Scientific
Research
Publishing

The Pattern of B_y Deflections Produced from Field-Aligned Currents Earthward of the Activation Source in the Earth's Magnetosphere

Dimitrios V. Sarafopoulos

Department of Electrical and Computer Engineering, Democritus University of Thrace, Xanthi, Greece
Email: sarafo@ee.duth.gr

Abstract

In this investigation effort, we eventually infer that the overall quadrapole pattern of B_y deflections, in the vicinity of a source in the Earth's magnetotail, is most likely due to field aligned currents (FACs) and not to Hall currents associated with an X-type collisionless reconnection. This categorically expressed statement is based upon sufficient observational evidence tightly associated with our own suggested model and the preceded works of the same author. Using representative events measured by satellite, our main aim is to describe the nature of the fundamental mechanism determining the polarity of the B_y deflections associated with intense earthward ion-plasma flows. A major finding is that we either observe magnetic flux rope (MFR) like structures (that is, entities having all the morphological features of ropes; *i.e.*, a dipolar signature of B_z occurring simultaneously with peaked B_y and B_{total} deflections) or mere B_y deflections, however, the sign for all these (B_y deflections) is always determined by the satellite placement in north (positive) or south (negative) plasma sheet. Therefore, the MFR-like structures located earthward of the source are most likely pseudo-MFRs; there is neither a tubular topology nor an axial magnetic field, the B_y deflections are produced by FACs. According to the presented model, a fundamental concept is that both ions and electrons are simultaneously accelerated at the source site; in turn, the earthward streaming electrons (ions) form a bifurcated electron (ion) FAC just outside the electron diffusion region-EDR (IDR). In this way, inside the IDR (and earthward of the source) positive (negative) B_y deflections in north (south) plasma sheet (PS) are produced due to FACs, and not to (inward) Hall currents as in the context of an X-line. Moreover, the ions form an "ion jet" within the IDR, while just outside this region they produce positive (negative) B_y deflections in north (south) PS caused by ion FACs. The ion jet in the IDR is enveloped by the bifurcated electron FAC. Eventually, although the resulting pattern of B_y deflections, due to both electron and ion FACs, is apparently the same with that resulting from Hall currents (in the X-line model), the underlying natural

processes are, however, radically different. Certainly, the dominant "spatial entity" within the IDR is the ion jet-current (and not the Hall-electron current). Additional implications of the ion jets are also discussed.

Keywords

Magnetic Reconnection, Magnetic Flux Rope in Magnetotail, Field-Aligned Currents, Plasma Sheet, Double Layers

1. Introduction

Any reader has faced conclusions like "these observations suggest that three dimensional localized/transient structures could play an essential role in the dynamics of the thin current sheets, while a gross X-line picture can be established only in an average sense" [1]. Nevertheless, the X-type collisionless reconnection model is the fundamental concept of almost all the contemporary works (e.g., [2]-[7]). Only sporadically are expressed "departures from the magnetic reconnection picture suggesting that the breakdown region is more appropriately interpreted as a turbulent region expected from current disruption and dipolarization than the ion and/or electron diffusion region in a simple picture of a magnetic reconnection site" [8]. In contrast, the author of this work finally suggests that we must be careful and rather re-examine this model because the commonly detected B_y deflections, in the source's vicinity, may be entirely due to field aligned currents (FACs). And if the previous assumption holds true, *then the cross-tail magnetic fields have been erroneously attributed to electron Hall currents*. It is a matter of peculiar interest because, in our understanding, both of them (*i.e.*, either the Hall or the FACs) cause the same pattern of guide fields.

This effort further supplements the results from a preceded work of Sarafopoulos [9] engaged with the issue of B_y deflections at times of intense tailward plasma flows (in the Earth's magnetotail). It is concluded that if the tail is locally bending to an upward or downward direction, then the sign (*i.e.*, the polarity) of the core of the involved magnetic flux rope (MFR), being essentially an intense B_y deflection, will be positive or negative, respectively. And a model interpreting the diagnosed behaviour was introduced: Once a tailward **"ion jet"** is produced by the source within the ion diffusion region (IDR) in a thinned plasma sheet, then *it might form clockwise or counter clock wise ion vortices (i.e., loop-like ion currents) outside the IDR.* That is, each vortex develops a "magnetic core" with the appropriate sign. Therefore, in this context, the MFRs embedded in tailward plasma flows are not directly attributed to magnetic reconnection taking place in an X-line. Additionally, in the just cited work, for two events characterized by a long-lasting (*i.e.*, up to ~25 min) intense B_y deflection, the sign of B_y was interpreted by the involved "one-sided ion surface current". That is, a current caused as the ion jet (along the X-axis and inside the IDR) encounters an upward or downward curved tail. The present effort is focused on substorm-associated B_y deflection events occurring with earthward plasma-ion flows. Our chief inference is that the FACs similarly play the key role causing B_y deflections and determining their polarity pattern. This work is based on *in situ* Geotail-satellite observations directly related to our own proposed model concerning the source, its electron and ion diffusion regions (EDR and IDR) and the associated currents extended up to the fluid scale lengths. A model that definitely leads to many diametrically opposite processes in comparison with those following the principles of the X-type reconnection. We assume that the demagnetized ions, in a thinned plasma sheet (PS), have the potentiality to *stream outward from the source while moving within "an ion channel" within the IDR and along the tail in central plasma sheet* (*CPS*). A mechanism generating these "ion jets" was proposed by Sarafopoulos [10] [11] based on a twin-Double Layer (twin-DL) structure, and more specifically, on its phase of explosive activations. In this work, each earthward ion jet is associated with ion FACs formed outside the IDR and producing the studied B_y deflection pattern. In parallel, the electrons ejected earthward of the source form electron FACs producing the appropriate B_y deflection pattern within the IDR. The tailward ion jet is also associated with electron FACs that produce a certain B_y deflection pattern in PS. Again, we repeat that the jetting ions (both earthward and tailward of the source) are allowed to stream along the tail and within the IDR; in contrast, the required electrons neutralizing the positive charge of jet, essentially move perpendicular to the neutral sheet and along the magnetic field lines. In this manner, the principle of plasma quasi-neutrality is not violated, while at the same time field-aligned currents

are built up connecting the tail with the ionosphere. And all these will be analytically exhibited in the next sub-sections.

It is stressed that we mostly deal with plasma-ions ejected earthward of the source; they finally play a crucial role forming large scale FACs, and in turn, B_y deflections via Ampere's law. Another fundamental process always involved in a substorm is the magnetic field "dipolarization process" via single or multiple energization episodes. And the question is whether this process would shape structures like the magnetic flux ropes (MFRs), wherein the maxima of the B_y deflections occur (at the same time) with dipolar negative-then-positive (transitional) signatures of B_z and peaked B_{total} values. We observe that occasionally, indeed, the dipolarizations are associated with MFR-like structures; however, in other cases the B_y and B_z signatures frequently occur in a random way and fail to give any basic rope signature; for instance, you could not diagnose any dipolar signature along the B_z trace while the B_y is strong. Most interestingly, the MFR-like structures (earthward of the source) although they comprise all the morphological features of ropes, they are really pseudo-MFRs (*i.e.*, neither cores nor helical structures exist). *The inferred rule is that the B_y deflections are always positive (negative) in north (south) PS; they are caused by FACs.* In the past, Sarafopoulos [12] investigated two notable events using the THEMIS satellites, for the one case, and the Cluster mission, for the other, and concluded that the magnetic field signatures associated with his two "MFR-like structures" could be readily reproduced by filamentary FACs flowing earthward and being wavy modulated over the meridian XZ-plane. He exhibited an MFR-like structure with a *positive B_y excursion for THEMIS-C and,* almost simultaneously, *a negative for THEMIS-B*; an apparent inconsistency for the same supposed core-entity to have both polarities. For the first time strong evidence was provided that effects of Ampere's law may have been previously interpreted as MFRs embedded in tailward plasma flows. He also applied the same explanation upon "a rare Cluster phenomenon" that was previously cited in literature and categorized as "an irregular, complicated MFR structure" [13].

Additionally, in a work using data from the CLUSTER tetrahedron, Sarafopoulos demonstrated [14] that **tens of B_y and B_z signatures** observed in succession during a very indicative interval of 9 min can be (qualitatively) well reproduced by two branches of filamentary FACs: One branch in northern and the other in southern plasma sheet. The satellites repetitively go through the IDR and the plasma flow changes its direction from earthward to tailward and vice versa; additionally, *B_y deflections with opposite polarities commonly occur at the same time*. Thus, he concluded that pseudo-MFRs are systematically formed by filamentary currents; although these structures have morphological features similar to those of real MFRs. Amid very high geomagnetic activity, he could not realise any authentic MFR entity that would be associated with the dramatic magnetic field reconfigurations. Thus, each B_y deviation really seems to be the effect of Ampere's law. Moreover, one may conclude that all the plasma-ion flows, for at least 10 min, rather occurred within the IDR; thus, the IDR can be regarded as an **extended region** characterized by fluid scale lengths along the X-axis. With the Cluster tetrahedron, he had, at times, an estimate of the plasma sheet thickness being close to the ion inertial length for the studied period.

In general, although the particle flows (occurring inside or outside the IDR) may be long-lasting, the "source region" is associated with "an instantaneous switching" of flow from earthward to tailward. A representative reversal time of ~10 s, for simultaneous plasma and energetic particle flows, is clearly given in an early work by [15]; the source extent along the X-axis was estimated to less than 10,000 km.

It was already noted that either the MFR-like structures or the simple B_y deflections are due to FACs. The deflections being either short-lived (*i.e.*, 1 - 2 min or less) or long-lasting (*i.e.*, up to a few tens of minutes) are probably derived from FACs and not any Hall currents, which serve in the collisionless X-line reconnection theory to explain the development of the B_y-guide fields, as considered by Sonnerup [16] and Terasawa [17]. It is critical to discriminate between the IDR wherein an acceleration source is presumably at work (a microscale process) and the macroscale structures basically related to ion FACs.

In this work, we also deal with cases for which the guide field B_y is monopolar almost throughout the whole PS, in the vicinity of the source; that is, for these cases there is an apparent disagreement with respect to the quadrupole Hall current structure. We shall present cases where the $\pm B_y$ deflections are not symmetric with respect to the neutral sheet plane; thus, we do not get symmetric scatter plots of B_x and B_y like those shown (indicatively) by Runov *et al.* [4]. The events with "asymmetric B_y patterns" occur at both sides of the source and are readily interpreted on the basis of our suggested model.

Certainly, we discriminate the intra-magnetosphere driven B_y deflections from those due to possible penetration of B_y from the solar wind; we study intense and transient variations clearly dictated by high velocity substorm-associated plasma flows. In two measured events, three successive and explosive increases of plasma flow initiate three distinct B_y deflections.

In the next subsection, we shall exhibit our model that potentially determines the origin and sign for the B_y deflections with intense earthward plasma-ion flows. In the third subsection, we shall present events with $\pm B_y$ deflections categorized in different classes while searching their ultimate excitation mechanism. The discussion subsection becomes extensive because the initially introduced model has been further refined; in addition, we undertake an effort to provide evidence that our model is closer to reality than the already available model related to the X-type reconnection. After all, it becomes evident that the basic idea of conversion of magnetic to kinetic energy via reconnection might be nothing more than an erroneous assumption.

2. The Proposed Model

We focus our attention on the region positioned just **earthward from an activation center** in the Earth's magnetotail; this center is assumed to be the source accelerating particles, heating plasma and ejecting populations both earthward and tailward. The source is developed in a region with thickness comparable to the ion inertial length; the so-called "ion diffusion region (IDR)" given that inside this volume the ions remain demagnetized. In this framework, we are not interested in determining the specific excitation mechanism of the source; instead, we primarily pay attention to the magnetic field geometry and functionality just in front of the activated source. And it should be noted that the source here is confined in an area extended from 20 to 30 R_E away from the Earth, given that we are based on Geotail datasets recorded at these distances. At the source region the ions are completely demagnetized; however, earthward from the source, they progressively become magnetized since the curvature radius R_c (for the magnetic field lines) increases from less than one ion gyroradius (r_{gi}) to several ones. Therefore, the earthward streaming ions are allowed to penetrate closer to the Earth; finally, they become fully magnetized when the curvature R_c reaches the value of ~$9r_{gi}$ [18].

At this point, we introduce a rather radically different interpretation of observations based on a model slightly different from that associated with the typical "X-line" collisionless reconnection. Our fundamental notion is that (regardless of any specific mechanism converting magnetic energy into mechanical) the ions, once produced at the source site, can stream (with high velocities) within the IDR forming an "ion jet". In contrast, the electrons (produced by the same source) escape much earlier from their activation site; they become magnetized at the source's neighborhood, and essentially move far away along the magnetic field lines threading the source and enveloping the "ion jet".

In **Figure 1**, the source (S) produces the electron (red color) and the ion (blue color) currents over the XZ (*i.e.*, the meridional) plane. Within the IDR (blue rectangle) an ion jet (being actually the ion current) is directed outward along the X-axis, and produces (outside the IDR) the bifurcated ion current flowing along the magnetic field lines that envelop the central plasma sheet (CPS) region. **These ion currents** will produce (outside the IDR and inside the PS) a quadrupole magnetic field structure similar to the B_y pattern related to Hall currents found in the X-line model. Closer to the source and inside the IDR, the same quadrupole pattern is basically created by the electron field-aligned currents. Therefore, observationally, *one may anticipate the same pattern of B_y deflections*
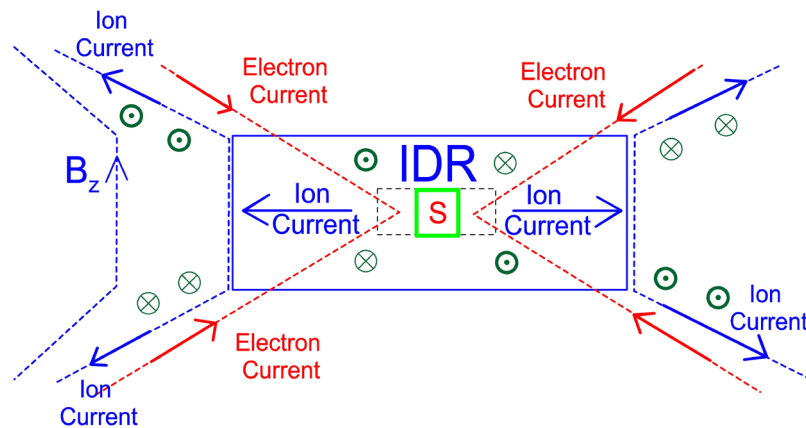

Figure 1. The source (S) produces the electron (red color) and the ion (blue color) currents over the shown XZ plane. Within the IDR (blue rectangle) an ion jet (being the ion current) is directed outward along the X-axis, and produces (earthward and out of the IDR) the bifurcated ion current flowing along the magnetic field lines that envelop the central plasma sheet (CPS) region. We observe the same pattern of B_y deflections in PS either outside or inside the IDR.

either outside or inside the IDR; *that is, the same pattern of B_y should be observed either at "fluid scales" or at* **"*ion scales*"**. We are going to explain why the B_y deflections, studied in this work (at the earthward side of the source), are due to ion FACs (and not to any Hall-electron currents). The magnetic field and current topologies tailward of the source have been recently studied and published by the same author [9]; thus this work complements the previous one.

Furthermore, the earthward ejected ions, at the very moment of their exit out of the IDR, form a termination boundary. The ions penetrate toward the Earth, impinge over the northward-directed magnetic field lines and are finally reflected backward. The whole process looks similar to that one taking place at the magnetopause boundary: The solar wind particles generate a **surface magnetopause current** which, in turn, reinforces the magnetic field inside the cavity and diminishes the magnetosheath-side magnetic field. Consequently, a magnetopause layer is formed which is often called the Chapman-Ferraro layer. Likewise, the earthward ejected ions build up a distinct boundary layer with extremely high B_z values in CPS. Moreover, *this boundary systematically steepens*, so that an impulsive increase of B_z is finally produced. The incoming ions give rise to a downward surface current that progressively becomes more and more intense producing the so-called "dipolarization front". The latter is of fundamental importance: The front here is not merely related to "piled up" magnetic field lines or a simple relaxation of tail from a more stretched magnetic field topology or only a newly reconnected flux tube; it is an exceptionally steep B_z-front (locally) formed in CPS and presumably extended to several Earth radii across the tail. Therefore, this front modulates the near Earth magnetotail as it is shown in **Figure 2**. In our view, the ion populations behind the front will produce the ion FACs generating the B_y deflections with different polarities in north and south PS. Inward of the ion FAC, a satellite (S/C) has to detect an earthward plasma flow plus a positive (negative) B_y deflection in north (south) PS. In **Figure 2**, earthward (tailward) from the source (S), the satellite is indicatively shown moving tailward (earthward), although actually the whole structure moves earthward (tailward).

During the dipolarization process, as illustrated in **Figure 2**, the tail is reconfigured from a stretched topology (thin-dashed lines) to a more dipole-like one (blue-solid line). But the coexisting B_y and B_z variations are not self-consistently organized forming a real rope structure. In the vast majority of presented cases (with earthward plasma flows), we probably observe a satellite initially affected by the ion FAC and, in turn, crossing the dipolarization front. The profound feature is a transition from a region dominated by the B_y to another one with a prevailing B_z component. Consequently, the majority of the shown MFR-like structures are probably **pseudo-MFRs**.

In the context of a hypothetically pulsating source, which was studied in detail by Sarafopoulos [11], one would probably identify successive and quasi-periodic activation episodes, while the tail repetitively recovers its more dipole-like structure through successive-distinct dipolarization fronts. Unavoidably, in each front, the B_y deflection (with the appropriate sign) interrelates with each B_z increase; in addition, the satellite will most likely move inward (given that the tail inflates) while detecting earthward fluxes. In a future research effort, if one would like **to check** the proposed scenario concerning the dipolarization process, then he or she has to use as a powerful tool the energetic ion fluxes being downward directed close to the B_z-front. Actually, such a situation with an earthward-downward flow of 30 - 300 keV ions can be observed during the dipolarization phase in the work of Vogiatzis *et al.*, [19], in their Figure 3.
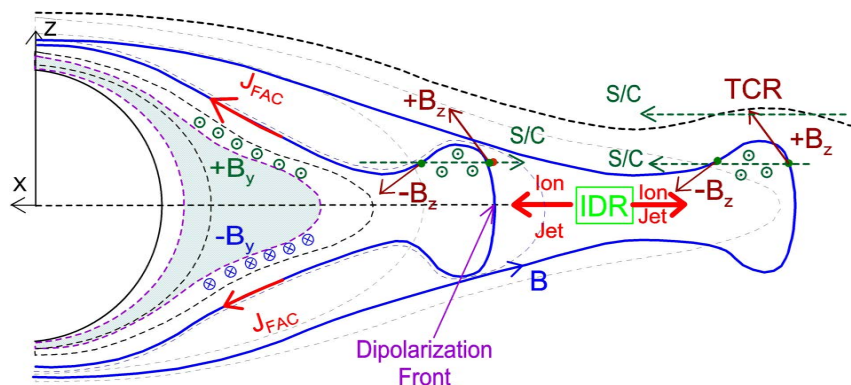
Figure 2. Earthward (tailward) from the source (S), the satellite (S/C) is indicatively shown moving tailward (earthward), although actually the whole structure moves earthward (tailward). The earthward (and likewise the tailward) ejected ions produce an impulsive increase of B_z in CPS, the so-called "dipolarization front". Inward of the ion FAC, a satellite has to detect a positive (negative) B_y deflection in north (south) PS.

On the basis of our model (**Figure 1** and **Figure 2**), *we suggest that the polarity for the B_y deflections (outside the IDR) should systematically obey a well-defined pattern*, a simple rule. The polarity of B_y must be determined, at the satellite position, by the nearby flowing FAC. The same succession of B_y and B_z deflections is anticipated either the B_y belongs to a real- or pseudo-MFR structure. The morphological features are the same, but the ultimate process is different. The B_y deflections (caused by FACs) are rather loosely related to B_z variations.

Tailward from the IDR, although it is out of the main scope of this work related almost exclusively to earthward plasma flows, the antisunward streaming ions of the "ion jet" might produce a "B_z front" moving tailward like the dipolarization front moving earthward. The physical process would be the same and the geometry very similar. Thus, a satellite (S/C) crossing the B_z front will detect a positive-then-negative B_y deflection. Outside the PS, the satellite would detect a travelling compression region (TCR) each time a front moves earthward or tailward (intersected by the satellite).

In summary, we again underline that, irrespectively of any precise interrelationship between the B_z and B_y variations, two fundamental features-processes principles associated with each activation are worth noticing: First, that the B_z has to enter a range of more positive values (due to the dipolarization effect) and, second, that the polarity of B_y must be determined, at the satellite position, by the nearby flowing FAC.

3. Observations

3.1. An Introductory Event

In this indicative case study presented in **Figure 3**, three successive plasma-ion surges are directed earthward
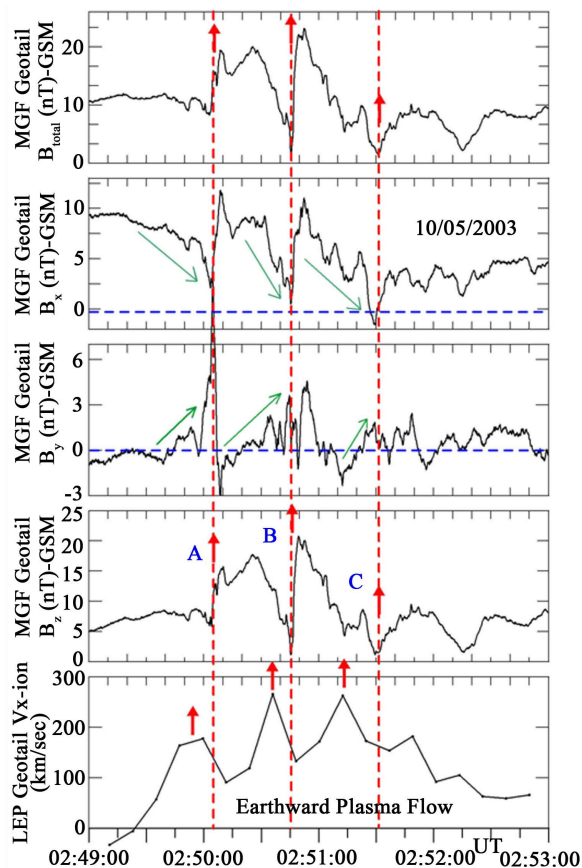
Figure 3. Three successive plasma-ion surges earthward directed (bottom panel) are tightly associated with three distinct dipolarizations labeled A, B and C (in fourth panel). The B_z for the dipolarization B abruptly increases ~20 nT; that is, more than twice as compared to the pre-disturbed B_{total}. It is inferred that the supposed rope-like "structure A" has neither a B_y core, nor a helical structure.

(bottom panel) tightly associated with three distinct dipolarizations labeled A, B and C (in fourth panel) and marked with red arrows along the B_z trace. We use the magnetic field datasets (in nanoteslas) provided by the Geotail/MGF instrument [20] with 62-ms resolution, while the plasma data are generated by taking the moments over 12-s intervals of ion distribution functions measured by the low energy particle (LEP) instrument [21]. The event was observed at $(X, Y, Z)_{GSM} = (-28.1, 1.3, 4.4)$ R_E, and we may conclude that the magnetosphere is repetitively transiting from a stretched geometry to a more dipole-like configuration *every ~40 s*. That is, the source is clearly activated three times ejecting earthward three ion jets. In a more detailed look, we would like to comment and organize our observations in a chronological sequence, as they probably took place during this event:

1) First, we suppose that the plasma flows signify separate source activations; at the same time, we assume that each dipolarization process was initiated just earthward of the IDR, although it will arrive (at S/C) a little time later. The latter is evident by the apparent S/C motion; it moves inward (*i.e.*, toward the neutral sheet) three times. Obviously, we interpret the decreases of B_x as plasma sheet expansions which were initiated before the arrival of stepwise increases of B_z; the tail's rearrangement begins at the same time with the source activation.

2) Each increase of B_y is assumed as due to an earthward flowing FAC; thus, within the north plasma sheet, the B_y is switched from a slightly negative to a large positive value three times, every time the S/C crosses the FAC while moving inward. The current is caused by the ion jet directed earthward from the source; the ions ride on the magnetic field lines just out of the IDR. We consider that the ions flow faster along the magnetic field lines, and consequently arrive earlier than the dipolarization front itself. Thus, the B_y increases before each front arrival. And each reduction of B_z, before each front, is due to the plasma diamagnetic effect, plus an ongoing inflation of tail.

3) Three successive dipolarization fronts arrive at S/C while the B_z increases as much as an order of magnitude. The crossing of each front coincides with a rapidly reducing plasma velocity until the next activation takes place.

The above processes can be understood in the context of **Figure 2**. According to our model, the source is activated three times and ejects (earthward) three distinct ion jets. The latter initiates three successive increases of FACs which, in turn, are manifested by the B_y deflections. And actually, for the presented event, the earthward flowing FACs produce positive deflections of B_y in north plasma sheet, where Geotail was located.

It seems that the FAC is particularly intense for the first plasma surge; this is the reason for the extreme enhancement of B_y from about zero to 12 nT (*i.e.*, a temporal effect). For the dipolarizations B and C, the current crossing changes the sign of B_y to -3 nT (*i.e.*, a spatial effect). Only for the first dipolarization the peaked B_y value coincides to a B_z transition to more positive values. Thus, one could classify this structure as a typical MFR one. Nevertheless, the whole phenomenon (of **Figure 3**) probably carries the information that this MFR-like structure is not different from the next two. The whole phenomenology (in our view) is the result of an ion FAC and the depolarization front which is propagating. The satellite is first influenced by the nearby flowing FAC because the B_y deflection increases almost simultaneously with the initiation of an ion flow. Conversely, the B_z increase delays since it is depended on the slower process that piles up magnetic flux close to the Earth. Consequently, the structures A-C are essentially interpreted here as (mainly) due to temporal rather than spatial effects, although both effects interrelate. ***Therefore, we conclude*** ***that the supposed rope-like "structure A" has neither a B_y core, nor a helical structure***. And we conclude, from this indicative phenomenon, that the peaked values of B_y and B_z may coincide or not; **this is not the critical factor for a deeper understanding of the ultimate physical process**. We think that the same underlying mechanism produces all the three structures in **Figure 3**; it would be misleading to categorize only the "structure A" as belonging to a particular class.

During the second ion jet, the B_z abruptly increases ~20 nT; that is, more than twice as compared to the pre-disturbed B_{total}. Such a striking reconfiguration remind us the process taking place over the dayside magnetopause boundary and this view is described in the preceded section.

3.2. Polarities for the B_y Deflections Associated with Earthward Plasma Flows

There are cases for which the B_y deflections are essentially decoupled from any bipolar signature visible along the B_z trace or any peaked value observable along the total magnetic field trace; accordingly, these events are obviously incompatible with any real MFR structure. In **Figure 4**, we present six events with positive or negative B_y deflections occurring with very intense earthward plasma-ion flows, given that the V_x velocity increases up to 1400 - 3000 km·s^{-1}. They are mostly observed in combination with (or during) the dipolarization phase of
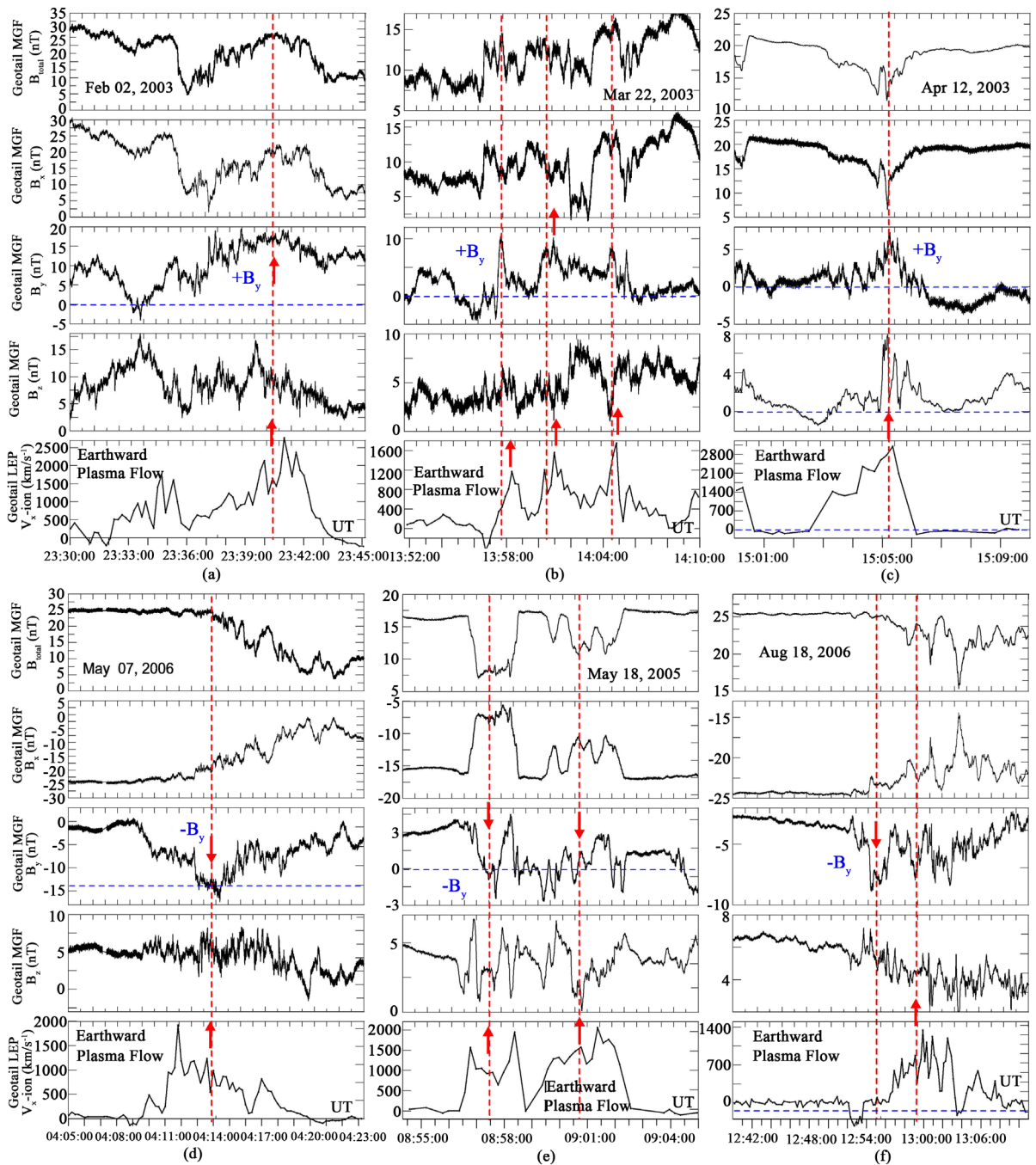
Figure 4. Six events with positive and negative B_y deflections occurring with very intense earthward plasma-ion flows (up to 1400 - 3000 km·s^{-1}). The B_y polarity is positive in the north plasma sheet (where the B_x is clearly greater than zero, events (a)-(c)) and negative in the south plasma sheet (B_x less than zero, events d-f). The event "b" shows three successive and impulsive plasma flows; the second B_y deflection clearly precedes (~2 min) the second intense local dipolarization.

the magnetic field (characterized by the high and positive values of B_z, fourth panels) simultaneously occurring with strong B_y deflections (third panels). In particular, we pay attention to the B_y polarity which is positive in the north plasma sheet, where the B_x is clearly greater than zero, as shown by the events a-c; and negative in the south plasma sheet with B_x less than zero, as shown by the events d-f. In the context of the already presented model, the FACs generated by the earthward ejected ions will cause B_y deflections (outside the IDR) with the appropriate polarity in the north and south plasma sheet. It is worth noticing that the event "b" shows three suc-

cessive and impulsive plasma flows accompanied by three distinct positive B_y deflections. Most importantly, the second B_y deflection clearly precedes (~2 min) the second intense local dipolarization. The latter lines up with the concept that the ion flow first affects the B_y component (via the FACs); while the B_z is later affected by the flux pile-up. In general, the B_y deflection increases stronger with the plasma velocity than any B_z variation. In seldom cases we can observe (*i.e.*, with regard to the situation of event "f") that the $|B_y|$ deflection increases even before the detection of plasma flow; additionally, no clear dipolarization is detected at all for this event.

3.3. Polarities for B_y Deflections Associated with MFR-Like Structures and Earthward Plasma Flows

Figure 5 shows four events with an MFR-like structure occurring with a) an earthward plasma-ion flow (*i.e.*, positive values for the velocity V_x, fifth panels); b) a distinct dipolarization (*i.e.*, negative-then-positive B_z variation) evident along each B_z trace (fourth panels); c) maximized B_y values (marked with dashed-vertical lines) occurring simultaneously with the dipolarizations; and d) peaked values of the total magnetic field when the B_z changes sign. Consequently, based on morphological criteria, one can plausibly argue that we observe four typical MFR structures; that is, the bipolar B_z signature may correspond to the helical structure and the B_y deflection is potentially the rope's core. However, we suggest a different interpretation: ***The sign for the B_y deflection is determined by the satellite placement in north (positive) or south (negative) plasma sheet***. Actually the events "a" and "b" are characterized by negative B_y deflections in south plasma sheet (B_x negative) and the events "c" and "d" are related with positive B_y deflections in north plasma sheet (B_x positive), in agreement with the exhibited model in subsection 2. Therefore, in our framework, the shown structures <u>***are actually pseudo-MFRs; neither cores nor helical structures do really exist***</u>. The duration of each event varies from 1 to 2 minutes and the time in between the peaked $|B_y|$ and $|B_z|$ values varies from 10 to 60 s. If the reader thinks that the B_x trace, for the event "b", is not sufficiently representative (case corresponding to south PS), then he/she could consult two similar examples studied in the past a) by Snekvik *et al.*, [22] with CLUSTER, or b) by Sormakov and Sergeev [23], in their Figure 2; on both cases the negative B_y deflections clearly occur in south PS with earthward plasma flows.

The fundamental principle, in our model, is that the FACs are developed and diagnosed before the arrival of the dipole-like structure (*i.e.*, a temporal effect). First, a source activation occurs producing an earthward ion jet, and inflating the PS as a whole. In turn, the ion jet sets up the FACs (associated with the B_y deflection), while the PS expansion is organized as a dipolarization front. And the reader must pay attention to the fact that ***the B_y deflection, at times, essentially occurs simultaneously with the negative B_z deflection (and not when the B_z changes sign, as conventionally expected with respect to a rope structure). The latter is absolutely clear for the "a" and "b" events of*** **Figure 5** ***if we focus our attention to the really dominant $|B_y|$ values***. They clearly occur before the abrupt increase of B_z from negative to positive values; something that is evident in **Figure 6** showing the ratios of B_z/B_{total} (blue line) and B_y/B_{total} (red line). When the B_z is very small or negative, the (by far) dominant component is the B_y. We obviously identify not a symmetric loop-like rope structure, but a mere boundary crossing, a simple passage from one region to another.

In summary, we conclude that the observed B_y deflections essentially form a certain pattern; they are positive in the north and negative in the south plasma sheet. A more systematic-statistical approach would further support this finding; the already described selected events are considered as representative.

4. Discussion

4.1. Asymmetric FACs

In a recently published work, Sarafopoulos [9] emphasized that in a thin plasma sheet, after an explosion process initiated recurring activations of substorm, the bulk tailward motion of demagnetized ions (forming an "ion channel" inside the IDR) is catalytically affected by the local magnetotail's motions. He suggested that even an ***ion vortex is formed*** from a tailward ion jet affected by local upward or downward tail's motions. The type of motion eventually determines the clockwise or counterclockwise direction of the ion cyclic motion (over the XZ plane) and, consequently, the sign for the B_y deflection due to this vortex-current. The upward (downward) motion is associated with a positive (negative) B_y deflection. In a similar way, in this work we initially stress that the earthward ejected ions stream along an "ion channel" (inside the IDR) which eventually splits into two
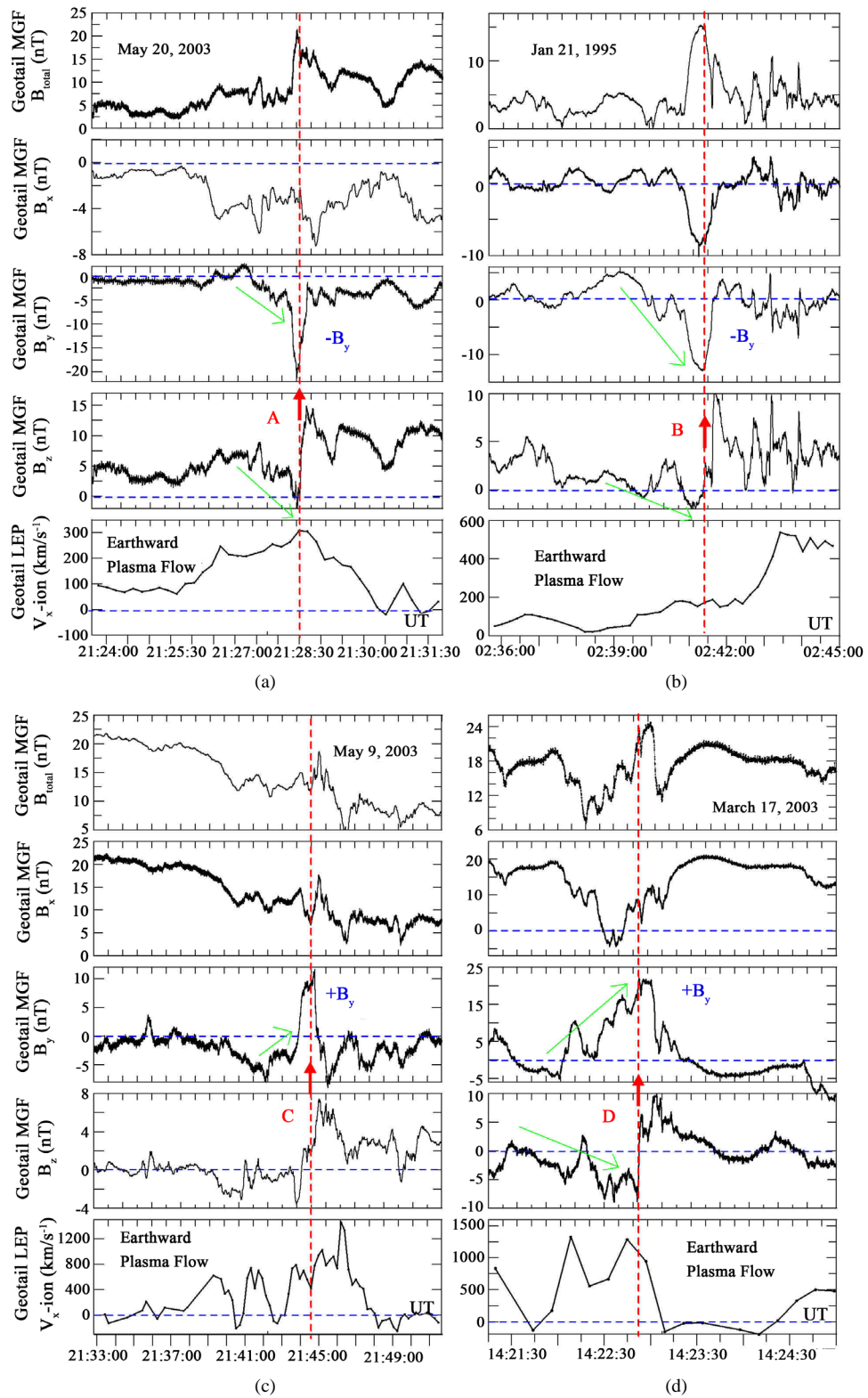
Figure 5. For these pseudo-MFR structures, the sign for the B_y deflection is determined by the satellite placement in north (positive) or south (negative) plasma sheet. Actually the events (a) and (b) are characterized by negative B_y deflections in south plasma sheet (B_x negative) and the events (c) and (d) are related with positive B_y deflections in north plasma sheet (B_x positive).
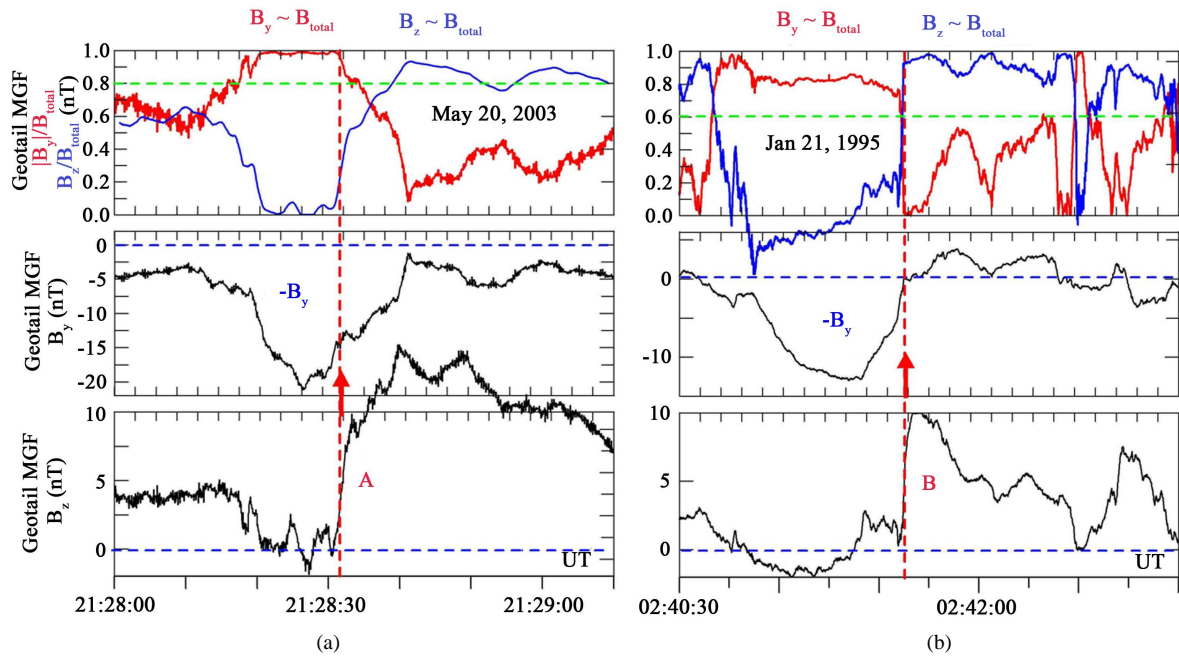
Figure 6. The ratios of B_z/B_{total} (blue line) and B_y/B_{total} (red line) for the events (a) and (b) of **Figure 5**. The dominant $|B_y|$ deflections essentially occur simultaneously with the negative or lower B_z values. We rather have to identify two separate regions, and not three as one would anticipate in a real rope.

branches forming the "downward FACs" and causing the appropriate B_y deflections. Furthermore, it is more realistic to assume that the two current branches are probably asymmetric. This concept is schematically illustrated in **Figure 7(a)**, where the northern branch of FAC is much more intense than the southern one. And this magnetosphere response could result by two combined factors: First, a local downward motion of magnetotail (earthward of the source) and, second, the ballistic character of orbits of demagnetized ions within the IDR. Thus, the earthward ejected ions essentially ride on the lines of northern hemisphere PS. Consequently, a satellite (S/C) crossing the whole plasma sheet will (almost exclusively) detect positive B_y deflections; only adjacent to the south branch of FAC, a negative and weak B_y deflection might be detected. Parenthetically, it would be instructive to highlight that the same type of asymmetry could be detected for a tailward ion jet associated with an upward tail's motion: The satellite has to record, throughout the whole plasma sheet, a positive B_y deflection caused by an ion surface current, as it is shown in **Figure 7(b)**. That is, each tail's motion does not necessarily lead to a vortex-like current, as one could speculate.

   In supporting the claim of asymmetric currents (introduced in the preceded paragraph), we present in **Figure 8** an indicative event occurred on June 22, 2002, around 06:35 UT. In this episode the satellite, while receiving an earthward plasma flow with high velocities, moves from the southern to northern PS and detects prevailing positive B_y values. Only the more negative excursions of B_x are associated with negative B_y deflections; in parallel, the positive B_y deflection is indeed particularly intense in north PS. Additionally, we show the scatter-plot of B_x and B_y (at the bottom panel), for the period 06:33:55 to 06:36 UT; actually, the positive B_y values dominate irrespectively of the B_x sign. The thick-red line constitutes the (third order) polynomial fitting to the data. Needless to say that this result is obviously in disharmony with any north-south symmetric FAC or even the possibility of a symmetric guide field generated by Hall currents in a typical X-line, if the latter was the case. We schematically know that the guide field must change sign around a neutral sheet crossing. Consequently, the diagnosed asymmetry may introduce a radically different perspective from what was emphatically pointed out by Runov *et al.*, [4]; they presented scatter-plots between B_x and B_y showing a symmetry (of variations) with respect to the neutral sheet. Certainly, in the above mentioned work, the authors assume that the satellite was inside the IDR. In any case, it remains a question how the exhibited asymmetry (with respect to the neutral sheet) could be interpreted and explained in the context of an X-line "reconnection model".

   It was already pointed out that we deal with structures related to earthward plasma flows; however, since the issue of "asymmetric scatter plots" around the neutral sheet like the one of **Figure 8**, is particularly important,

(a)   (b)
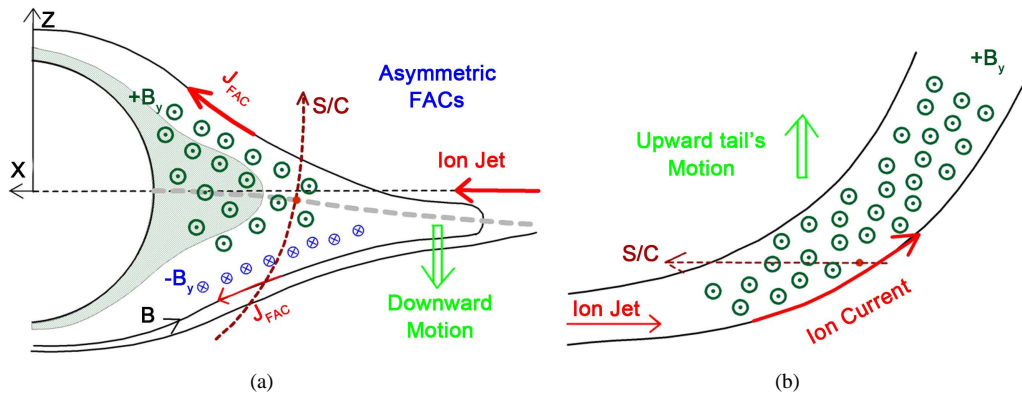
Figure 7. (a) The earthward ejected ions streaming in an "ion channel" inside the IDR eventually form the "downward FACs" and cause the appropriate B_y deflections. In this more realistic scheme the two branches of FACs are asymmetric; a response resulting by a local downward motion of the magnetotail (earthward of the source) and the ballistic character of orbits of demagnetized ions within the IDR; (b) For a tailward ion jet associated with an upward tail's motion, the satellite records a positive B_y deflection throughout the whole plasma sheet.
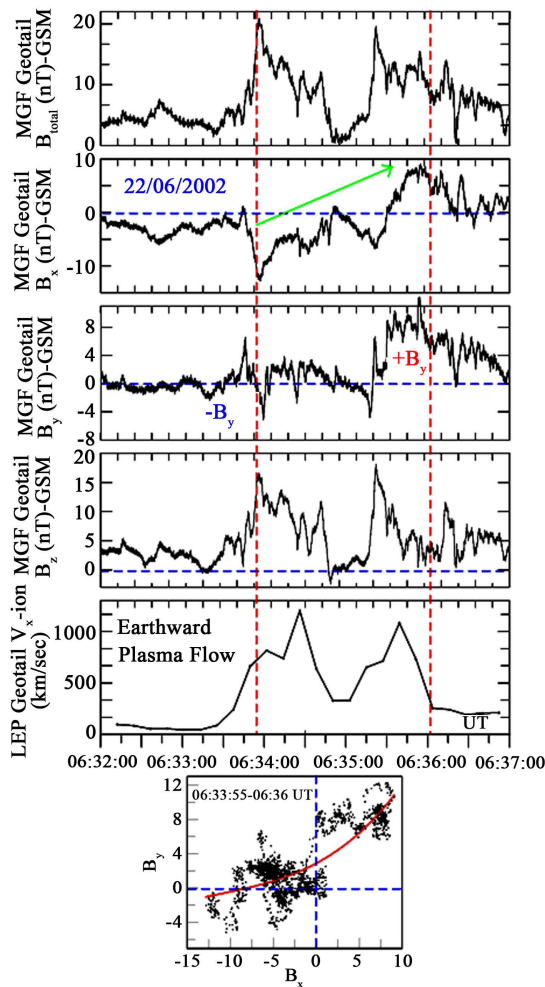

Figure 8. The satellite, while receiving an earthward plasma flow with high velocities, moves from the southern to northern PS and detects prevailing positive B_y values. Only the more negative excursions of B_x are associated with negative B_y deflections; in parallel, the positive B_y deflection is indeed particularly intense in north PS. Additionally, the scatter-plot of B_x and B_y, for the period 06:33:55 to 06:36 UT demonstrates that the positive B_y values dominate irrespectively of the B_x sign.

either with earthward or tailward flows, it turns out to be helpful to know that the exhibited asymmetry is commonly detected at both sides of the source. That is, we shall extend our discussion by two more cases occurring when the satellite has just crossed the source when moving tailward. The latter will further deepen our horizon and we shall better understand a few new key factors related to the magnetotail's response, given that this asymmetry was not emphasized in the past. Thus, we show in **Figure 9** two cases for which the Geotail, after passing by the source, and the earthward flows are switched to tailward, encounters asymmetric (B_x, B_y) scatter-plots. The asymmetry is profound; the same polarity of B_y is detectable almost throughout the whole PS. The events occurred a) on 11/05/2006, at ~09:22 UT **with a downward motion of the magnetotail and a negative B_y deflection** extended from $B_x = -15$ to $+ 15$ nT, and b) on 17/03/2003, at ~14:04 UT, **with an upward tail's motion and positive B_y deflection** within a region confined in between ±15 nT. Negative (positive) B_y deflection is observed even with negative (positive) B_x values in case 9a (b). Scatter-plots for these events (shown in **Figure 9(c)** and **Figure 9(d)** correspond to the periods from 09:19 to 09:24 UT (for the first event), and from 14:02:20 to 14:07 UT (for the second event). **The guide field B_y is almost monopolar**, negative (for the left panel) and positive (for the right), irrespectively of the sign of B_x. Obviously, this result is not in agreement with the typically symmetric "B_y-guide field" produced by Hall currents in the context of a collisionless X-line. *In our view, the shown B_y deflections are not due to Hall currents*; they are modulated by the joint action of a tailward directed ion jet plus an upward (downward) motion of the tail. The ions stream within the IDR and finally ride on the already **curved magnetic field lines** of the southern (northern) plasma sheet and move along the lines causing *positive (negative) B_y deflections within almost the whole plasma sheet*. The deflections are dictated by the surface ion current and Ampere´s law; an indicative interpretation scheme is shown in **Figure 7(b)** where a tailward ion jet encounters an upward curved magnetic field structure (*i.e.*, lines like a convex function with monotonically increasing slope, at the plasma sheet/lobe interface). Conversely, if the tailward ion jet encounters downward curved magnetic field lines (*i.e.*, lines like a concave function with monotonically decreasing slope, at the plasma sheet/lobe interface), then a negative B_y deflection will be caused across the whole plasma sheet. *It is a great challenge for the X-line reconnection model to give a convincing interpretation* for the coexisting values of $B_y \cong 20$ nT and $B_x \cong B_z \cong 0$ nT, at ~14:04 UT, in **Figure 9(b)**.

4.2. The "Dipolarization Front" as an "Injection Boundary"

Within the "ion channel" (being inside the IDR) the demagnetized ions cross the magnetic field lines and do not convect with them; they do not obey to the "frozen-in condition". Most importantly, the earthward ejected ions finally build up a termination boundary with $B_z \cong B_{total}$, even at the very CPS, as it was proposed in Section 2. Already from 1992, Sergeev *et al.* [24], noted "that the amplitude of the main B_z impulse is systematically larger at the satellite which is closer to the centre of the PS, both in the tailward and in the earthward streaming MFRs". The incident ions (over the boundary) give rise to a downward surface current, which progressively grows more intense. This local dipolarization is of fundamental importance because the ion populations behind the front will produce the FACs causing the B_y deflections with different polarities in north and south PS. And according to this scenario, given that it is impossible to have an MFR entity with two oppositely directed "B_y cores", the usually observed (earthward of the source) structures are "pseudo-MFRs"; very close to the Earth a genuine MFR is obviously not formed. According to Sarafopoulos [9] a rope embedded in the tailward plasma flow is often formed *when a local motion (upward or downward) of the tail affects the "ion channel" of the IDR*. Something similar, very close to the Earth, is rather unreasonable to occur because the source is relatively close to the "dipolarization front-surface". In contrast, if the source is activated far away in the tail, then an MFR could be formed embedded in the earthward plasma flow, too.

Furthermore, the abrupt increase of B_z in CPS is associated (for a satellite crossing the whole structure) with a south-then-north signature (of B_z). The latter is schematically shown in **Figure 2** via a satellite (S/C) moving tailward, although, actually, the whole structure moves earthward. This geometry is the same with that proposed by Sergeev *et al.* [24] and Sormakov and Sergeev [23]. They suggested that "a reconnected magnetic tube moving earthward can crumple the background field by creating a compressed B_y on its front and strongly increasing the B_z values in the positive direction; a short-time negative variation in B_z occurs due to the inclination of the compressed background field". In our view, such a compression actually takes place, an impulsive B_z boundary is really built in CPS and the bipolar B_z signature is of chief importance; however, we add in this scenario the key role resulting by the ion surface current over the B_z front. *The fundamental difference (expressed in a sim-*
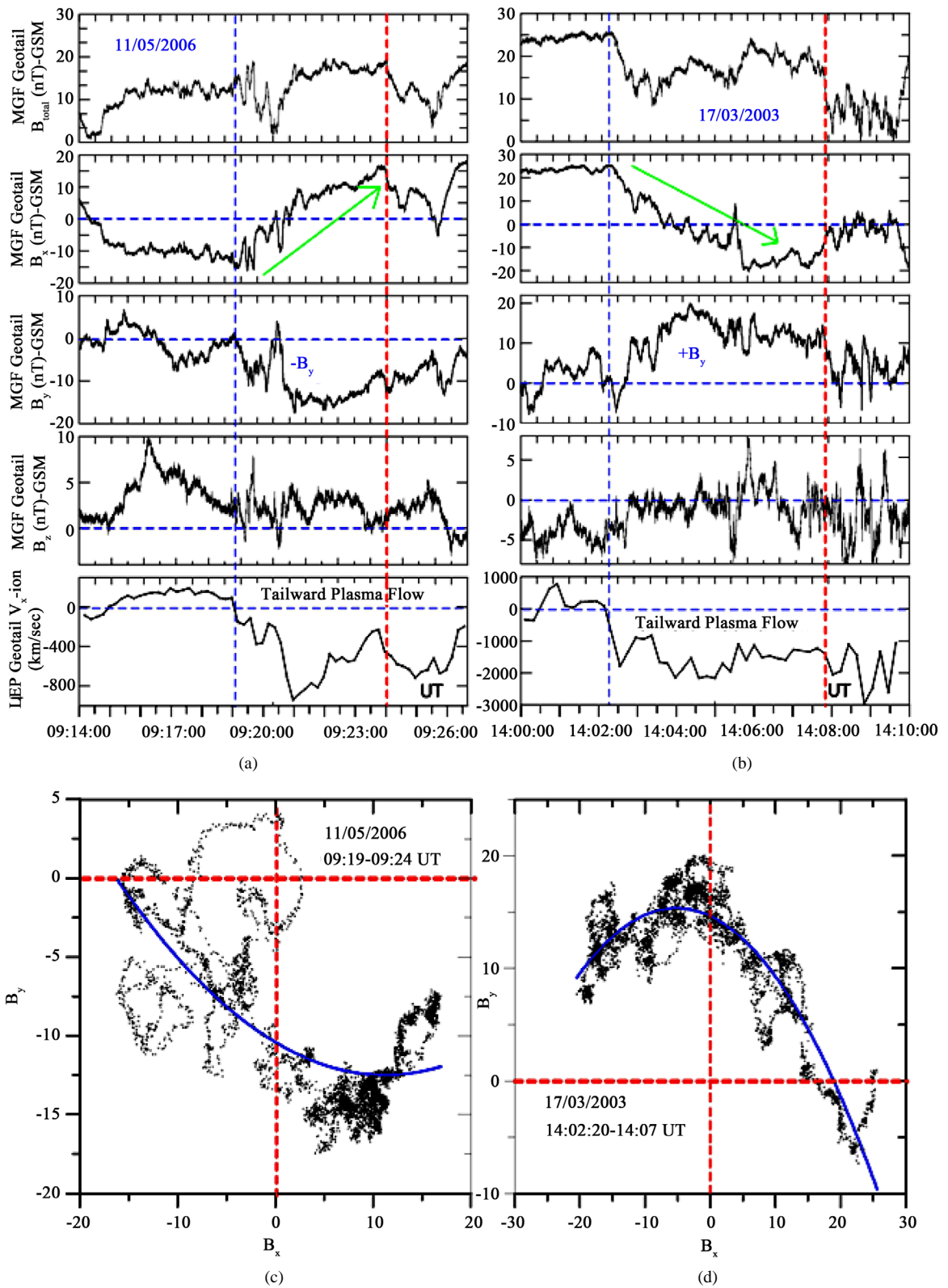
Figure 9. Scatter plots for the events of **Figure 8**; they occur (a) on 11/05/2006, from 09:19 to 09:24 UT; and (b) on 17/03/2003; from 14:02:20 to 14:07 UT. Although the B_x values are evenly distributed around the zero level, however the guide field B_y is almost monopolar, negative (for the left panel) and positive (for the right).

plified manner) *is that in the X-line model the source ejects plasma*, *whereas in our model the source ejects ions* (*outside the IDR*). The ions build up the impulsive B_z boundary (outside of the IDR) and produce the FACs associated with *the B_y deflection pattern*. In all the presented MFR-like events the $-B_z/+B_z$ signature is highly asymmetric, the gradients of B_z are extremely high and, most importantly, the B_y deflection frequently occurs simultaneously with the negative B_z values, as we have pointed out in subsection 3.3. And the background field does not always determine the B_y polarity: For the event "4a", although the background B_y is essentially zero, the B_y deflection is more than -20 nT, while for the events "4c and d" the background field is slightly negative and the B_y positive!

If the "B_z boundary" is built, it is supposed to play an additional role. From the already suggested production mechanism, energetic ions highly varying in energy (*i.e.*, 30 - 1000 keV) must be incident on the boundary from their tailward source; in our approach, *the B_z front is not built after an elapsed time of convection*. Thus, we would logically infer that this distinct boundary associated with *the dipolarization front is probably the so-called "injection boundary"* (as defined by McIlwain [25] or Lopez *et al.*, [26]). The latter is considered to be a region tailward of which all electrons and protons are energized together at the same time, at substorm onset; and the particle signatures observed by satellites therefore show the normal dispersion due to the different energy depended drift speeds of the particles from the injection boundary to the satellite [27]. Furthermore, it should be underlined that the location or shape of such an injection boundary was a matter of conjecture [28]. In our approach, the dispersionless injection signature would be obtained if indeed the satellite was within or very near to the injection boundary region, *but the particles are not locally accelerated*. The particles are accelerated at the source far away tailward, and in turn, propagate as *an ion jet* (*carrying plasma ions and energetic populations at the same time*) *that modulates the dipolarization front, which is finally detected by the satellite as a dispersionless injection*. Again, in our view, we do not need a near-Earth acceleration mechanism being at work adjacent to the injection boundary; the particles are not energized by a local plasma instability. Certainly, the idea about particles moving inward, perhaps from several R_E away, is an old one: In the "convection surge" model [29]-[31] particles are energized by the dipolarization process, and subsequently convected earthward by the inductive electric field. Even long drift paths could be possible in this perspective, if the magnetic field change propagated with the particles and cancels the normal radial magnetic field gradient that otherwise might separate particles of different energies. Simulations supporting the latter concept are performed by Sarris and Li [32]. The concept underlying this work may be distinguished from the others in that the populations are essentially energized at the source site by a specific mechanism, for instance, the explosive phase of the twin Double Layer (DL) structure, as we already suggested [11]. According to the Double Layer model, the resulting ion particles are going to build the B_z dipolarization front. We basically decouple the dipolarization front from any reconnection process taking place via a supposed X-line; the produced energy cannot be considered as the result of any reconnection, but as the result of an electrostatic discharge potentially occurring within the twin-DL structure.

4.3. Overall Pattern for B_y Deflections

This work, along with the recently published one by Sarafopoulos [9], could lead to a unified scheme concerning the pattern of B_y deflections at both sides of the source, *on fluid scale lengths*. Taking into account that we study plasma flows or magnetic field deflections lasting (typically) 3 min and having velocities (on average) 500 k·ms^{-1}, then the involved scale length is about 15 R_E; *i.e.*, this work focuses on the so-called fluid scale.

Furthermore, in order to achieve an overall pattern of B_y deflections, we apply the fluid-scale results (that line up with our observations) to the microscale response of a typical X-line. We try to obtain the best fit of our results to the mainstream X-type reconnection model, although major inconsistencies finally remain. Thus, in the next subsection, while raising additional objections against the X-line model, we finally support a radically different opinion.

At presently, we consider a simplified, symmetric topology, for the region of the source, although we have (to a certain extent) scrutinized asymmetric (with respect to the neutral sheet) B_y patterns. We are particularly interested in the area located earthward of the source; accordingly, the earthward side of the outflowing source is sketched in **Figure 10**. The reader can recognize basic features for all the three scales: The smallest scale lengths (and the shortest timescales as well), corresponding to an electron accumulation area, are confined inside the EDR (green line rectangular), the ion scale lengths corresponding to the region inside the IDR (which is en-
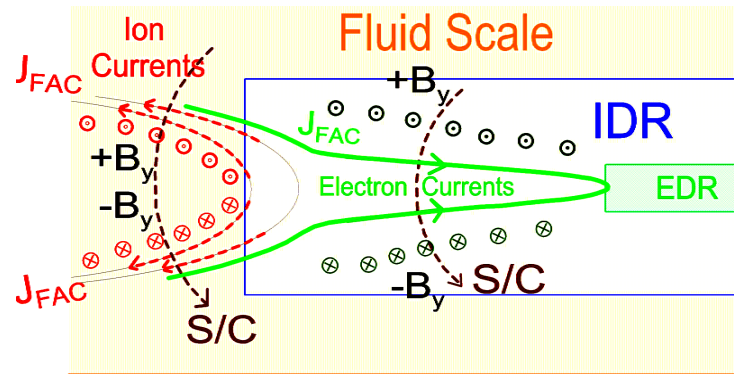
Figure 10. Both electrons and ions move earthward from the source; the electrons become adiabatic just outside the EDR (green rectangle), whereas the ions become adiabatic just outside the IDR (blue rectangle). The B_y pattern outside the IDR is the same with that related to the Hall current inside the IDR in the X-type reconnection model. The so called "electron currents" within the IDR correspond to the Hall current according to the X-line model; in contrast, we are of the opinion that they represent a bifurcated electron FAC. The two branches of (in parallel) currents are mutually attracted and, in this way, tend to preserve the thin current sheet structure; thus, they sustain a "lengthened ion channel" within the IDR. The current density for the electron FACs is much higher than the current density of ions moving earthward.

closed by the blue line), and eventually the fluid scale lengths (that include the space outside the IDR). At present, it is assumed that the narrow region of the so-called "electron currents" (in **Figure 10**) corresponds to the "Hall current of collisionless reconnection". In general, in order to achieve coupling of different scales, measurements of at least two satellites are required; however, in this work we merely use single satellite datasets plus the knowledge gained from previous studies.

The electron Hall current, within the IDR, results from a fundamental difference between ions and electrons in collisionless plasma [16]: The ions are unmagnetized, whereas the electrons remain magnetized and move ***strictly transverse to the electric and magnetic fields***; our **Figure 10** is a restricted two-dimensional version over the XZ plane. In this context, the electron populations are carried outward by the newly reconnected (within the EDR) magnetic field lines, whereas the ions will ride on the reconnected lines later; that is, the ions will become adiabatic when they arrive at the boundary of the IDR. Therefore, earthward of the IDR, two branches of the field-aligned ion current would be apparently formed connecting the source to the ionosphere. Furthermore, these FACs will produce the appropriate B_y magnetic field variations; as a result, a magnetic field domain is developed in the neighborhood of an activated source (on fluid scale lengths). Interestingly, ***the B_y pattern outside the IDR is the same with that related to the Hall currents inside the IDR***. A satellite (S/C) moving in trajectories like those shown in **Figure 10** and crossing either the Hall current (within the IDR) or the two branches of the ion current (outside the IDR) will identify (inside the PS) the same transition of deflection from $-B_y$ to $+B_y$. In this perspective, the early results of Runov *et al.* [4] concerning the pattern of B_y deflections, within the IDR, ***could be supplementary*** to our B_y related results on larger scales. ***However***, a major objection will be raised in the next subsection concerning this item.

In addition, in our framework, asymmetric B_y patterns (at both sides of the source) could be easily interpreted. For instance, if the tail earthward of the source locally moves downwards, then only the north hemisphere plasma sheet surface ion current would be essentially developed and exclusively associated with a prevailing positive B_y deflection, like the event of **Figure 8**. On the other hand, if the tail, tailward of the source, is locally moving upward (downward), then only "one-sided surface ion current" would be mainly formed. The latter corresponds to the event shown in **Figure 9(a)** and **Figure 9(b)**, where actually the tail locally moves downward (upward) and the dominant B_y deflection is negative (positive).

4.4. Questioning the Existence of Hall Currents

In this subsection we are going to express our skepticism about the alleged existence of Hall currents originating from an X-line collisionless reconnection; that is, we refer to the electron currents supposed to be outward directed for the inflow regions and inward directed for the outflow ones, inside the IDR. First, we deal with the inflow region Hall currents: Axiomatically, the EDR is (in the context of an X-line) highly populated by the incoming electrons; consequently, an amphipolar electric field E_z pointing inward is formed (within the IDR).

Schematics showing such an electric field can be found even in textbooks like the one of Heikilla [33]. In this regard, we would like to make three comments as a preparation for the forthcoming discussions: First, if the E_z were greater than E_y, then *a downward drift will prevail* for the inflowing electrons and the Hall current J_z would be totally blocked off. Second, if the reconnection geometry were actually X-shaped, then *the electrons following a line convecting inward will probably escape along the line by repulsive electrostatic forces*, and the Hall currents would be insignificant, too. Third, if the reconnection process actually took place in the tail and the electrons indeed generated a Hall current due to the drift $\mathbf{E}_y$ x $\mathbf{B}_x$, then the Hall current J_z flowing against the E_z would initiate a dynamo process (given that $E_z \cdot J_z < 0$); conversion of magnetic energy is probably not required.

In a second place, we scrutinize the supposed Hall currents flowing along the "outflow regions" of an X-line: It is commonly accepted that the just reconnected magnetic field lines, a process taking place inside the EDR, will move outward (in a narrow region along the X-axis) carrying the "frozen-in" field electrons. The resulting electric field will be inward directed with respect to the X-line, while the electrons are propelled by the "sling effect". However, we assume that it is highly unrealistic to assume an electron drift taking place inside the IDR. The electron convection velocity is much less than "the ballistic" electron velocity (due to the source) along the magnetic field lines. For only 500 eV electrons the ratio of convection to ballistic velocities will be ~1/7. In our view, a more pragmatic approach would be as follows: First, the electrons and ions are accelerated in the same manner at the source region (S) simultaneously by a mechanism associated with the "twin-Double Layer structure" in its explosive phase, as proposed by Sarafopoulos [11]. Then, both electrons and ions move outward from the source, with the difference that the electrons are apparently going to become adiabatic just outside the EDR (green rectangle in **Figure 10**), whereas the ions will become adiabatic just outside the IDR (blue rectangle for the same figure). The electrons, when leaving the EDR, ride on the magnetic field lines and *produce a bifurcated electron current* (inside the IDR), an electron FAC as it is shown in **Figure 10**. Therefore, the outward streaming electrons produce homo-parallel and mutually attracted currents plus the associated B_y guide fields. *In this context the guide fields are indeed caused by an electron current, but not a Hall current; <u>Hall currents do not exist at all</u>. Moreover, the attracted electron currents* tend to preserve the thin current sheet structure and, in this way, *sustain a lengthened "ion channel" within the IDR*. The ions outside the IDR will produce a bifurcated ion current (dashed red line in **Figure 10**), which inside the PS creates a B_y pattern similar to that of Hall current, too. However, in our situation these B_y deflections are related to the fluid scale (and not the IDR).

In summary, the earthward streaming electrons of the source (along the lines) obviously produce an electron FAC (and not a Hall current, as it was hypothesized in past works to occur very close to an X-line). A satellite (S/C) crossing (brown-dashed line trajectory within the IDR) the electron FAC current will detect the same B_y pattern as in the erroneously assumed situation of Hall current, which, according to its definition, flows as a convection current perpendicular to the plane of the B_z and the E_y-field.

In a similar way, the ions jetting tailward of the source (marked by S in **Figure 11**) will sustain the electron FACs flowing along the magnetic field lines enveloping the jet; therefore, the B_y deflections recorded by a satellite (inside the PS) *<u>will be due to the electron FACs and not the electron Hall current</u>*, although the pattern is the same. Therefore, based on the latter inference, we can argue that, in past research efforts, the B_y deflections
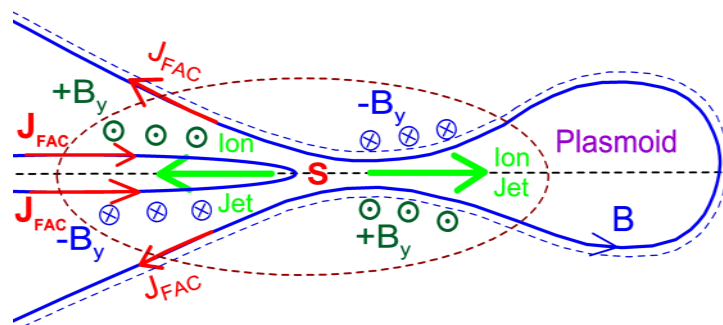
Figure 11. The Tw ion jet (generated by the S-source) crosses the magnetic field lines streaming tailward within the IDR (brown-dashed line) and frequently forms a plasmoid. The electrons, neutralizing the positive charge of the jet, constitute the FACs enveloping the ion jet and producing B_y guide fields. The latter would be misinterpreted as caused by Hall currents given that the B_y pattern detected by a satellite inside the PS is the same with that of a Hall current (inside the IDR). Moreover, the mutually attracted electron FACs tends to preserve the thin current sheet structure.

due to ion or electron FACs could have been erroneously credited to Hall electron currents (e.g., as in the statistical work of Ueno *et al.* [34] *and* Eastwood *et al.*, [35]).

4.5. Questioning the Concept of "Reconnection"

Obviously, reconnection as magnetic field reconfiguration actually takes place; the major question is whether this process converts magnetic energy into mechanical one and produces energetic populations. In addition to what was presented in the preceded paragraph, the fundamental idea of transport of magnetic flux, via convecting magnetic field "frozen-in" plasma, may be very misleading in many cases, too. Although the schematic picture showing the circulating magnetic flux, in the Earth's magnetosphere, is very attractive, however, it does not mean that such a circulation must be really based on the frozen-in condition or even the reconnection concept. The convection is probably not the dominant process when explosive events (during substorms) are underway; instead, we are of the opinion that ***a major driving mechanism that largely modulates the magnetosphere's topology is the jetting ions out of the source and within an extended IDR***. Thus, the dipolarization front may be built up by an earthward ion jet, and large scale MFRs propagating tailward (of the source) may originate from tailward ion jets [9]. At times with low geomagnetic activity, the ions and electrons alike will drift earthward performing $E_y \times B_z$ motions. At substorm-times, an "ion jet" (*i.e.*, an exodus "ion channel") streaming outwards from the acceleration source will readily cross the magnetic field lines. That is, in this way the ***"ion channel"*** ***essentially determines the extent*** (***along the X-axis***) ***of the IDR measuring***, ***at times***, ***a few*** R_E. The criterion for the IDR may be (a) that $V_x \cong V_{x\perp}$ (where the $V_{x\perp}$ is the earthward directed component of the plasma-ion velocity being perpendicular to the magnetic field in very CPS) and (b) that the $B_{total} \cong B_z$ (*i.e.*, the field is almost vertical to the current sheet plane). The extent of the "ion channel" is determined according to the same criterion, while the acceleration source will be much more localized. In general, the magnetic field reconfigures as the current systems progressively dictate; however, the plasma does not carry the magnetic field lines. Naturally, the positive (negative) B_z values are related to earthward (tailward) $E_y \times B_z$ ion drift motions; nevertheless, within the IDR we can even observe tailward flows with positive B_z values (as commonly were observed; for instance look at the work of Ohtani *et al.*, [36]).

It may be a profound truth that the concept of "merging or reconnection" is a gigantic pseudo-science (Alfvén, [37] [38]); what is actually happening in magnetotail, may be far from any frozen-in condition or the reconnection process converting magnetic energy to mechanical one. Obviously, as reconnection we do not mean here a simple magnetic field reconfiguration; the main point constantly remains the mechanism accelerating particles up to ~1 MeV [39]-[41]. In a persistently thinned PS, where all the phenomena take place within the IDR, the FACs (and not the Hall currents) will be the ultimate source producing guide fields. If an IDR is locally established in tail, then the ions will cease drifting earthward within this region; consequently, a net earthward electron flow will be established. Furthermore, ***the IDR will become a cavity with increased charge densities*** (for both charge carriers); and such a cavity potentially leads to the "twin-DL structure" with repetitive activations as suggested by Sarafopoulos [11]. And the DLs would convert the magnetic energy into mechanical one and readily produce energetic particles.

4.6. Further Comments on the Work of Runov *et al.* [4]

The work of Runov *et al.* [4] was frequently cited by many authors; therefore, it would be constructive to support further our different explanation scheme for the presented observations. A scheme unrelated to the X-type reconnection model in which a few unanswered issues intrude, too.

The quadrapole magnetic field structure around the source was indeed observed; the question focuses on their ultimate driving mechanism. We have clearly suggested in this work that the B_y pattern was accomplished by FACs established within and outside the IDR. And we further discuss three worth noticing points in respect to this work:

1) They study B_y deflections caused by Hall currents obviously within the IDR. Hence, they observe proton bulk velocities up to ~1000 km·s^{-1} within the IDR. Naturally, a question is raised: Which is the mechanism, in the context of the X-line model, forcing the ions to be accelerated within the IDR at these high velocities? The "moving magnetic field lines" does not offer such a mechanism; probably the exact opposite happens. A highly localized source (as we have proposed, for instance, the twin-DL structure) accelerates both electrons and ions simultaneously and, in turn, eject them outward within the IDR.

2) They do not show plasma-electron bulk velocities perpendicular to the local magnetic field having higher

velocities than those observed for protons (e.g., look at the simulations of Pritchett, [42]). Thus, they do not actually observe Hall currents; they just make a conjecture. The presence and operation of FACs can therefore be expected with high probability.

3) The flow reverse of plasma from tailward to earthward occurred in the range of ~1 min; and this is the involved time unit for the analyzed quadrapole field. However, we have very clear results that such a reverse of plasma flow, and most importantly, a simultaneous reverse for the ~300 keV ions, happens even within 10 s [15]. Consequently, the studied region has wider extent than the source; a region in which the source populations sustain the related FACs.

4.7. The Locally "Pinched" Plasma Sheet

In a locally thinned current sheet the demagnetized ions form the cross-tail bifurcated J_y-currents (**Figure 12**), which, along with the existing magnetic field, produce the inward directed magnetic forces $\mathbf{F} = \mathbf{J_y} \times \mathbf{B_x}$. Moreover, these ion currents and the homoparallel electron J_y-current (of akis) are mutually attracted as well. Thus, the PS locally "pinches" and the curvature radius of akis further decreases leading to even higher demagnetization rates. The resulting collapse of the negatively charged akis, being an integral part of the twin-DL structure, generates an electrostatic discharge within the space of DLs. The transient electric fields may accelerate energetic particles up to ~1 MeV, while the PS undergoes a local dipolarization. Therefore, around the "pinched" region, the cross-tail current is disrupted generating $\pm\Delta B_z$ deflections. And the deflections (along with the produced ion jets within the IDR) are probably developed in two propagating fronts just outside the IDR: A strong front characterized with negative B_z values that moves tailward, and a positive B_z-front that moves earthward. The latter is usually described by the term "X-type reconnection". If the negative ΔB_z deflection is weak then one would observe tailward plasma flows at the same time with the prevailing positive B_z values; a situation often verified by observations.

5. Conclusions

B_y deflections in the Earth's magnetotail occurring with very intense *earthward plasma-ion flows* are associated or not with bipolar signatures visible along the B_z trace and simultaneously peaked values of the total magnetic field. Thus, the B_y deflections are categorized as related or not to MFR-like structures. However, presenting indicative events, we conclude that *the sign for the B_y deflection is always determined by the satellite placement in north (positive) or south (negative) plasma sheet*. Therefore, the near Earth MFR-like structures must commonly be _pseudo-MFRs_; neither cross-tail cores nor helical structures really exist.

In our suggested model, the overall B_y pattern is essentially due to FACs, and not the Hall currents associated with X-type collisionless reconnection. The B_y deflections related to observations earthward of the source, on fluid scale lengths, are produced by ion FACs outside the IDR. The B_y deflections related to observations on ion scales are produced by electron FACs inside the IDR. _We give convincing evidence that Hall currents (along the tail) do not exist at all within the IDR; in contrast, ion jets streaming outward from the source come closer to reality as they can be verified by measurements._ The electrons just earthward of the EDR form FACs enveloping the ion jet. The ions arriving at the boundary of the IDR become adiabatic and form FACs producing, in turn, B_y deflections on fluid scales. We assume that the electrons and ions alike are simulta-
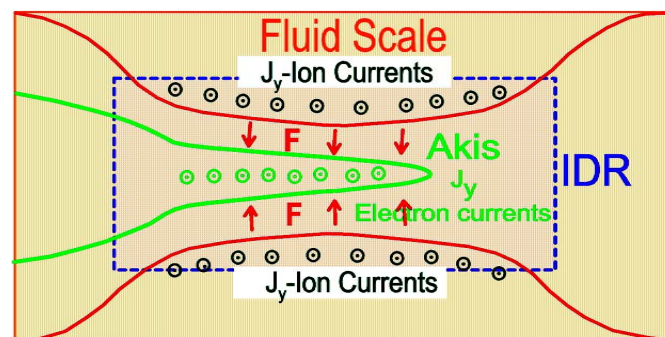
Figure 12. Locally "pinched" PS due to the magnetic forces (F) caused by the cross-tail ion and electron homoparallel and mutually attracted J_y-currents.

neously accelerated by the source in its explosive phase; the mechanism may be an electrostatic discharge working on a structure like the "twin-Double Layer" one, as proposed by the same author [11].

There are cases for which the guide field B_y is monopolar almost throughout the whole PS; these events constitute the "asymmetric B_y patterns", occurring at both sides of the source, and *are well interpreted by our suggested model.* If the tail, earthward of the source, locally moves downwards (upwards), then only the north (south) hemisphere plasma sheet surface ion current would be essentially developed and exclusively associated with a prevailing positive (negative) B_y deflection. If the tail, tailward of the source, is locally moving upward (downward), then only "one-sided surface ion current" (flowing tailward) would be mainly formed (outside the IDR). That is, if the tail locally moves downward (upward), then the dominant B_y deflection will be negative (positive). *It is a great challenge for the X-line reconnection model to give a convincing interpretation* for the asymmetric B_y deflections of magnetosphere.

Acknowledgements

References

[1] Nakamura, R., Baumjohann, W., Asano, Y., Runov, A., Balogh, A., Owen, C.J., Fazakerley, A.N., Fujimoto, M., Klecker, B. and Rème, H. (2006) Dynamics of Thin Current Sheets Associated with Magnetotail Reconnection. *Journal of Geophysical Research*, **111**, A11206. http://dx.doi.org/10.1029/2006JA011706

[2] Øieroset, M., Phan, T.D., Fujimoto, M., Lin R.P. and Lepping, R.P. (2001) *In Situ* Detection of Collisionless Reconnection in the Earth's Magnetotail. *Nature*, **412**, 414-417. http://dx.doi.org/10.1038/35086520

[3] Nagai, T., Shinohara, I., Fujimoto, M., Hoshino, M., Saito, Y., Machida, S. and Mukai, T. (2001) Geotail Observations of the Hall Current System: Evidence of Magnetic Reconnection in the Magnetotail. *Journal of Geophysical Research*, **106**, 25929-25949. http://dx.doi.org/10.1029/2001JA900038

[4] Runov, A., Nakamura, R., Baumjohann, W., Treumann, R.A., Zhang, T.L., Volwerk, M., Vörös, Z., Balogh, A., Glaßmeier, K.-H., Klecker, B., Rème H. and Kistler, L. (2003) Current Sheet Structure Near Magnetic X-Line Observed by Cluster. *Geophysical Research Letters*, **30**, 1579. http://dx.doi.org/10.1029/2002GL016730

[5] Asano, Y., Mukai, T., Hoshino, M., Saito, Y., Hayakawa, H. and Nagai. T. (2004) Current Sheet Structure around the Near-Earth Neutral Line Observed by Geotail. *Journal of Geophysical Research*, **109**, A02212. http://dx.doi.org/10.1029/2003JA010114

[6] Fuselier, S.A. and Lewis , W.S. (2011) Properties of Near-Earth Magnetic Reconnection from *In-Situ* Observations. *Space Science Reviews*, **160**, 95-121. http://dx.doi.org/10.1007/s11214-011-9820-x

[7] Treumann, R.A. and Baumjohann, W. (2014) Collisionless Magnetic Reconnection in Space Plasmas. arXiv:1401.5995v1 [physics.space-ph]

[8] Lui, A.T.Y., Zheng, Y., Rème, H., Dunlop, M.W., Gustafsson, G. and Owen, C.J. (2007) Breakdown of the Frozen-In Condition in the Earth's Magnetotail. *Journal of Geophysical Research*, **112**, A04215. http://dx.doi.org/10.1029/2006JA012000

[9] Sarafopoulos, D.V. (2014) What Does Determine the Sign of Core in Magnetic Flux Rope Structures of the Earth's Magnetotail, Is Submitted for Publication. *Journal of Engineering Science and Technology Review*, **7**, 1-12.

[10] Sarafopoulos, D.V. (2012) Twin-Double Layer Structure Producing Tailward Ion Jets in the Earth's Magnetosphere. *Journal of Engineering Science and Technology Review*, **5**, 76-84.

[11] Sarafopoulos, D.V. (2015) Anatomy of the Pulsating Double Layer Sourcein the Earth's Magnetotail. *Journal of Engineering Science and Technology Review*, **8**, 21-38.

[12] Sarafopoulos, D.V. (2011) A Pseudo-Magnetic Flux Rope Observed by the THEMIS Satellites in the Earth's Magnetotail. *Journal of Atmospheric and Solar-Terrestrial Physics*, **73**, 2279-2288. http://dx.doi.org/10.1016/j.jastp.2011.06.005

[13] Lui, A.T.Y., Dunlop, M.W., Rème, H., Kistler, L.M., Gustafsson, G., and Zong, Q.-G. (2007) Internal Structure of a Magnetic Flux Rope from Cluster Observations. *Geophysical Research Letters*, **34**, L07102. http://dx.doi.org/10.1029/2007GL029263

[14] Sarafopoulos, D.V. (2013) Substorm-Associated Dual System of Field-Aligned Currents Interpreting Major Bipolar Magnetic Field Signatures in the Earth's Magnetotail. *Journal of Engineering Science and Technology Review*, **6**, 149-164.

[15] Pavlos, G.P. and Sarris, E.T. (1989) Encounter with a Source of Energetic Particles Inside the Plasma Sheet. *Annales Geophysicae*, **7**, 531-539.

[16] Sonnerup, B.U.O. (1979) Magnetic Field Reconnection in Solar System Plasma Physics. Vol. 3, Edited by L. T. Lanzerotti, C. F. Kennel and E. N. Parker, North Holland, New York, 45-108.

[17] Terasawa, T. (1983) Hall Current Effect on Tearing Mode Instability, 828. *Geophysical Research Letters*, **10**, 475-478. http://dx.doi.org/10.1029/GL010i006p00475

[18] Büchner, J. and Zelenyi, L. (1989) Regular and Chaotic Charged Particle Motion in Magnetotail-Like Field Reversals, 1. Basic Theory of Trapped Motion. *Journal of Geophysical Research*, **94**, 11821-11842. http://dx.doi.org/10.1029/JA094iA09p11821

[19] Vogiatzis, I.I., Isavnin, A., Zong, Q.-G., Sarris, E.T., Lu, S.W. and Tian, A.M. (2015) Dipolarization Fronts in the Near-Earth Space and Substorm Dynamics. *Annals of Geophysics*, **33**, 63-74. http://dx.doi.org/10.5194/angeo-33-63-2015

[20] Kokubun, S., Yamamoto, T., Acuna, M.H., Hayashi, K., Shiokawa, K. and Kawano, H. (1994) The GEOTAIL Magnetic Field Experiment. *Journal of Geomagnetism and Geoelectricity*, **46**, 7-21. http://dx.doi.org/10.5636/jgg.46.7

[21] Mukai, T., *et al.* (1994) The low energy particle (LEP) Experiment Onboard the Geotail Satellite. *Journal of Geomagnetism and Geoelectricity*, **46**, 669-692. http://dx.doi.org/10.5636/jgg.46.669

[22] Snekvik, K., Haaland, S., Østgaard, N., Hasegawa, H., Nakamura, R., Takada, T., Juusola, L., Amm, O., Pitout, F., Rème, H., Klecker, B. and Lucek. E.A. (2007) Cluster Observations of a Field Aligned Current at the Dawn Flank of a Bursty Bulk Flow. *Annals of Geophysics*, **25**, 1405-1415. http://dx.doi.org/10.5194/angeo-25-1405-2007

[23] Sormakov, D.A. and Sergeev, V.A. (2008) Topology of Magnetic Flux Ropes in the Magnetospheric Plasma Sheet as Measured by the Geotail Spacecraft. Cosmic Research, **46**, 387-391. Pleiades Publishing, Ltd., 2008. Original Russian Text, D.A. Sormakov, V.A. Sergeev, 2008, Published in *Kosmicheskie Issledovaniya*, **46**, 403-407. http://dx.doi.org/10.1134/S0010952508050031

[24] Sergeev, V.A., Elphic, R.C., Mozer, F.S., Saint-Marc, A. and Sauvaud, J.A. (1992) A Two-Satellite Study of Nightside Flux Transfer Events in the Plasma Sheet. *Planetary and Space Science*, **40**, 1551-1572. http://dx.doi.org/10.1016/0032-0633(92)90052-P

[25] McIlwain, C. (1974) Substorm Injection Boundaries, *Magnetospheric Physics*, Edited by B. M. McCormac and D. Reidel, Hingham, Mass, 143-154.

[26] Lopez, R.E., Sibeck, D.G., McEntire, R.W. andKrimigis, S.M. (1990) The Energetic Ion Substorm Injection Boundary. *Journal of Geophysical Research*, **95**, 109-117. http://dx.doi.org/10.1029/JA095iA01p00109

[27] Mauk, B.H., and Meng, C.-I. (1983) Characterization of Geostationary Particle Signatures Based on the "Injection Boundary" Model. *Journal of Geophysical Research*, **88**, 3055-3071. http://dx.doi.org/10.1029/JA088iA04p03055

[28] Friedel, R.H.W., Korth, A. and Kremser, G. (1996) Substorm Onsets Observed by CRRES: Determination of Energetic Particle Source Regions. *Journal of Geophysical Research*, **101**, 13137-13154. http://dx.doi.org/10.1029/96JA00399

[29] Quinn, J.M. and Southwood, D.J. (1982) Observation of Parallel Ion Energization in the Equatorial Region. *Journal of Geophysical Research*, **87**, 10536-10540. http://dx.doi.org/10.1029/JA087iA12p10536

[30] Mauk, B.H. (1986) Quantitative Modeling of the "Convection Surge" Mechanism of Ion Acceleration. *Journal of Geophysical Research*, **91**, 13423-13431. http://dx.doi.org/10.1029/JA091iA12p13423

[31] Delcourt, D.C., Sauvaud, J.-A. and Pedersen, A. (1990) Dynamics of Single-Particle Orbits during Substorm Expansion Phase. *Journal of Geophysical Research*, **95**, 20853-20865. http://dx.doi.org/10.1029/ja095ia12p20853

[32] Sarris, T. and Li, X. (2005) Evolution of the Dispersionless Injection Boundary Associated with Substorms. *Annales Geophysicae*, **23**, 877-884. http://dx.doi.org/10.5194/angeo-23-877-2005

[33] Heikkila Walter, J. (2011) Earth's Magnetosphere Formed by the Low-Latitude, Book of Elsevier.

[34] Ueno, G., Ohtani, S., Mukai, T., Saito, Y. and Hayakawa, H. (2003) Hall Current System around the Magnetic Neutral Line in the Magnetotail: Statistical Study. *Journal of Geophysical Research*, **108**, 1347. http://dx.doi.org/10.1029/2002JA009733

[35] Eastwood, J.P., Phan, T.D., Øieroset, M. and Shay, M.A. (2010) Average Properties of the Magnetic Reconnection Ion Diffusion Region in the Earth's Magnetotail: The 2001-2005 Cluster Observations and Comparison with Simulations. *Journal of Geophysical Research*, **115**, A08215. http://dx.doi.org/10.1029/2009JA014962

[36] Ohtani, S., Miyashita, Y., Singer, H. and Mukai, T. (2009) Tailward Flows with Positive B_Z in the Near-Earth Plasma Sheet. *Journal of Geophysical Research*, **114**, A06218. http://dx.doi.org/10.1029/2009JA014159

[37] Alfvén, H. (1986) Keynote Address, NASA Conference Publication 2469. Proceedings of a Workshop Held at George C. Marshall Space Flight Center Huntsville, Alabama, 17-19 March.

[38] Alfvén, H. (1986) Double Layers and Circuits in Astrophysics. *IEEE transactions on plasma science*, Vol. PS-14, 779-793. http://dx.doi.org/10.1109/TPS.1986.4316626

[39] Sarafopoulos D.V. and Sarris, E.T. (1988) Inverse Velocity Dispersion of Energetic Particle Bursts inside the Plasma Sheet. *Planetary and Space Science*, **36**, 1181-1199. http://dx.doi.org/10.1016/0032-0633(88)90072-4

[40] Sarafopoulos, D.V., Sidiropoulos, N.F., Sarris, E.T., Lutsenko, V. and Kudela, K. (2001) The Dawn-Dusk Plasma Sheet Asymmetry of Energetic Particles: An INTERBALL Perspective. *Journal of Geophysical Research*, **106**, 13053-13067. http://dx.doi.org/10.1029/2000JA900157

[41] Sarafopoulos, D.V. (2008) A Physical Mechanism Producing Suprathermal Populations and Initiating Substorms in the Earth's Magnetotail. *Annales Geophysicae*, **26**, 1617-1639. http://dx.doi.org/10.5194/angeo-26-1617-2008

[42] Pritchett, P.L. (2001) Collisionless Magnetic Reconnection in a Three-Dimensional Open System. *Journal of Geophysical Research*, **106**, 25961-25977. http://dx.doi.org/10.1029/2001JA000016