OSCILLATIONS OF FLUX TUBE SLIPPAGE IN THE QUIET PLASMA SHEET

A.A. Petrukovich[1], **W. Baumjohann**[2], **R. Nakamura**[2], **A. Runov**[2], **and A. Balogh**[3]

[1]*Space Research Institute, Moscow, 117997, Russia. Email: apetruko@iki.rssi.ru*
[2]*Space Research Institute, Graz, Austria.*
[3]*Imperial College, London, UK.*

ABSTRACT

Cluster observations in the magnetotail revealed abundance of strongly inclined current sheets. We determine magnetic configuration during long period (up to 15 min) wavy sheet motions with significant inclination changes, occurring during quiet conditions. These waves appear to propagate azimuthally, their amplitudes are proportional to steepness, while wavelengths are about 2–5 R_E. They can be interpreted as periodic almost vertical slippage motion of the neighboring magnetic flux tubes in the high-β plasma sheet, rather than large-scale flapping.

Key words: magnetotail, current sheet.

1. INTRODUCTION

Multi-spacecraft Cluster project provides an opportunity to determine gradient and orientation of a magnetic or plasma structure. First four years of Cluster magnetotail observations revealed structural complexity of the plasma sheet with abundant crossings of significantly inclined current sheets [9, 8].

Here we concentrate on a rather common type of events: series of current sheet crossings, in which neighboring sheets have significantly differing or sometimes alternating inclination. This phenomenon can be understood (in a first approximation) as a wave of vertical displacement of a fictitious neutral sheet surface. 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. Our events have typical duration of several minutes and are detected in the quiet high-β plasma sheet.

However since main cross-tail current sheet is actually a three-dimensional object, formed by curved magnetic flux tubes, such a deformation can have two different forms (Fig.1). In a bend-type modification flux tubes rotate, following the change in the sheet normal direction. Alternatively, in a slip-type (shear-type) modification flux tubes just slip (vertically) relative to their neighbors and magnetic field direction inside a sheet is not changing. In a couple of previous investigations bending variant was advocated [3, 4, 5]. Taking advantage of multi-spacecraft Cluster data we distinguish between these two variants of dynamical behavior and determine several characteristics of observed oscillations.

For this study we selected events with "slow wavy change" of B_x (i.e., with at least two crossings in a row), occurring in a quiet high-β plasma sheet with plasma bulk velocity below 100 km/s. Additionally it was required, that current sheet properties (normal, velocity, etc) are decipherable by the Cluster tetrahedron [7], leading and trailing crossings in each oscillation exhibit significant difference in orientation and both sheets are moving in the same direction (actually always outwards).

Cluster 4-sec resolution magnetic field data [1] were used for the analysis. Components x, y, z are in GSM frame of reference. l, m, n are in the proper frame of an idealized planar sheet (maximal variance direction, electric current direction, normal direction). Angles ϕ, θ are in a special coordinate system, with X as the polar axis [7]. Zero values of polar and azimuthal angles correspond to the horizontal sheet with the normal along Z. The polar angle θ is measured from the YZ plane. Positive values correspond to normals, inclined Earthward, negative - tailward. The azimuthal angle ϕ (in YZ plane) is measured from the Z axis (positive for normal with positive Y component).

We describe an azimuthally propagating wave of the neutral sheet plane with a simple model:

$$\mathcal{Z} = \mathcal{Z}_0 \cdot f((\omega - kV_{yd})t - k\mathcal{Y}) + V_{zd}t$$

where V_{zd} and V_{yd} are doppler velocities due to background bulk motion; ω — wave frequency; k — wave vector; $\mathcal{Z}, \mathcal{Y}$ - local vertical and azimuthal directions; t — time; $f(x)$ - some harmonic or other periodic function. Note that $\partial\mathcal{Z}/\partial\mathcal{Y} = tan(\phi) = -\mathcal{Z}_0 k f'$, that is, the wavelength can be determined knowing the sheet inclination and the oscillation amplitude. However, frequency ω

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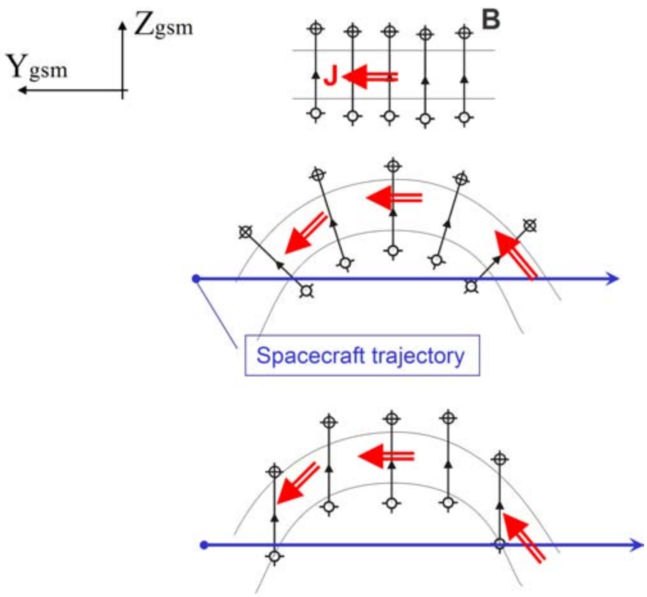

Figure 1. Schematic view of magnetic configuration in the planar cross-tail current sheet (top), current sheet with bend deformation (middle), current sheet with slip deformation (bottom).

remains unknown, because doppler shift can not be uncoupled.

2. THE EXAMPLE

Figure 2 presents probably the most fortuitous observation of the phenomenon under study, providing possibility to study a wave train with variety of amplitudes and tilts under rather stable external conditions. We analyzed waves, marked by the grey rectangles (20 crossings in 10 "pairs", Fig.2a). Cluster was located at (-16.0, -10.0, 1.5) R_E, the normal to the model neutral sheet [10] was just 9^o from the GSM vertical, IMF was azimuthal ($B_y = 1-2$ nT, $B_z = 0.6$ nT).

In the planar one-dimensional current sheet approximation, generally valid for this set of crossings, electric current contributes only to the B_l magnetic component, while the B_m (guide) and the B_n (normal) components are constant and can be used to determine the flux tube orientation. Hereafter, magnetic field with subtracted B_l component will be called the "sheet's proper magnetic field". For each 4-sec data point the instantaneous normal was determined as the direction of B_x gradient (Fig.2d,e). This method is valid for a planar current sheet, if l and x directions are not too close to orthogonality.

A positive-negative-positive signatures in B_x (Fig 2a), if measured with a single spacecraft, would be interpreted as an up-down-up current sheet motion. The four-point analysis reveals significant sheet tilts (Fig.2d,e), changing from crossing to crossing as much as $\pm 70^o$ (for ϕ). Parameters of crossings are summarized in Fig.3. Field values and normal angles were averaged over the "middle" of each crossing, defined as $B_l^a - 2$ nT$< B_l < B_l^a + 2$ nT, where $B_l^a = (B_l^{min} + B_l^{max})/2$.

In Fig.3a the difference between normal directions for pairs of consecutive crossings was compared with the difference between respective sheet's proper magnetic field directions. The change in the sheet normal direction was 50–150^o, while the magnetic orientation was rather stable, changing only 5–25^o.

In the slip deformation model, the gradient component a the flux tube plane is constant, while the gradient component along the normal should change proportionally to cosine of the effective sheet tilt angle. In accordance with this model, changes of dB_l/dn are consistent with the cosine function (Fig.3b). A more unexpected feature is the clear proportionality between magnetic amplitudes and tilt angles (relative to the normal of the model neutral sheet) of waves, so that larger waves are steeper (Fig.3c). Finally, there is some dependence between wavelengths (2–5 R_E) and tilt angles (Fig.3d), but there is no clear frequency dependence (not shown here). Determination of a wavelength depends on a type of $f(x)$ function, defining the wave form. We used the harmonic wave profile.

In a summary, described variations have following common features:

1. Magnetic field directions inside neighboring current sheets are almost the same in the geophysical frame of reference.

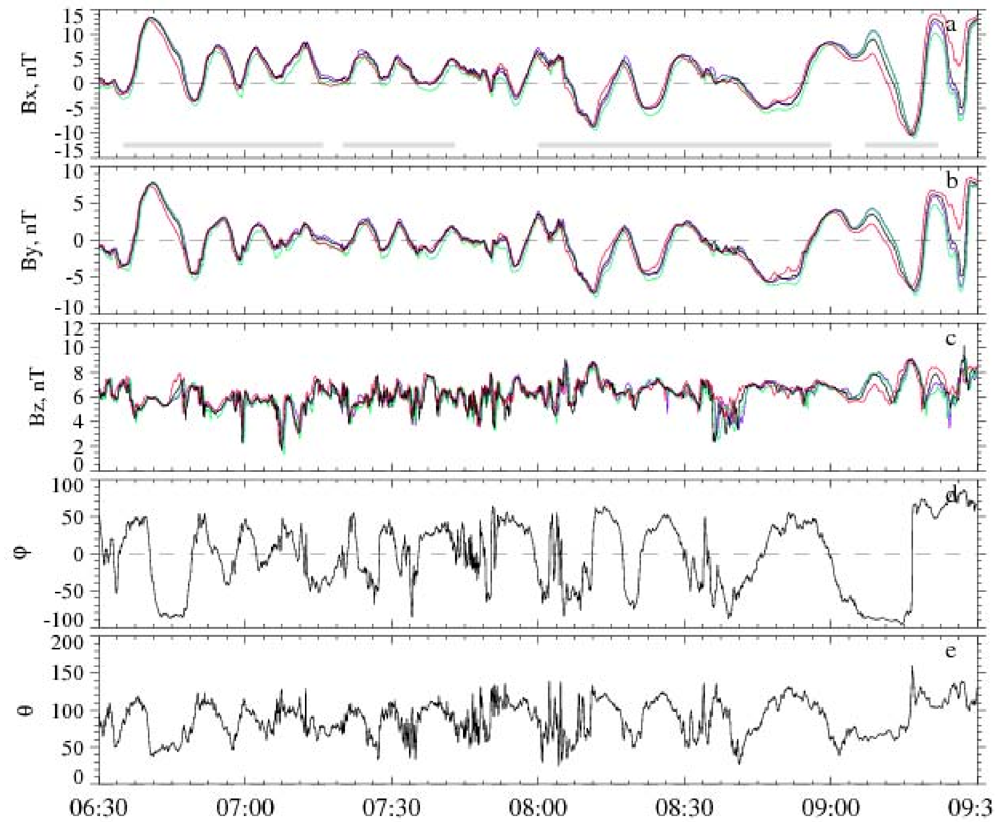

Figure 2. Cluster observations at August 3, 2004. From top to bottom: three magnetic GSM magnetic components, two angles of the normal direction (see text for details).

2. Magnetic gradient along the normal depends on the tilt angle, so that gradient along the flux tube is approximately constant.

3. Magnetic amplitudes are related to tilt angles.

4. Spatial amplitudes are of the order of couple Earth radii and correspond to $\beta > 1$ plasma sheet region.

5. Wavelengths of oscillations are of the order of 2–5 Earth radii.

3. DISCUSSION AND CONCLUSIONS

Our observations definitely support a model of an azimuthally propagating slip-type displacement wave of magnetic flux tubes. Only cases of quiet plasma sheet without fast plasma flows were analyzed. All events happened to be on the flanks, and are characterized by small B_y and large B_z magnetic components. 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. Extended analysis will be published elsewhere.

Accuracy of all non-local estimates (amplitudes and wavelengths) critically depends on quality of gradient measurements. Our four-point gradient estimation assumes linearity of magnetic profiles (constant gradient). For a traversal of the inner part of a Harris profile, gradient is underestimated by a factor of 0.8–0.9. Wavelength estimates can differ by a factor of 1.5 depending on a choice of waveform (harmonic or triangular).

Maximal observed waves' magnetic amplitudes correspond to $\beta > 1$ plasma sheet. Therefore the discussed phenomenon should be understood as a dynamic modification of the inner sheet, rather than some large-scale bulk motion. Recently suggested type of ballooning mode with similar characteristics well fits our observations [2].

Concluding, to understand properly variety of Cluster current sheets, an integrated approach, combining multipoint spatial analysis with reconstruction of magnetic and plasma configuration, is necessary. Such an investigation may reveal details of sheet dynamics, which are of interest for basic plasma physics.

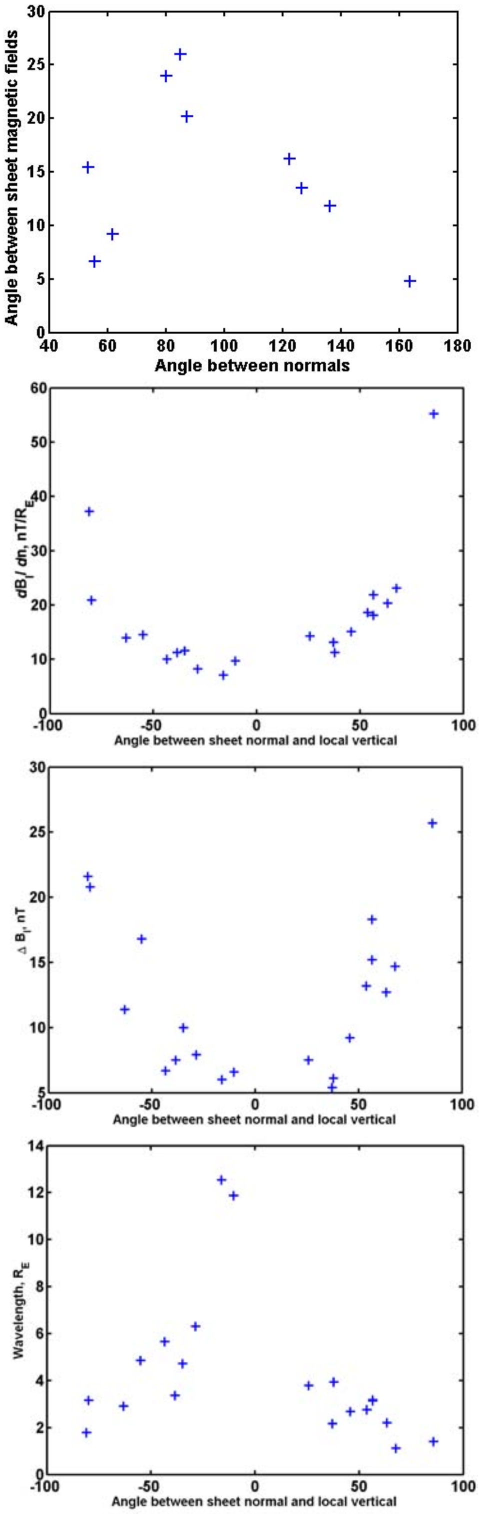

Figure 3. Properties of current sheet crossings. From top to bottom: (a) Angle between sheet's magnetic field directions in neighboring crossings compared with the difference in normal directions. (b) B_l gradient along the normal versus the angle between the sheet normal and the normal to the model neutral sheet for each crossing. (c) The same for magnetic amplitudes (d) The same for wavelengths.

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