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Reconstruction of time-varying reconnection rate and X-line location

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Abstract. Remote-sensing method developed on the basis of time-dependent Petschek-type reconnection model is applied to Cluster magnetotail measurements from 8 September 2002, where a series of earthward propagating NFTEs (nightside flux transfer events) was observed. The method utilizes single-spacecraft magnetic data as an input and provides the reconnection rate and the location of X-line as an output. For the first time the method is applied to a composite reconnection event consisting of three successive NFTEs following each other without any time delay. The reconnection distance is found to be between 27 and 30 R_E in the tail. The reconstructed electric field involves three 1-min scale pulses with total duration of ∼4 min. The peak rates for individual pulses vary from 0.6 to 1.1 mV/m.

Keywords. Magnetospheric physics (Electric fields) – Space plasma physics (Experimental and mathematical techniques; Magnetic reconnection)

1 Introduction

Reconnection is believed to be a key plasma process underlying many magnetotail phenomena. In particular, plasmoids/flux ropes (Slavin et al., 2003a; Zong et al., 2004), traveling compression regions (Slavin et al., 2003b), and nightside flux transfer events (Sergeev et al., 1992, 2005) are considered to be manifestations of reconnection. Nevertheless, interpretation of these phenomena in the frame of reconnection theory is not unequivocal. Similar magnetic features, namely, NFTEs (nightside flux transfer events) and TCRs (traveling compression regions) are interpreted on the basis of different reconnection models and, thus, represent different observational concepts (Sharma et al., 2008).

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Currently, the most popular approach is associated with Multiple X-line Reconnection (MXR) model, which suggests simultaneous existence of several (at least two) X-lines. Such kind of reconnection leads to the formation of plasmoids (closed loops of magnetic flux) or flux ropes, which also look like a loop being viewed along the core axis. Local increases in the plasma sheet thickness, caused by plasmoids/flux ropes, compress the neighboring plasma and magnetic field and in that way produce specific TCR-perturbations in the tail lobes: the bipolar B_z-variation (where z is the direction normal to the current sheet) and the B_x-compression. Thus, TCRs are interpreted as lobe signatures of plasmoids/flux ropes and, in some sense, they reflect the geometry of reconnection.

An alternative approach is based on the impulsive reconnection model, which implies time-varying reconnection rate and a single X-line. In this model two oppositely propagating bulges form, which cause perturbations in the tail lobes resemblant to TCRs: the bipolar B_z-variation and the B_x-compression over the bulge. These bulges (and associated lobe perturbations as well) are referred to as NFTEs (the term was introduced by Sergeev et al. (1992) in order to emphasize impulsive nature and profound similarity between magnetopause FTEs and magnetotail reconnection events). The shape of each bulge is defined by changes in the reconnection rate. Hence, NFTEs are considered to be transient structures, which reflect time variations of the reconnection process.

Besides underlying interpretation, there is a topological difference between plasmoid/flux rope and NFTE. Both are convex structures with a typical scale of a few R_E propagating in the plasma sheet, both produce similar remote signatures. However, in contrast to the plasmoid/flux rope (which transfer closed magnetic flux), the reconnected flux carried by the NFTE-bulge is locally opened (see Fig. 1).

To complete the list of possible scenarios explaning the appearence and propagation of TCR-like perturbations we should mention the low-frequency waves (streaming sausage

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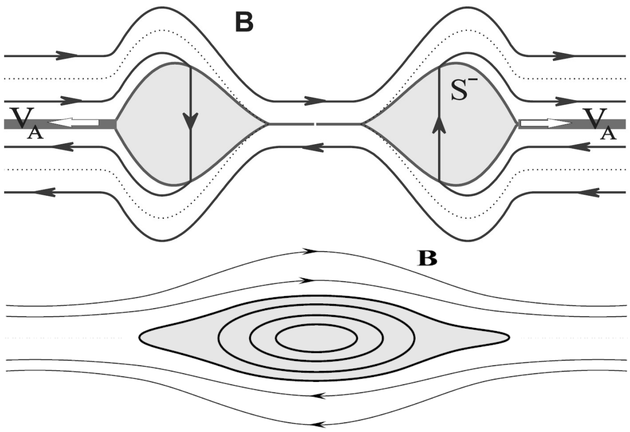

Fig. 1. Magnetic structure of an NFTE bulge according to the model of time-dependent Petschek-type reconnection (upper panel): Current sheet separating two plasma domains with opposite magnetic fields B decays into a system of MHD discontinuities and shocks S, which form two outflow bulges propagating in opposite directions with the Alfvén speed V_A. The dotted line is a separatrix between the reconnected magnetic flux and the non-reconnected one. The shaddowed area represents the bulge itself. Lower panel: Magnetic structure of a plasmoid/flux rope according to the model of multiple X-line reconnection.

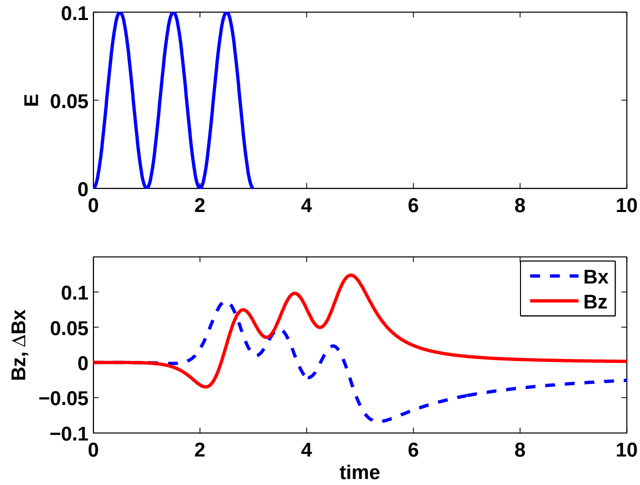

Fig. 2. Triple reconnection pulse and the corresponding magnetic field perturbations.

and kink instabilities of the current sheet). Requiring no reconnection, these waves produce the same twin signature in the plasma sheet/PSBL (plasma sheet boundary layer) or in the lobes: the bipolar B_z-variation plus the B_x-compression (Lee et al., 1988; Miyashita et al., 2005; Takada et al., 2005).

In spacecraft data one can see isolated bipolar variations of the B_z-component, and sequences of bipolar pulses as well. The latter are usually interpreted in favor of MXR mechanism or in favor of sausage/kink modes. Nevertheless, according to the above-stated a sequence of bipolar wave forms can be generated not only by a chain of flux ropes or by low-frequency waves, but also due to intermittent reconnection at a single X-line. In this paper a composite reconnection event consisting of three successive bipolar variations, observed by Gluster spacecraft in the magnetotail on 8 September 2002, is used as an example to support the scenario of time-varying reconnection with a single X-line. The support is based on application of a recently introduced tool (Semenov et al., 2005; Ivanova et al., 2007), which allows to reconstruct time-varying reconnection rate and X-line location from single spacecraft magnetic data.

2 Reconstruction technique based on time-dependent Petschek-type reconnection

In this section we give a brief description of the reconstruction tool developed on the basis of time-dependent Petschek-type reconnection model. For technical details we refer the reader to Semenov et al. (2005), who developed the reconstruction technique for symmetric configurations (like the magnetotail) in the limit of an incompressible plasma, and to Ivanova et al. (2007), who extended it to a compressible plasma and configurations with possible asymmetry (like the magnetopause).

The model of time-dependent Petschek-type reconnection (Heyn and Semenov, 1996; Semenov et al., 2004) generalizes the classic Petschek mechanism for an unsteady regime. The unsteady solution allows to simulate different reconnection regimes (impulsive, quasi-stationary, intermittent) and, thus, to investigate the dynamics of the reconnection process depending on a variable reconnection rate. It also describes the current sheet state after reconnection has ceased.

In the frame of this model the reconnection rate (the electric field at the X-line) is prescribed a priori as an arbitrary function of time restricted by the causality: $E(t)\equiv 0$ for $t\leq 0$. The local appearance of the electric field leads to a decay of the current sheet into a system of MHD discontinuities and shocks (Biernat et al., 1987; Heyn et al., 1988), which form two outflow bulges containing accelerated plasma (Fig. 1, upper panel). Once reconnection ceases (i.e. the electric field at the X-line drops to zero), the outflow bulges detach themselves from the reconnection site and move in opposite directions along the current sheet.

The model is analytical and is predicated on a number of simplifying assumptions: (i) plasmas and magnetic fields in reconnecting domains are homogeneous; (ii) the initial current sheet contains no normal component and is thin enough to be approximated by a tangential discontinuity; and (iii) the reconnection electric field is much less than the electric field calculated from the background magnetic field and the Alfvén velocity $E\ll E_A=v_A B_0/c$ (Petschek, 1964).

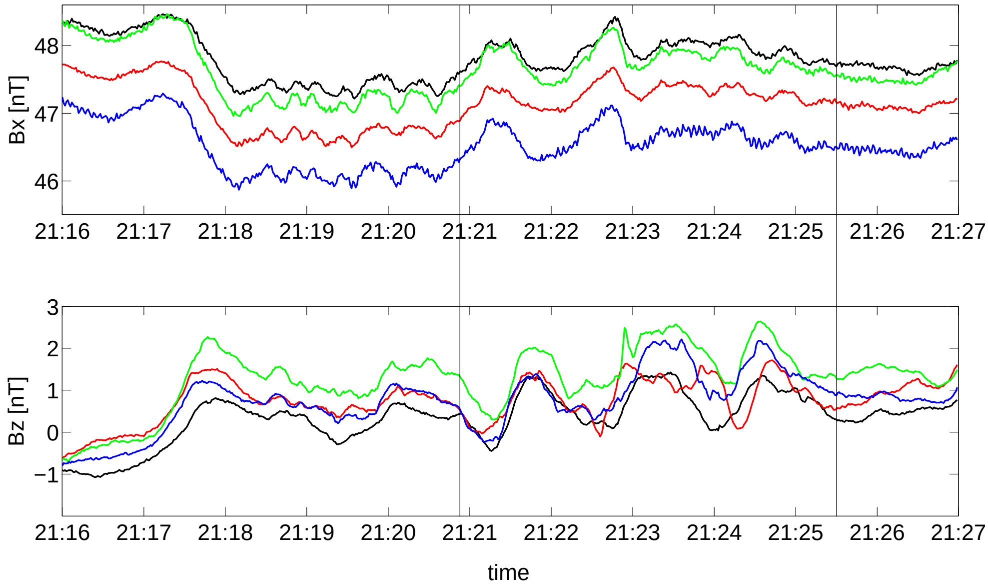

Fig. 3. Composite reconnection event on 8 September 2002 observed by Cluster. The interval chosen for reconstruction is marked by the vertical lines.

Perturbations caused by the moving outflow bulges in the surrounding medium are found from the set of compressible ideal MHD equations linearized with respect to the constant background. External perturbations (observed outside the bulges) can be written in the form of a convolution integral:

$$B_z(t,x,z) = \int_0^t d\tau K_z(\tau,x,z)E(t-\tau). \qquad (1)$$

Here E is the reconnection electric field, x and z are the observational coordinates along and normal to the current sheet, counted from the reconnection site (X-line) located in the origin (0,0).

The kernel of convolution $K_z(\tau,x,z)$ contains information on: (1) the medium parameters; (2) waves and discontinuities launched by reconnection; and (3) position of observation with respect to X-line. Physically, the kernel characterizes the response of the medium to an elementary, delta-shaped pulse of reconnection (Penz et al., 2006).

External perturbations are caused by bending of magnetic field lines around the outflow bulge and, since the shape of the bulge depends on the time profile of $E(t)$, they, naturally, reflect all changes in the reconnection rate (see Eq. 1). For an intermittent electric field consisting of three successive pulses the model predicts a triple bipolar B_z-variation and a triple B_x-compression (Fig. 2).

Qualitative agreement between model predictions and spacecraft observations had given rise to an idea of inverting the problem. The inverse solution gives the reconnection electric field if magnetic perturbations are given (whereas the direct solution defines perturbations for the specified electric field). Indeed, if the magnetic variation $B_z(t)$ at some observational point (x,z) is known (from spacecraft measurements), the relation (1) can be seen as an integral equation for the unknown electric field $E(t)$. Employing a standard method for solving integral equations of the convolution type, namely, the method of Laplace transforms, we get a simple relationship between Laplace images of the electric field, the B_z-variation, and the convolution kernel:

$$E(p) = \frac{B_z(p)}{K_z(p)}. \qquad (2)$$

Once the position of the spacecraft with respect to the X-line is known, the inverse Laplace transform of relation (2) gives $E(t)$. In reality, of course, the relative spacecraft location is not known a priori. To find it, a minimization procedure is utilized as follows: a trial spacecraft position $(\tilde{x},\tilde{z})$ is assumed and the corresponding reconnection electric field $\tilde{E}(t)$ is obtained. Since the trial coordinates are not correct in general, the function $\tilde{E}(t)$ is usually negative on a part of the time interval. However, the real electric field must be positive. Therefore, the absolute value $|\tilde{E}(t)|$ is then inserted into the direct solution to obtain the magnetic field variations B_z, B_x. Minimizing the standard deviation between the calculated B_z, B_x and those measured by the spacecraft, one can find both, the optimal electric field $E(t)$, and the position of the X-line with respect to the spacecraft.

To wind up the description of the technique, we should emphasize that our method requires magnetic data collected outside the disturbing bulge (since it exploits the inverted external solution).

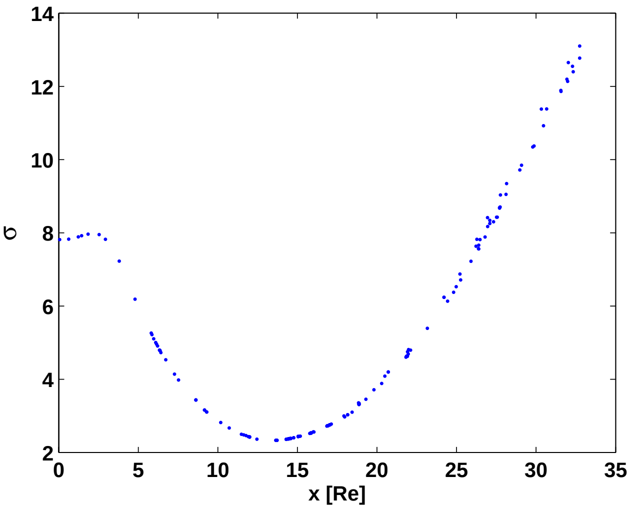

Fig. 4. Standard deviation as function of x for spacecraft C4. The minimum 13.7 R_E corresponds to X-line location at 29.7 R_E.

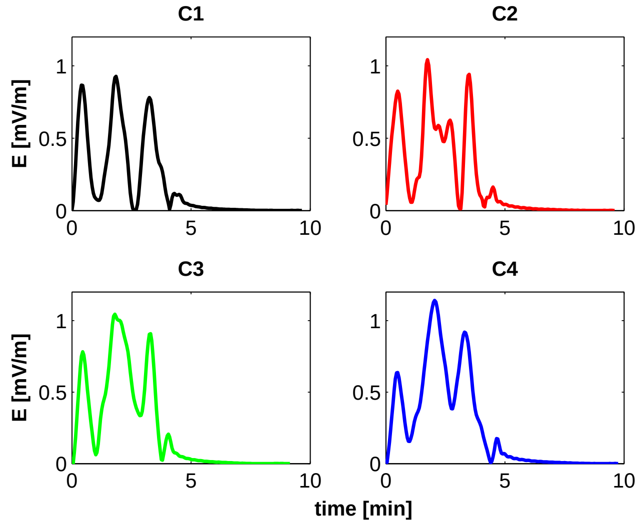

Fig. 5. Reconstructed electric field.

Up to now the method was applied to isolated reconnection events only. In this paper we demonstrate that it can be successfully applied also to composite reconnection events, consisting of several NFTE/TCR-signatures. As an example we consider a series of earthward propagating NFTE-variations detected by Cluster spacecraft in the magnetotail on 8 September 2002.

3 Application to Cluster composite event on 8 September 2002, 21:21 UT

On 8 September 2002 a well-isolated substorm with a peak AE index ~400 nT took place between 20:00 and 23:00 UT. A unique radial (THEMIS-like) spacecraft constellation near the midnight meridional plane (including Cluster, Geotail, Polar and LANL) together with ground observations gave a good chance to investigate in details the time development of this substorm. Here we discuss only those aspects of the substorm, which are relevant to our concerns. For further information the reader is referred to (Sergeev et al., 2005).

A clear growth phase (preceded by long quite period with a northward IMF) started around 20:15 UT, soon after the arrival at the magnetopause of a southward IMF. Owing to a continuous magnetic flux income the tail current was gradually increasing and the magnetic configuration was stretching until 21:10–21:20 UT. The expansion phase onset was detected by auroral and ground magnetic observations at 21:18 UT in the sector 22:00–24:00 MLT. Possibly, it was triggered by the irregular IMF turning to the north observed around this time. We emphasize that the change of orientation was irregular, followed by recovering of southward orientation and continuation of magnetic flux storing in the lobes.

At the time of interest Cluster spacecraft were located in the midtail with the barycenter at [−16.7; 0.2; 4.5] R_E GSM. Since the plasma sheet was getting thinner during the growth phase, the spacecraft exited from the plasma sheet after 21:00 UT and returned into it only after 21:37 UT. Being located in the lobes, the spacecraft observed a series of earthward propagating signatures (around 21:17, 21:21, 21:22 and 21:24 UT) with typical time scale ~1 min (Fig. 3), which are consistent with the picture of multiple NFTEs or TCRs. Variations recoded by different Cluster spacecraft are similar, hence, the spatial scale of the disturbing bulges was relatively large (the distance between probes was more then 3000 km). A systematic phase shift between different components, namely – cold oxygen perpendicular flows v_z (not shown here) and B_z variations anticorrelate, the beginning of positive B_z pulse corresponds to the maximum in B_x variation – allows to interprete them as NFTEs (Sergeev et al., 2005).

A time delay of 6–8 s between spacecraft C4 and C1 for the first pulse testifies that the structures were moving towards the Earth with a speed of 500–700 km/s. The more accurate estimation of the horizontal velocity of the leading structure (centered at 21:17:22 UT) using all components at all four spacecraft (according to the algorithm of Slavin et al., 2003b) gives V_x=627 km/s and V_y=−72 km/s (Sergeev et al., 2005). Thus, the x-component of the propagation velocity was much greater then the y-component. In addition, Cluster spacecraft were located near the central meridional plane of activation 22:00–24:00 h MLT. Combination of these two factors minimized 3-D effects in Cluster observations, which gives a chance to apply our 2-D technique.

Earlier these NFTEs (ignoring the first one at 21:17 UT) were processed separately using the first (incompressible)

Table 1. X-line locations (R_E in the tail) for separate NFTEs obtained by the incompressible variant of the method (Semenov et al., 2005).

	NFTE 1	NFTE 2	NFTE 3
C1	29.2	29.2	28.6
C2	29.9	30.0	29.3
C3	30.7		29.3
C4	30.9	29.5	29.7

variant of the reconstruction procedure (Semenov et al., 2005). For convenience of the reader the results obtained are summarized in Table 1. As one can see, the location of X-line for all three NFTEs is the same (the differences are within the accuracy of the method). Coincidence of the recovered values gives an evidence to consider these structures as having the same spatial origin. In such case there is no necessity to separate the pulses and the sequence can be treated as a composite reconnection event.

Here we apply the improved reconstruction technique (which takes into account plasma compressibility) to the whole sequence, starting from 21:21 UT and ending at 21:25.5 UT. The first NFTE (around 21:17 UT) was excluded from consideration, since it is isolated from the others and has the unipolar signature.

The initial spacecraft data were normalized with respect to B_0=40 nT, T_0=60 s and the propagation velocity V_x=630 km/s. The position of the neutral sheet Z (GSM) $\sim$1 R_E is known from the modeling of magnetic field configuration made by Sergeev et al. (2005). Thus, minimization has been carried out only with respect to variable x in the range X (GSM)<35 R_E, which corresponds to the area of the most probable NENL (near Earth neutral line) location. Minimization of the standard deviation with respect to x exhibited existence of a well-pronounced minimum for every spacecraft (Fig. 4). The recovered electric field consists of three pulses, each having the duration of $\sim$1 min (Fig. 5). The amplitude of the pulses vary from 0.6 to 1.1 mV/m. The reconstruction results obtained from different spacecraft are consistent, in particular, for all spacecraft the median pulse has the greatest amplitude and duration. The X-line lies in the interval between 27 and 30 R_E in the tail (Fig. 6).

The deviation between the input data and the recovered signal can be seen in Fig. 7. Agreement in B_z-component is very high, but the quality of reconstruction of the B_x-variation is not satisfactory for this event. The possible reason of divergence is that the series of reconnection pulses creates its own positive trend in B_z-variation and negative trend in B_x-variation (see Fig. 2). On can see from Fig. 3 that this kind of trend actually appears in the B_z-component of the spacecraft data. As for the corresponding trend in B_x it is, probably, overlapped by more strong positive trend created by the ongoing entrance of additional magnetic flux into the lobes.

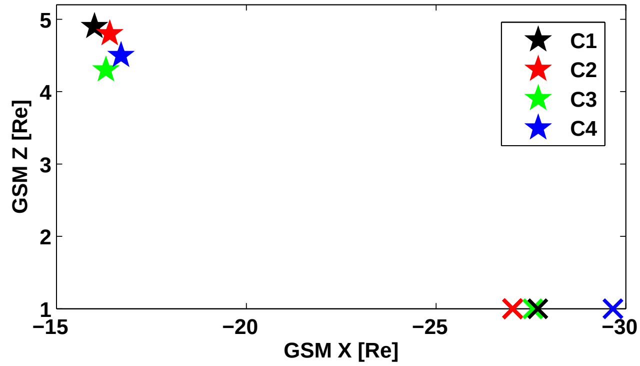

Fig. 6. Cluster spacecraft arrangement (star markers) and reconstructed locations of X-line (cross markers).

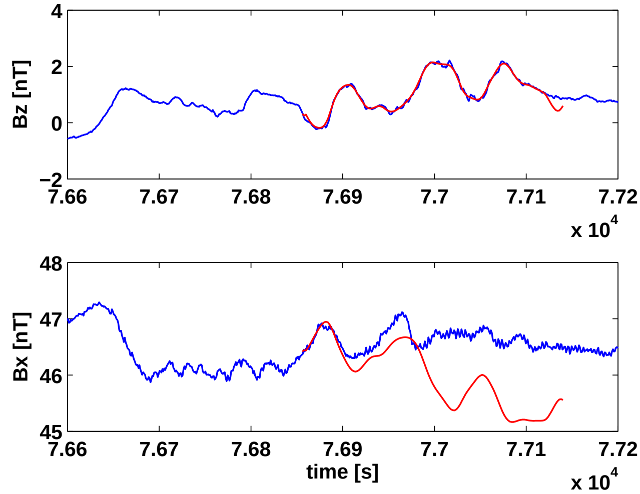

Fig. 7. Initial signal from spacecraft C4 (blue line) and the recovered signal (red line).

4 Conclusions

In the present paper we have demonstrated for the first time that the reconstruction method based on the time-dependent Petschek-type reconnection model can be applied not only to isolated FTEs/TCRs but also to composite reconnection events consisting of several bipolar pulses. In that way multiple bulges passing by a spacecraft may be interpreted in terms of impulsive (time-varying) reconnection. However, we note that similar magnetic signatures can be produced by multiple X-line reconnection or by low-frequency waves. Differentiation between these basic scenarios will demand detailed investigations in future.

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