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SLIPPING DEFORMATION OF THE PLASMA SHEET MAGNETIC STRUCTURE

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Abstract. Cluster observations revealed an abundance of crossings of significantly inclined current sheets in the magnetotail. We determine magnetic configuration of some of such wavy crossings, observed during quiet conditions. These waves appear to move azimuthally and can be interpreted as relative (almost vertical) slipping motion of the neighboring magnetic flux tubes in the inner plasma sheet, rather than the large-scale flapping. Sheet motions with significant inclination changes can be explained with the mechanism, proposed by Golovchanskaya & Maltsev, 2005.

Introduction

The multi-spacecraft Cluster project provides an opportunity to determine the gradient and orientation of a magnetic or plasma structure. The first four years of Cluster magnetotail observations revealed structural complexity of the plasma sheet with an abundance of crossings with significantly inclined current sheets (Sergeev et al., 2004; Runov et al., 2005a). In several targeted investigations some such events were interpreted as a wavy displacement of the main crosstail current sheet, propagating flankward (Zhang et al., 2002), or as a quasi-stationary structure of vertically shifted flux tubes, flapping azimuthally around the spacecraft location (Petrukovich et al., 2003).

Here we concentrate on a rather common type of observation: a series of current sheet crossings, in which nearby crossings (in time) have significantly differing or sometimes alternating inclination. This phenomenon can be understood (in a first approximation) as a wave of vertical displacement of a notional neutral sheet surface (e.g. Zhang et al., 2002, 2005). It is distinctly different from, for example, a back-and-forth flapping motion of a stationary configuration, which reveals itself as a series of current sheet crossings with the same inclination.

Since the main cross-tail current sheet is actually a 3-D object, formed by curved magnetic flux tubes, two variants of deformation can occur (Fig. 1). During a bend-type change flux tubes rotate, following the change in the sheet normal direction. Alternatively, during a slip-type (shear-type) change, flux tubes just shift (vertically) relative to their neighbors and the magnetic field direction inside a sheet is not changing. Additionally, in the course of bending, the current sheet thickness remains constant, while under a slip-type deformation the current sheet thickness diminishes proportionally to the cosine of the sheet tilt angle.

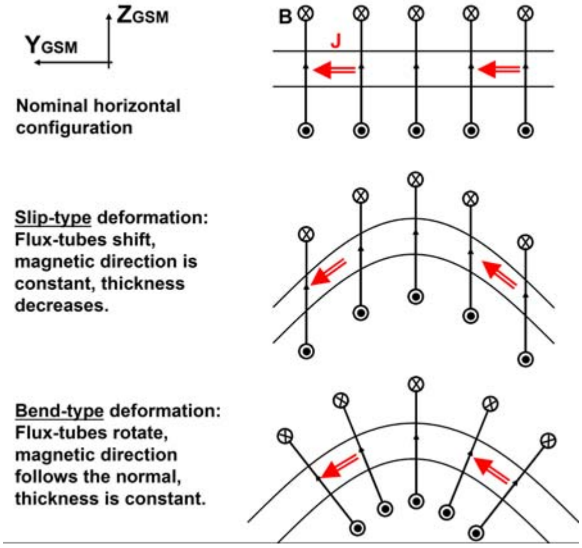

Figure 1. Variants of the cross-tail current sheet deformation. Configuration with By=0.

Data selection

For this study we selected an event with a "slow wave-like change" of B_x, occurring in a quiet high-β plasma sheet. Additionally it was required that current sheet properties (normal, velocity, etc.) are decipherable by the Cluster tetrahedron (Petrukovich et al., 2005), with leading and trailing crossings in each oscillation exhibiting a significant difference in orientation, and both sheets moving in the same direction (actually always away from the tail center).

Cluster 4-s resolution magnetic field data (Balogh et al., 2001) were used for the analysis. Components x, y, z are in the GSM frame of reference.

With four-point observations one can determine the spatial gradient, assuming a constant gradient (linearity) on the scale of spacecraft separation, the stationarity of the configuration, and a constant uniform relative plasma frame velocity. Local (independent at each spacecraft) variations, overlaying the large-scale change in question, are neglected. In the magnetotail, plasma sheet observations of the magnetic gradient are usually interpreted in the approximation of a uniform planar

current sheet crossing. The sheet's normal direction can then be assigned to the B_x gradient direction (assuming that the actual magnetic maximum variance direction most likely is not orthogonal to X). This "magnetic normal" can be computed instantaneously for each set of magnetic field measurements by the four spacecraft. The alternative method is to determine the normal and velocity along the normal, analyzing interspacecraft time delays within the crossing (equivalent to the computation of the "time" gradient dt/dr) (Runov et al., 2005b). Magnetic gradient normals always point northward, while timing normals are in the direction of motion. Other independent sheet characteristics are the maximum variance direction defining the orientation of the main sheet magnetic component B_l , and the electric current direction (computed as rot(B)). For the majority of our events the timing and magnetic gradient normals were coincident and orthogonal to maximal variance and current vectors with an accuracy of about $10–15^o$. Therefore, the approximation of a planar sheet is acceptable.
Since angles between the experimentally determined normal, maximal variance and shear directions are not exactly 90^o, we established for each crossing a similar orthogonal proper frame of reference with l along the maximal variance, m=n_b x l (n_b is magnetic normal, averaged over the middle of the crossing, as described in the end of this section),
n=l x m.
In the planar uniform current sheet approximation only the B_l component is created by the cross-tail current and vanishes in the neutral sheet, while the rest of the magnetic field (B_m,B_n) is constant and remains in the neutral sheet, reflecting the flux tube configuration, IMF influence, etc.

Hereafter, the magnetic field B_n,B_m will be called the "sheet magnetic field". In examining its changes from crossing to crossing, one can decide on the mode of sheet deformation, as explained in the Introduction and Fig. 1.

Data

On August, 3, 2004 Cluster detected a series of 20 wave-like current sheet crossings with a variety of amplitudes and tilts under rather stable external conditions(Fig.2). Cluster was located at (–16.0, –10.0, 1.5) R_E. (see Petrukovich et al, 2006 for details).
In Fig. 3 the difference between the normal directions for pairs of consecutive crossings was compared with the difference between the respective sheet's magnetic field directions. The changes in sheet normal direction were $50–150^o$, while the magnetic orientation was rather stable, varying only $5–25\ ^o$. l axis directions for all crossings are similar and are pointing to the Earth. The angle between the normals and the sheet magnetic field directions increases for more tilted events, so that the guide field component (B_m) dominates in more vertical sheets (not shown here). In the slip deformation model, the B_l magnetic gradient in the flux tube plane is constant, while the gradient component along the normal should increase proportionally to an inverse cosine of the effective sheet tilt angle. In the bend deformation model the gradient along the normal is constant. Changes in dB_l/dn are more consistent with the slip variant (Fig. 4). An unexpected feature is the clear proportionality between the magnetic amplitudes and the tilt angles of the waves, so that larger waves are steeper (Fig.5). Finally, the typical wavelength of this current sheet oscillation is 2–5 R_E.

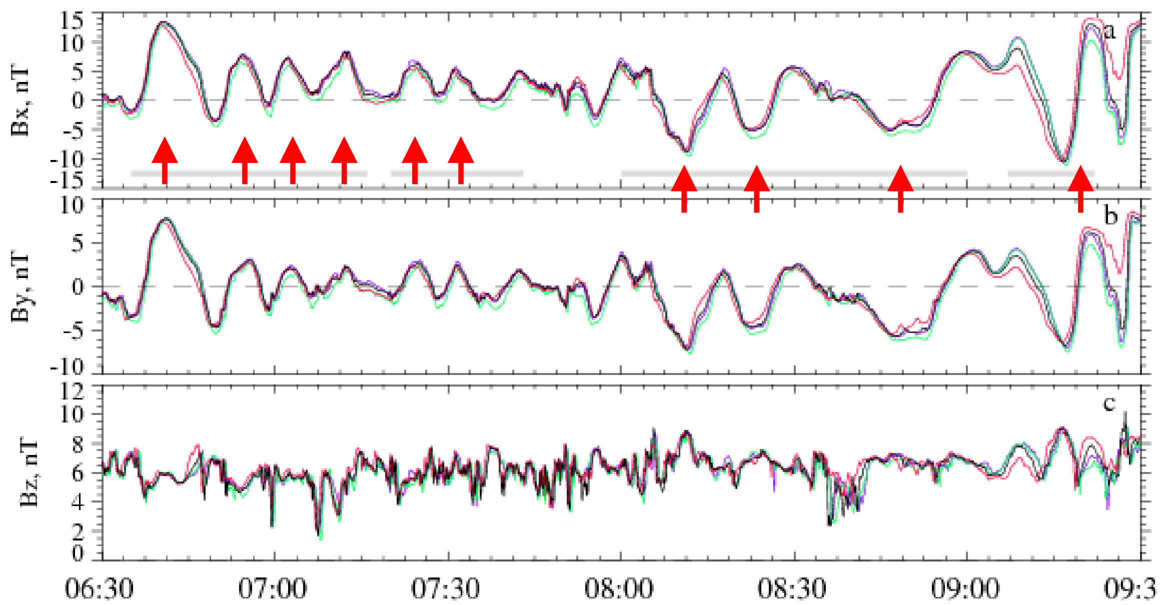

Fig.2 Cluster observations on August 3, 2004. Analyzed pairs of crossings are marked by arrows.

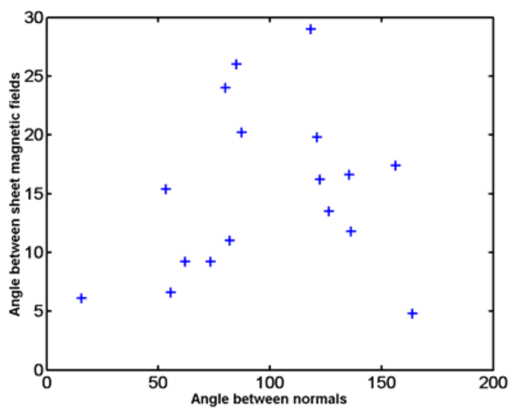

Fig. 3 Comparison of angles between normals with angles between sheet magnetic field for pairs of consecutive crossings

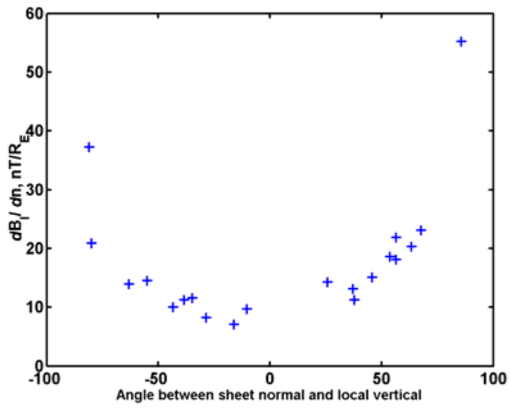

Fig. 4 The current density is increasing (thickness is decreasing for more tilted sheets.

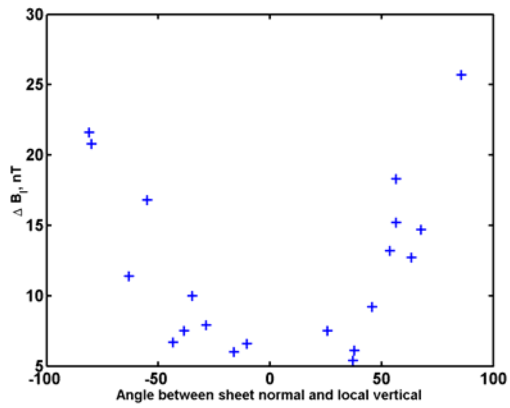

Fig.5 More tilted sheets have larger amplitudes.

Discussion

Our observational findings definitely support a model of an azimuthally propagating slip-type displacement of magnetic flux tubes. All selected events are characterized by small B_y and large B_z magnetic components, suggesting rather thick plasma sheets.

On a completely speculative basis, bending deformation might be more probable for thin intense current sheets with large B_y and small B_z, when neighboring flux tubes are more coupled.

It should be noted, however, that only leading and trailing edges of an assored wave are actually observed as two sheet crossings (see also discussion by Runov et al. (2005a)). The whole wave profile is unknown and is not necessarily sinusoidal.

An interesting feature is a link between the tilt angle of a sheet and the magnetic amplitude of a variation, making larger-amplitude waves steeper.

The observed wavy deformation of the plasma sheet has the mesoscale scope in the vertical and azimuthal directions, extending a few Earth radii. Considering the radial direction, this deformation can be alternatively understood as an azimuthally and radially localized dynamic "hump", or as a coherent motion of a "slice" of plasma sheet flux tubes, occupying a significant range of downtail distances.

In a number of other observations, comparable amplitude magnetic field variations or simultaneous current sheet crossings were detected by spacecraft 6 and 10 R_E apart radially and aligned in local time (Petrukovich et al., 2003; Zhang et al., 2005). However, for those events, full identification of the deformation mode was not performed.

The discussed phenomenon should be understood as a dynamic modification of the inner (high-β) plasma sheet – a formation of an intensified layer with varying tilt, embedded in a much thicker plasma sheet, rather than a steady sheet profile with some large-scale bulk tail motion. Figure 6 is the sketch of the modification in a plane orthogonal to the B_l direction, B_y=0. Up and down motions of slipping flux tubes are seen as variations in contours of equal B_l (marked levels $\pm B_L$,$\pm B_0$, 0). It is assumed that the oscillation is smaller far from the neutral sheet: the amplitude of the variation in contours $\pm B_L$ is smaller than in contours $\pm B_0$. The magnetic amplitude of a wave is equal to the maximal B level, crossing the nominal neutral sheet plane in the course of an oscillation (B_0 in the middle of the picture). If a virtual spacecraft is located near the nominal neutral sheet plane, it will observe magnetic oscillations $\pm B_0$, interpreted as crossings of inclined current sheets. As a consequence of slip deformation, the distance between the $\pm B_0$ levels (thickness) is smaller and the current density is larger for tilted sheets, than for the horizontal sheets. Therefore, the dynamic inner part might be interpreted as the intensified (relative to Harris profile) inner current layer, embedded in a thick current sheet (J_L), supporting the large-scale magnetic field reversal $\pm B_L$. This dynamic layer has no permanent thickness, since it depends on the amplitude of oscillation and tilt.

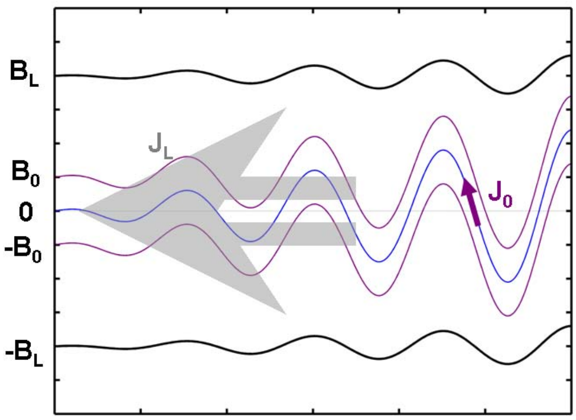

Fig. 6 The scheme of dynamic sheet modification. See text for details. The thin variable current layer J_0 creates the magnetic wave $\pm B_0$, observed by a spacecraft as a series of sheet crossings. The full magnetic gradient $\pm B_L$ is supported by a much thicker horizontal current J_L.

A recently suggested type of ballooning mode, describing a displacement of the magnetic flux tubes in the XZ plane from the equilibrium position in the antisymmetric sheet (Golovchanskaya and Maltsev, 2005), fits well our observations. A further investigation is necessary to understand whether the oscillation amplitude and wavelength (or sheet tilt) are coupled in this mode, as was observed in the experiment.

Conclusions

Our investigation targeted wave-like variations in rather a quiet, thick (large B_z) sheet. However, similar fast crossings of strongly inclined sheets are frequently observed in rather diverse conditions. Accurate determination of the magnetic configuration, which is needed to decide on the type of sheet deformation, is not always possible, especially in the case of isolated single crossings, or in highly disturbed conditions.

Further insight into the Cluster magnetotail data, including new analysis methods, is necessary to solve this problem, on the whole. Besides a proper understanding of the plasma sheet structure, the investigation may reveal details that are of interest for basic plasma physics, namely, self-consistent adaptation of the current density to varying sheet thickness and values of normal and guide magnetic components.

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