CLUSTER RESULTS ON THE MAGNETOTAIL CURRENT SHEET STRUCTURE AND DYNAMICS

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ABSTRACT

First years of Cluster data analysis have started to justify large expectations of community by providing a new level of understanding of space plasma dynamics. We briefly summarize the state of art in two aspects, concerning the tail current sheet (CS) dynamics, and its structure. Both issues are central for understanding of the tail stability (including substorms) and in both cases our view drastically changed from previous picture. With greatly advanced capabilities of measuring gradients and propagation Cluster made clear that previous picture of smooth and almost planar sheets is rarely applied. Real sheet dynamics often includes large-amplitude meso-scale sheet corrugations in which the sheet (1) is strongly deformed and tilted, (2)the perturbation has a kink-like properties (with CS normal rotating in YZ plane) and (3) propagates systematically from central tail part toward its flanks. The formation/propagation mechanisms are under the study although many facts point out to their close relationship to substorm activations and BBF generation. On the other hand, fast current sheet crossings were systematically exploited to investigate the sheet structure. Whereas the thin embedded as well as bifurcated sheet patterns were shown to occur often, the major finding is that, unlike the pre-Cluster era in which the Harris-type model was exclusively used, we are actually in a world of essentially non-Harris and variable plasma distributions. This change requires a big effort in theoretical studies, both findings stimulated a burst of activity in the plasma theory of space current sheets.

1. INTRODUCTION

Space current sheets represent a general form of thin boundaries between different plasmas, where important instabilities and dissipative processes occur. Most available for direct studies are magnetospheric (magnetopause and tail) current sheets, whose instabilities determine the penetration of mass and energy through the boundary and their transport in the magnetosphere, as well as the conditions for explosive tail instability (substorm) to occur. Previously the difficulties of separating between temporal and spatial variations, and of measuring the gradients (i.e. electric currents, pressure gradients) and current sheet tilts strongly limited the possibilities to study the sheet structure, orientation and dynamics with a single spacecraft. There were indications in the past work, that current distribution across the sheet can deviate from Harris-type [1] behavior showing thin embedded current sheets [2,3], bifurcated sheet structure with off-central current maxima [3, 4] of the electric current, displaying broad range of scales from micro-scales (comparable to the ion inertial length or ions gyroradius in the strong lobe field, L_{CP}) up to the meso- scale of a few Re [2-5] and displaying specific behavior during substorms [3,6,7]. Indications of possible large tilts of plasma sheet boundary have also appeared in the literature [31].

However, these isolated observations did not change the common view of tail current sheet as flat, nearly 1-D (at r>15..20 Re) and Harris-like structure, as was assumed in the majority of theoretical works on magnetospheric stability and transport in previous years. Situation drastically changed after the launch and successful work of Cluster specially designed to probe gradients and investigate meso-scale plasma structures and their dynamics. Here we briefly summarize the state of art in two areas of recent active research, where our views drastically changed from previous picture. One of them, the flapping motions of the current sheet, manifests in observations as large variations of main magnetic field component in the tail, often with the change of Bx-sign indicating the crossing of tail current central surface. It is frequently observed, especially in active plasma sheet, and is interesting both as a spectacular phenomenon (origin, properties, possibility to use as a diagnostic tool of active processes) as well as a tool to probe the sheet structure by crossing quickly across considerable portion of the current sheet (CS) thickness. The information on the current and plasma distributions is such flapping sheets is another issue of our interest.

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2. OBSERVATIONS

2.1 Data base and analysis tools

The material presented is mostly based on systematic studies of Cluster FGM and CIS observations during July-October 2001 tail season, in which the spacecraft tetrahedron size was ~1300 km (therefore, the thinnest current sheets, <~1000 km are not included – see R.Nakamura paper in this issue). Rapid crossings of the current sheet have been identified based on sharp variation of Bx-component with requirements that it should be short enough ($\Delta t<300$s) with the amplitude change be a sizable fraction of the lobe field BL ($|\Delta Bx|>0.5$ BL~15nT). 186 such rapid crossings were selected and processed, including computation of all main available parameters used in current sheet studies, this data base has been made available for research on the Internet page {*http://geo.phys.spbu.ru/~runov/Cluster/2001_xings_survey/*}. A subset of 78 crossings in which all four spacecraft crossed the neutral sheet, sufficient amount of curlometer determinations were accurate enough (DivB/Curl B < 0.3 in > 60% of points) and variations at all SC were similar (allowing to use the timing) were analysed in [9], whereas a subset of best 30 crossings have been used in [10] to systematically address the structure of these current sheets. A similar data base for tail season 2004 is expected to be open soon.

The results of studies presented below are strongly dependent on the accuracy of estimating the local CS tilts, which requires some comments. Advantage of Cluster is that three different methods could be used, although no one is perfect. Fortunately they depend on different assumptions, so the cross-comparison between methods is always required to be sure in the results. The four spacecraft timing (assumes plane sheet structure and its either constant speed or constant thickness [11]) gives both the sheet orientation and velocity along the normal. Using magnetic field gradient estimations [12], the sheet tilt can be determined by suggesting its plane structure with the current direction (**m**, in the center of 1D sheet) lying on the neutral sheet surface (therefore, the unit vector of the sheet normal **n**=[**l**x**m**]/|[**l**x**m**]|, where **l**- is the maximum B-variability direction obtained from MVA). This method can be useful also to evaluate the geometry of the magnetic structure [13]. Finally, the well-known Minimal Variance Analysis [15] is widely used to estimate the sheet orientation (its accuracy depends on the medium-to-minimal eigenvalues ratio $\lambda2/\lambda3$, amount of data points and the amplitude of magnetic shear [14, 16]). Meanwhile, strictly, there is no obvious basic physics which causes the MVA to work well in 1D sheets (for example, in the Harris sheet the magnetic variance is zero not only in the normal direction, but also along the direction of electric current, so some other factors, either field-aligned currents or perturbations will determine the MVA smallest variance direction).

The performance of tilt estimators was tested by intercomparison between determinations by different methods for a subset of 39 crossings with a good MVA resolution ($\lambda2/\lambda3>5$) - Figure 1 [14]. The scalar products between different pairs of normals (timing, $\mathbf{n_T}$, current-based $\mathbf{n_J}$ and MVA based $\mathbf{n_{MVA}}$) is >0.9 (normals within 18° cone) for ~60% of comparisons including MVA, and about 80% for comparison between timing and current-based normals. Therefore, generally the agreement is good in the magnetotail, however the events with poor agreement also exist which requires a caution when analyzing the single events. A useful result for the single-spacecraft studies from such comparisons is that for fast current sheet crossings in the tail the optimal requirement for the MVA could be : amount of data points across discontinuity >20-30 and the eigenvalue ratio $\lambda2/\lambda3>4$, which still misses less than 50% of all crossings from the analyses.

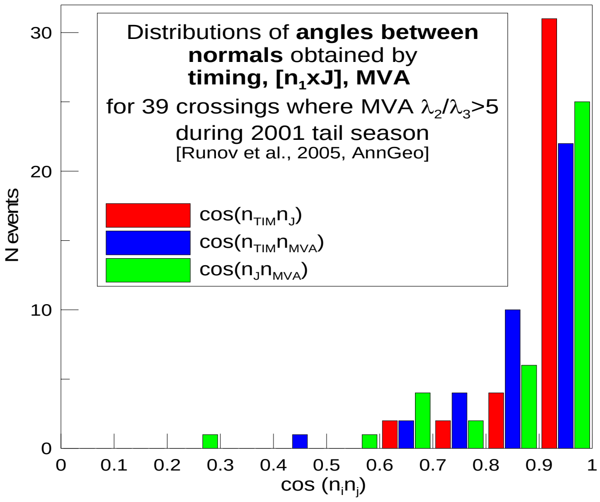


Figure 1. Scalar products between the current sheet normals determined with different methods for data set of 39 CS crossings for which the MVA results satisfy the success criteria ($\lambda2/\lambda3>5$, N>20)

Expanding the convective derivative approach [6], the instantaneous translational velocity of current sheet motion along the sheet normal (VC) and related distance across the current sheet (Z*) could be obtained from estimated magnetic gradient tensor [9] as

$$VC = -\,\partial B_l/\partial t \;/\; [\nabla_n B_l] \qquad (1a)$$

$$Z^* = -\int dt\, VC - Z^*(t_0) \qquad (1b)$$

where the integration is taken at the interval $[t_1,t]$, and t_1 and t_0 are the beginning of the crossing and the time of crossing the sheet center (where B_l–component changes its sign), correspondingly. As alternative approach, one may use the ratio B_l\BL as a proxy for Z*-coordinate, where B_l is the component in the direction of maximal B-field changes (along the 1st MVA eigenvector, being usually close to the X-direction in the tail) and BL is the equivalent lobe field obtained from the pressure balance ($BL=(B^2+2\mu_0 P_i)^{1/2}$).

2.2 Properties of flapping motions

Flapping motions are frequent and spectacular variations in the middle and distant parts of magnetotail which are known since first spacecraft observations in that region [17]. Their association with both solar wind perturbations and substorm activity was noticed [8, 18], they were often thought to be perturbations caused either by interplanetary shocks [2] or by the solar wind flow [19], and propagating along the tail. Another possibility that they are kink-mode type waves (due to KH or drift instability) was also discussed (e.g. [20]). Their properties, origin, occurrence and mode were not previously determined because of the limitations of single spacecraft studies.

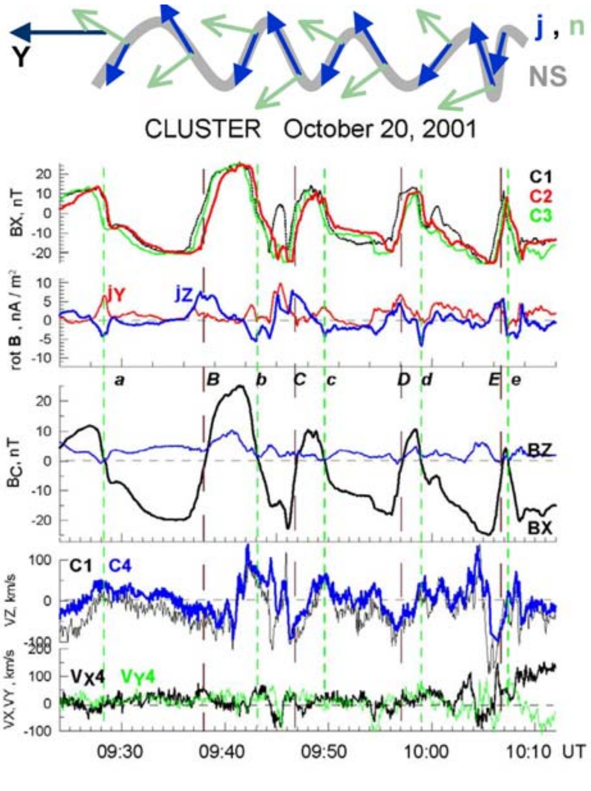


Figure 2. Cluster observations of flapping motions on October 20, 2001 [22]. Top panel shows a scheme of current sheet deformations with directions of electric current (dark arrows) and local CS normal (light arrows) shown for each crossing.

Appearance and mode identification. Example on October 20, 2001, when Cluster crossed the current sheet 9 times in a seria of flapping motions (Fig.2), and the case of isolated double crossing on August 12, 2001 (Fig.3) illustrate main features of flapping perturbations. They are: (1) large vertical component j_z of electric current (from curlometer technique) which is often the largest component in the sheet center; (2) large tilt of the CS normal from nominal (z) direction toward Y axis with n_y being the largest component of CS normal. As illustrated at the top of these figures, the variations, with alternating signs of both j_z and n_z at north-to-south (+/-Bx) and south-to-north (-/+Bx) crossings are consistent with wave-like oscillatory pattern of the neutral sheet repeatedly observed with Cluster [21-24]. The distribution of the normals obtained from timing with the sheet normals lying in YZ plane (more exactly, perpendicular to the main magnetic field and in the plane containing the electric current, see a statistics of the sheet normals in Figure 5 top]) is also typical for the kink mode.

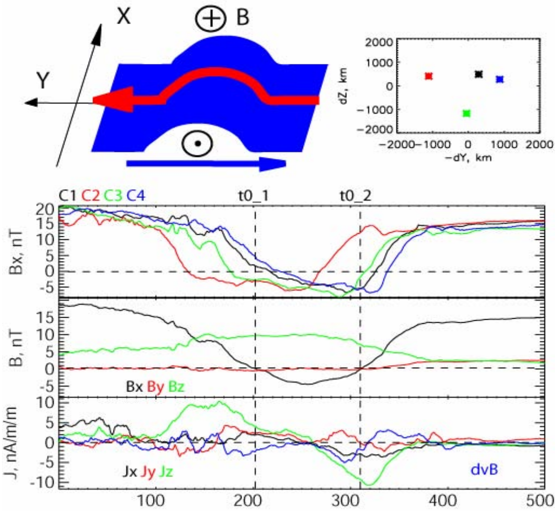


Figure 3. Cluster observations of isolated fold of the current sheet on August 12, 2001 [9] (time in seconds after 1525 UT). Dashed lines show the times of neutral sheet crossing at the barycentre.

Nearly simultaneous neutral sheet crossings synchronously observed by radially separated Cluster (at [-15.4,-8.9, 3.4]Re) and TC1 (at [-10.7,-6.8, 2.6]Re) spacecraft between 1320 and 15 UT on August 5, 2004 (Fig.4) combined with standard properties of waves deduced from Cluster (normals in YZ plane, dawnward propagation at the speed of 30 km/s) nicely confirm a kink-like geometrical structure of the wave whose scale-size along the tail exceeded ~5Re in that case.

We emphasize that, while the series of successive neutral sheet crossings like those in Figs. 2 and 4 are common, especially during disturbed times and substorms, one can also frequently observe isolated (often a pair of) crossings like those in Figure 3, suggesting that they could be the isolated (solitary?) folds of the current sheet. In fact (e.g. Fig.2) the series often look like a series of individual structures rather than a periodic process.

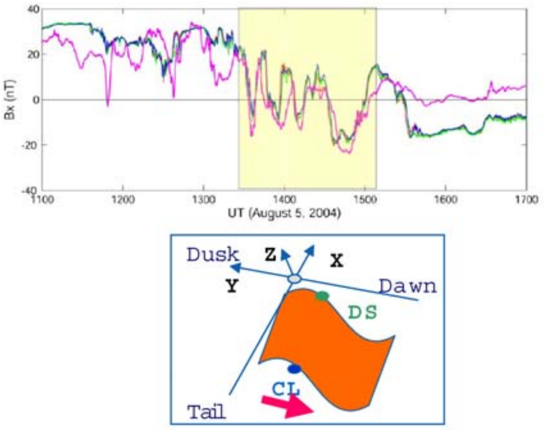
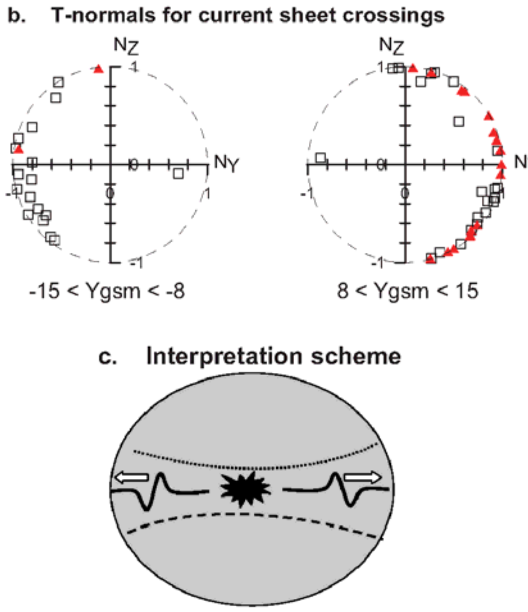


Figure 4. Simultaneous neutral sheet crossings at radially separated Cluster and TC1 spacecraft on August 5, 2004 [23] and scheme illustrating inferred geometry of current sheet perturbation

Velocities and amplitudes. Propagation of current sheet corrugations (folds) producing the local flapping motions shows a remarkably-organized pattern [9, 22]-Figure 5. As follows from timing analyses (which only extracts the velocity along the local CS normal) , the folds have preferential directions in the near-flank portions of the tail from the tail center to its flanks (see a scheme in Fig.5) . For example, the propagation is duskward in all crossings in Fig.2 (C2 trace delayed after other spacecraft), whereas it is dawnward (C2 leads other traces) in the dawnside observations shown in Figs. 3 and 4. In the central tail sector (roughly between Y~±8Re) both propagation directions can be met (even for different folds in the same event). This result has important implications to identify the origin and generation mechanism of kink structures.


b. T-normals for current sheet crossings

-15 < Ygsm < -8

8 < Ygsm < 15

c. Interpretation scheme

Figure 5. Statistics of current sheet normals in YZ plane (from timing at 4 Cluster spacecraft) for dawn and dusk tail sectors (b) and resulting interpretation scheme [22].

The propagation velocities and their relationship to the local plasma flows are also crucial factors. The (normal to the sheet) propagation velocity component Vtn is small, ~50km/s, varying from ≤20km/s to ~300 km/s in the subset of 78 crossings [9]. With the timescales of the crossing Δt~60-300s, the scale-sizes of structures S=Vn Δt varied between 1500 and 10000 km. Relationship of this propagation velocity to the plasma flow is a delicate question because for so small velocities the measurement problems (e.g. the offsets along the spin axis) are non-negligible even for the ion measurements. Another kind of problem is illustrated in the top panel of Figure 6 (from [14]) in which the subset of 54 crossings was selected with reliable normals (agreement between normals determined from timing and MVA was required to be ($\mathbf{n}_\mathbf{T}$*$\mathbf{n}_\mathbf{MVA}$) > 0.95). The top panel shows that even in high ion velocity events these flows are mostly aligned along the CS surface (Vt$_4$ and Vn$_4$ are the tangential and normal plasma flow components at spacecraft C4) so the normal flow component remains small (and its accuracy is very sensitive to the errors in the tilt determination etc). Comparison between propagation and ion flow normal component in Fig.6c indicates that (1) ion flows are typically in the same direction and show high correlation with Vn$_T$; and (2) the flow amplitude Vn$_P$ is close to the propagation velocity Vn$_T$ (for the subset of 25 slow flow events with large tilts ($|n_y|> n_z$) in which spacecraft C1 and C4 show similar proton bulk velocities in the neutral sheet suggesting little sheet variability). This preliminary result suggests that the folds in many cases could be transported with the plasma flow.

An interesting aspect of the flapping motions is that they include the vertical plasma flows (see e.g. Fig. 2, with positive(negative) Vz during SN (NS) sheet crossings, [14, 24]). The time integration of Vz (after suppression of artificial Vz offsets) gives an estimate of vertical amplitude of the fold, which is often about 1-2 Re. Therefore its vertical scale-size is comparable to both its horizontal scale size and the plasma sheet thickness, the flapping-related folds are in that sense the meso-scale non-linear structures.

Plasma sheet parameters. Based on a limited survey of 78 events [9] we may briefly summarize the typical values of other parameters of fast sheet crossings (having duration in the range 60-300 sec). The large tilts (exceeding 45^o from Zgsm direction) are very frequent and occur in roughly a half of cases [9,25]. Magnetic field in the sheet center was in average ~4nT (ranged between ~1 and 18nT), with the shear component (along the electric current direction) usually exceeding the normal component. The magnetic field curvature was directed Earthward (indicating closed field lines) in ~90% of events with remaining cases of tailward curvature being associated with tailward flows at probable location tailward of the reconnection site. The magnetic field curvature radius in the neutral sheet was most frequently Rc ~ 5 L_{cp} (L_{cp}- proton gyroradius in the strong lobe field BL), and, unlike the assumption of [32], it showed little correlation and differ significantly from the current sheet thickness.. The most frequent current sheet halfthickness was h ~ 10L_{cp} (varied between 1 and 20 L_{cp}). Any density/temperature values existing in the plasma sheet could be met. /Average velocities in the sheet plane (mostly Vx) are typically not big (<100 km/s in 65% of cases) whereas in roughly a quarter of all events the high-speed flows (>400 km/s) were met. The median value of κ-parameter ($\kappa=\{Rc\ BL/(L_{cp}\ Bns)\}^{1/2}$) characterising the adiabaticity of ion motion was ~0.6 indicating that ions are mostly non-adiabatic in these current sheets.

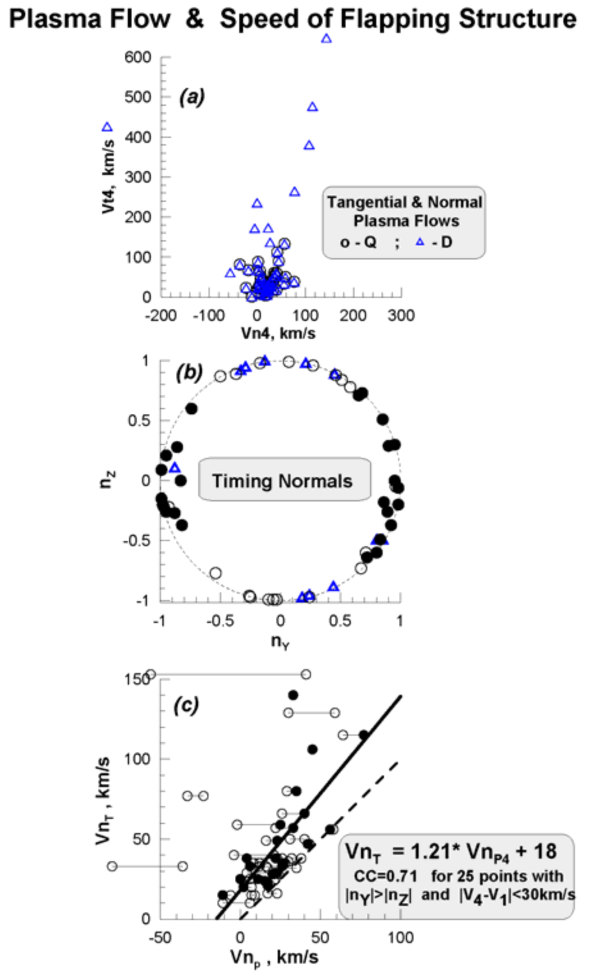


Figure 6. Comparison between plasma flows and normal component of propagation velocity obtained from timing.

Occurrence. Extending the Cluster-based study, the occurrence and tilts (direction of the CS normal inferred from MVA using criterions obtained from the Cluster study) of fast current sheet crossings (flapping events) were recently studied based on 3-year long data set of Geotail observations [25]. It confirmed that CS normals lie and rotate exclusively in the YZ plane (like those observed at Cluster distance r~15-18Re, see e.g. Figs. 5 and 6), supporting that the kink mode is preferentially responsible for the flapping events observed at distances between 9 and 30 Re and at all local times in the tail covered by Geotail. The occurrence rate of these events (having a typical time scale 100-300sec) increased strongly with the increasing distance (by an order of magnitude from 10-15 Re bin to 25-30 Re bin), and had a peak occurrence in the premidnight sector (Y~ 0...+10Re)- Figure 7. The latter feature is consistent with the propagation pattern of Figure 5 in a sense that both correspond to the source being in the central part of the magnetotail (more specifically, in its pre-midnight MLT sector).

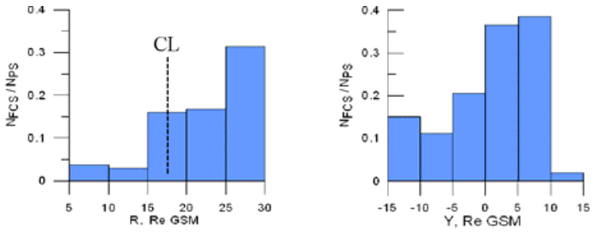


Figure 7. Occurrence frequency of fast current sheet crossings (normalised to the number of observation hours) as observed by Geotail [25]. Dashed line shows the distance of Cluster neutral sheet crossings.

Activity dependence. The occurrence distributions (peak premidnight, occurrence frequency increase downtail) are similar in flapping events and BBFs suggesting their possible relationship [25]. There exists, however, no simple local relationship: in the majority of flapping events the fast local flows are not observed [9]. Similarly, no simple dependences exist with the plasma density/temperature (could be met both in hot/rarified and cold/dense plasma sheets), or with other CS parameters. It could be however noticed that the most severe (very short and tilted, e.g. [26, 27]) CS crossings are observed near the reconnection site. These aspects yet wait for special study.

As concerns the global activity, the flapping events also show no simple dependence on the AE-index [9]. In many cases they are clearly associated with substorms (like those in Fig.2 -a strong substorm with peak AE~800nT at 1030UT, Fig.3 - following sharp AE increase up to <200nT, or Fig.4, a substorm ~300 nT at 1330UT which then subside by 15UT), repeating previous results [3, 5-8, 18, 19]. In many clear cases, however, large amplitude flapping events (solitary folds rather than the sequence of corrugations) could be found under very quiet magnetic activity, and even in the absence of any auroral activations as seen from FUV auroral images [28]. In the latter study a number of cases with clear association between the localized brightenings and fast CS crossings were also found, with azimuthal propagation of the kink outward from the brightening position in 5 of 6 cases. This certainly requires to be checked on the larger statistics.

2.3 Structure of flapping current sheets

Even the Cluster system, which for the first time allows the measurements of the gradients and electric currents, essentially provides the measurements of these parameters in one point of the current sheet. However, during fast flapping motions the spacecraft scans quickly the width of the current sheet allowing to study its structure. Since the latter is a key factor determining the current sheet stability, from the beginning of Cluster studies the structure of flapping current sheet was in the focus of research. Initial studies demonstrated variable and rapidly changing sheet structure [29] and provided clear demonstration of both thin sheets embedded into the center of thicker plasma sheet, as well as of bifurcated sheets (see also [24, 30]).

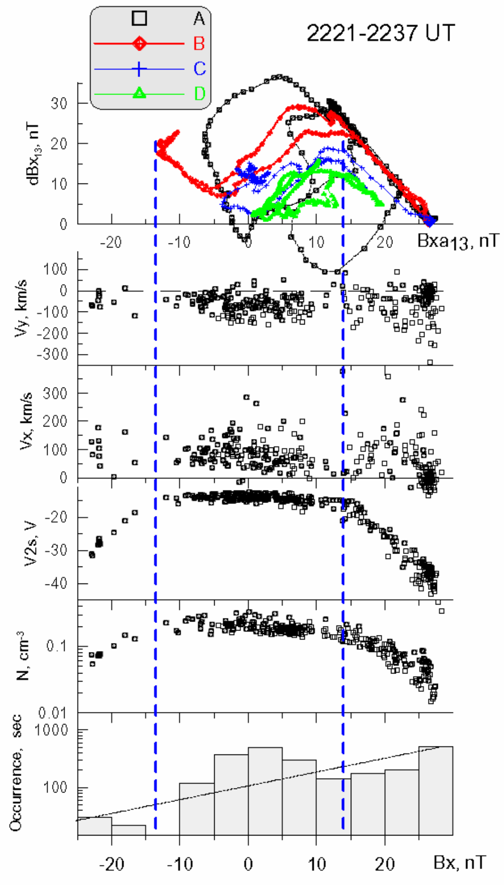


Figure 8. Cluster observations of stable bifurcated current sheet on September 26, 2001 [24].

In Figure 8 we reproduce the observations of stable bifurcated sheet structure [24] in which the Bx difference at two vertically separated spacecraft (a proxy of total current in the horizontal slab between these spacecraft, top hodogram) during four double subsequent traversals of the sheet displays the peak current at the same off-central location (where Bx~15nT ~ 0.5BL). Same conclusion follows from Bx-occurrence distribution over this time period (inversely proportional to the current density distribution, see e.g. [4]). In that case (also during small substorm, but without strong local Vx flows, see the middle panel in Fig.8) the bifurcated sheet was definitely a spatiall structure which persisted for more than 15 min (although the peak current slowly decreased in time). A notable feature is that the density distribution (and related spacecraft potential V_{2s}) shows no special features and stays flat over the central region between the current density maxima.

Vice versa, clear examples of fast changes of the sheet structure (including examples of both embedded central and bifurcated sheets) were demonstrated in some events [26, 29] with an attempt to interprete these changes by the different positions of the observer with respect to the reconnection region.

Systematic study of all fast CS crossings in 2001 allowed to characterize the physical parameters of 78 crossings [9] and address different types of the sheet profiles observed (for 30 most suitable crossings [10]). Figure 9 illustrate the profiles of the electric current density j_C (from curlometer technique) as a function of normalized (to BL) local magnetic field. (This provides a proxy of the distance across the sheet, with N(S) sheet edges being at $B_1/BL = +1(-1)$ and sheet center at $B_1/BL = 0$). The bottom line profiles (*NN* 26-30) correspond to the crossings illustrated in Figure 2, *NN* 5,6 to those in Fig.3 and *NN* 17-18 to those in Fig.8. The variability of possible current distributions is one of the main lessons of this survey. It includes a number of nice narrow peaks in the center (*NN* 6,11,13 etc) representing a group of central embedded sheets (Type I, about 1/3 of all examples). Crossings of that type had the peak current density of 5 to 12 nA/m^2 and the average half-width <~2000 km (about 5-7 L_{cp}). About 1/6 of crossings could be characterized as the bifurcated sheets (Type II, NN 14, 20, 22, 25, 27). They had the current density maxima at ~0.2…0.6 BL, in average located at $|B_1|$ ~ 0.5 BL and Z*~±2000km (~5 L_{cp}). Considerable part of remaining crossings (Type III, asymmetric crossings) showed one main off-center peak of the electric current. Preliminary investigation suggests this could result from transient effect rather than be a feature of stable asymmetric structure, as compared to the spatial origin of type I and II current sheets structure.

Another important lesson is that the classic Harris sheets are practically not observed. First illustration is that current density profile in Fig. 9 practically never fits to Harris distribution (the Harris type distributions based on current density and BL measurements for each crossing are shown by the dashed lines in Fig. 9). Second confirmation is that in all types of crossings, unlike the Harris model, the profiles of current density and plasma density (and pressure) have the different shapes. As a rule, the density has a nearly flat profile between B1 =-0.5BL and +0.5BL, similar to those illustrated in Figure 8.

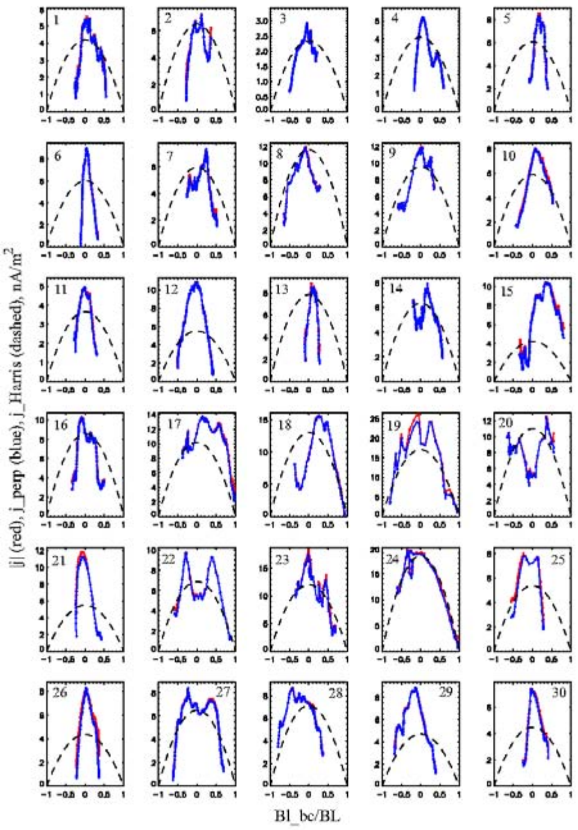


Figure 9. Distribution of electric current (from curlometer technique) across the current sheet during 30 selected fast current sheet crossings [10]. Harris-type median estimates are shown by dashed lines.

Comparison of current density profiles obtained from curlometer technique with the contribution from the protons ($j_p = ne<V_p>$, where $<V_p>$ is the proton bulk flow) shows a surprising disagreement (heavy ion contribution to the electric current is small, even in oxygen-dominated sheets it provides <20% of total current according to [33]). A common expectation is that, because the plasma sheet protons are much hotter than the electrons are, their drift and diamagnetic currents (V_{pD}) are much larger than those of electrons, and provide the main contribution to the total current. This is definitely not the case in observations. Not only the magnitudes are different, in majority of cases (for numbers starting from N7) the signs are opposite. The difference of scales at which curlometer and ion measurements are made, as well as transient effects can be discarded as the reasons of discrepancies. These results mean that, contrary to the expectations, the electrons are main contributors to the electric current. More important, this suggests that most of current sheets have a strong ‘dawnward’ convection (strictly, in the opposite direction as compared to the tilted current, in average with the speeds of the order of 25 km/s (in the range 10-200 km/s) [10]), which is not expected in the duskside plasma sheet. A supporting illustration to these facts provides Figure 8, where the proton flow Vy component during many crossings is repeatedly negative (with amplitudes between 0 and –100 km/s) across the whole width of the flapping current sheet. The origin of such anomalous convection and of the negative electric charge of the current sheet in these circumstances requires a special efforts in which the precise electron and electric field measurements will be also important. Recently one event was published with multiple short crossings of very thin and tilted sheets near the reconnection site [27] in which similar conclusion was made concerning the “dawnside convection” and negative electric charge in the plasma sheet. The events in our survey are of larger thickness, nevertheless they indicate some similarity. Certainly, this phenomenon deserves a special future study.

3. DISCUSSION

Contrary to previous picture, Cluster observations in the tail show convincingly that the current sheet, especially during active periods, undergoes complicated and severe meso-scale (few Re) dynamic deformations which in most visual form manifest as the flapping motions of the current sheet. Undoubtedly, the flapping motions is an essential element of the tail dynamics which strongly influences the observed variations and carries important information on the magnetotail active processes. One its important consequence is that the corrugations, having the structure most closely described by the known kink-mode, are the large-amplitude (of the order of ~1 Re scale) non-linear perturbations of complicated shape (sometimes displaying the overturn-like features with j_y component becoming negative), in which very large local tilts are observed (>45^o in a half of events according to surveys [9, 25]). Any attempt to reconstruct quantitatively the dynamic behaviour of tail parameters, e.g. during substorms, should fail if neglecting this feature.

On the observational side the picture of these perturbations is still far from completeness. We don’t yet know the lifetime of these structures and corresponding propagation distance, as well as are they actually the solitary structures or the parts of oscillatory pattern. New Cluster possibilities with larger-scale separations help to address these issues. Relationship to the plasma flows, reconnection process and auroral activity are other issues to study to address both the generation process(es) and possibility that different mechanisms contribute the flapping. The most probable picture arising from available observations summarised in this report is that current sheet corrugations are of internal origin and are born in the premidnight tail sector (0-10Re) from where they can propagate azimuthally toward the flanks. This location is where the magnetic reconnection starts at substorm onsets [34] and where the BBFs are observed most frequently [25], suggesting possible association with the magnetic reconnection and BBF generation. This view still lacks the definite supporting evidence of such association. It also has some apparent conflict with indirect evidence of dawnward convection in the flapping plasma sheet in premidnight tail discussed at the end of Section 2.3.

On the theoretical side the situation is even less clear since there are different possibilities analysed with the models of different sofistication degree and with not equally detailed predictions. As concerns the generation, the kink perturbations were frequently described as the result of drift- (e.g. [35]) or Kelvin-Helmholtz- (e.g. [36]) instabilities, or as a kind of standing modes in the (neutral) current sheet [37,38]). One of crucial tests is the propagation velocity, which is predicted to be slow and duskward in the case of instabilities. The latter conflicts with the flankward propagation direction of flapping waves (Fig.5), if such propagation is not due merely to the plasma convection (this can be reserved as a possibility as suggested by preliminary results of comparison with plasma flows given in Figure 6). Another potential candidate to generate the perturbations could be the localised magnetic reconnection in sheared magnetic field configuration, which was claimed to generate the surface waves [39], although no detailed predictions were made as concerns the properties and propagation distance to compare with. As concerns the propagation effects, the ballooning-like mode in the curved current sheet magnetic field was claimed to be able to propagate azimuthally in flankward directions from the source [40]. Excitation of nonlinear kink-like waves with phase velocity an order of magnitude less than the thermal ion speed was reported in numerical kinetic simulations of initially very thin current sheets [35] and of bifurcated sheets with realistic thickness [41], which give the perturbation shape and scales similar to some of observed events. Such simulations are important to foresee some possible details or complications (to which the attention can be payed in the data analysis), like the considerable grainy structure of the perturbed current [41], asymmetric current profiles (with possible asymmetric peak at off-center position [35]) or association with other modes (e.g. LHDI) which can modify the observed structures. More work has to be done to clarify all these issues.

As concerns the structure of electric current in the current sheets, important question is –whether the peculiarities observed (variable structure with different deviations from Harris distribution, including bifurcation, or off-center asymmetric peaks, or specific convection and current-carrying properties, etc) could be just the properties of transient perturbed (and possibly, non-1D) flapping sheets. No final answer can be given to this question yet, although with very different approachand with data selection criteria not tied to the flapping motion (which also avoided the tilted sheets) the main conclusions of [42] were similar. They particularly found that non-Harris features (including off-center peaks, and thin embedded sheets) are rather typical in the current sheet, that bifurcated sheets occur in ~17% of cases (very similar to our percentage [9]) with increasing probability when fast flows are observed nearby.

The understanding of the non-Harris features as well as is a challenge both for observations and theory. Both observations and theory emphasize to consider the role of electrons and electrostatic potential distribution in the current sheet. On the observational side, the results [10, 27] emphasize the electrons as the main current-carriers and indicate the converging (toward the sheet center) electric field (which provides the dawnward convection in the sheet, see section 2.3). These aspects still wait for a systematic study including the real electron observations. On the theoretical side, few different approaches have been suggested to describe the non-Harris features [43-45]. This is still an area of active work to understand the physics of real tail current, where a close interaction between theory and data analysis is anticipated.

Cluster observations of non-Harris sheets with different structures as well as studies of flapping perturbations stimulated a burst of theoretical works (couple dozens of papers published in recent couple years) and this also could be a one of important results of the Cluster mission.

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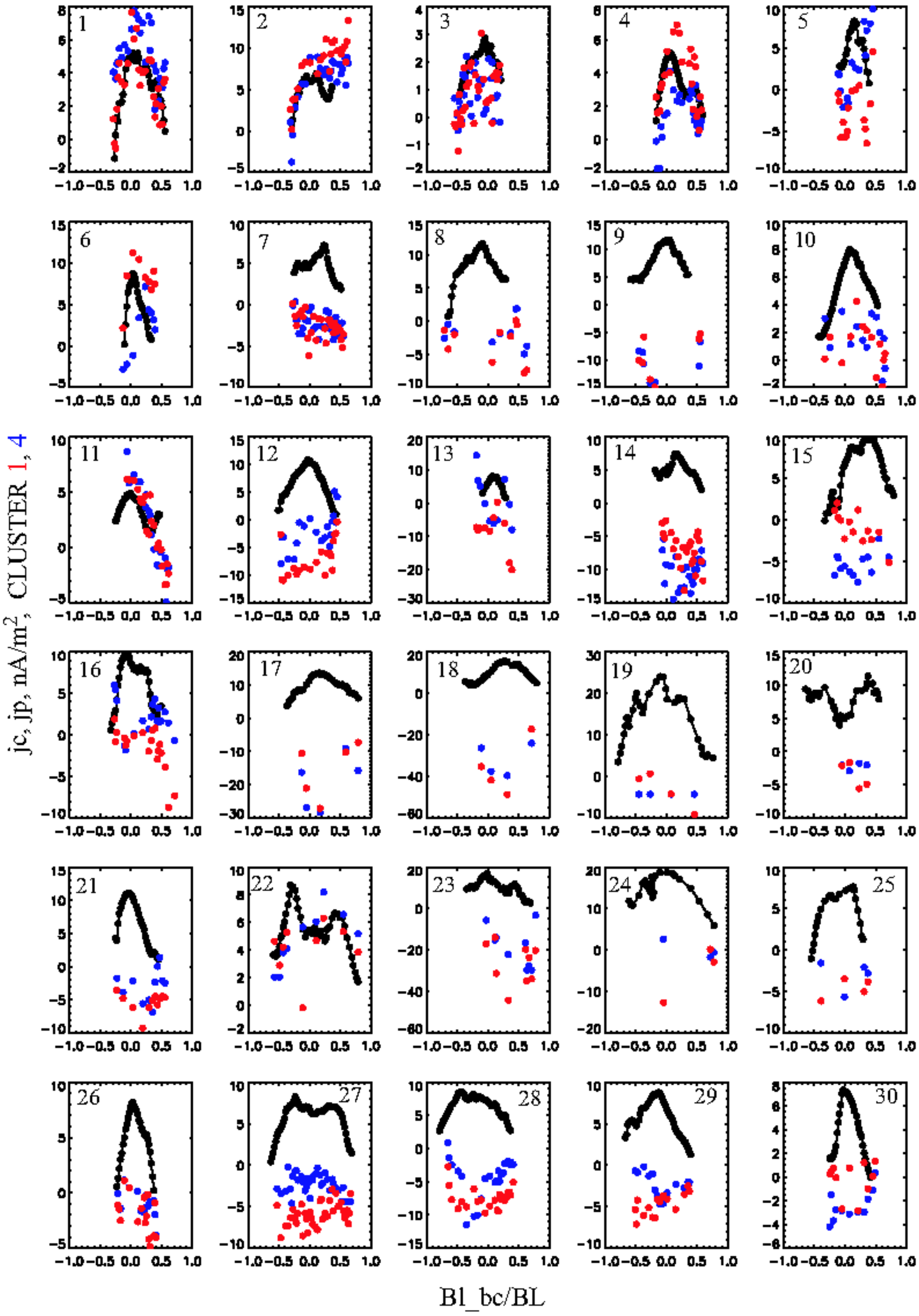

Figure 10. Comparison of electric current density calculated from magnetic field gradients (j_C=rotB/μ_0, black points) with the proton current contribution (j_P ,=ne<V_p> , grey points, from CODIF instruments on C1 and C4 spacecraft), from [10].

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