which is also propagating eastward. As pointed out in section 4, a simultaneous By and Bz signature, and azimuthal propagation are expected for an instability which develops in the azimuthal direction and leads to a cancelation of the tail current. In line with this, we observe that the CS thickens after the passage of each structure, as evidenced by large decreases in the Bx components. For instance, the large amplitude structure observed in By and Bz between 13:15 and 13:16 precedes a decrease in the Bx component at all s/c, and hence a decrease in the current density Jy. Current density perturbations move azimuthally eastward as expected from current disruption model.

The flow velocity remains small until 13:15. Between 13:15

and 13:16 a fast ion flow burst takes place (∼1000km/sec) while the CS thickness increases. This suggests the filamentary field aligned current structures produce a local reduction of Jy via ∇·J=0, which leads to enhanced Ey, and earthward ion acceleration. The induced electric field Ey and ion flow Vx are linked to the variation of Jy: $\partial J_y/\partial t \approx \partial^2 E_y/\partial z^2$, which is valid as long as $\partial/\partial z \gg \partial/\partial y, \partial/\partial x$, and $\nabla.E = 0$. These conditions are fulfilled for a thin CS, in the low frequency limit. For Jy25nA/m^2, H 2000km, and a rise time (for Ey or Vx) t∼25sec, we get Ey∼4mV/m, consistent with that measured by EFW. For Ey∼4mV/m, and Bz∼5nT we get Vx∼800km/sec., also in agreement with observations. Thus the short lasting fast flow bursts during the thickening of the CS can be interpreted as a consequence of the reduction in Jy.

6. 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 Ey). 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 Jy over a short time scale via an instability. We have shown here an example of how a large electric field Ey can be induced by a fast reduction in the Jy current. This reduction is associated with the development of filamentary current structures that can result from the development of an azimuthally propagating (ky) 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 indeed 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 Jy current is carried by bouncing electrons, as it is the case for the event discussed here, HF fluctuations can directly reduce Jy by scattering field aligned electrons, and/or reducing field aligned currents Jx.

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 Jy. This resembles a “chain reaction”.

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