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A shear B_Y field in the Earth's magnetotail and its variations in the current sheet

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ABSTRACT

We use Cluster and THEMIS simultaneous observations to study the spatial distributions of a shear B_Y field in the Plasma Sheet (PS) of the Earth's magnetotail at $-31\ R_E < X < -9\ R_E$. The best correlation between the B_Y field in the PS (B_{Y_PS}) and the Y-component of the Interplanetary Magnetic Field (IMF) (B_{Y_IMF}) was observed during the quiet PS periods when high speed plasma flows were not detected. During active PS periods the correlation between the B_{Y_PS} and B_{Y_IMF} was poor. The analysis of spatial distribution of the B_Y field along the direction perpendicular to the Current Sheet (CS) plane showed the presence of one of the following configurations, which can be self-consistently generated in the CS: 1) the "quadrupole" distribution of the B_Y field usually associated with the Hall current system in the vicinity of X-line and 2) the symmetrical "bell-shaped" distribution formed due to the B_Y amplification near the neutral plane of the CS. Multipoint observations revealed the transient appearance of the "quadrupole" B_Y distribution during the periods of X-line formation in the mid-tail. This distribution was observed during a few minutes within, at least, 12 R_E from the estimated X-line position. On the contrary, the symmetrical "bell-shaped" distribution is more localized in the radial direction and, generally, has a larger observation time (up to ~10 min). Thus, the internal CS perturbations caused either by the Hall currents related to reconnection or by the peculiarities of the local quasi-adiabatic ion dynamics sufficiently affect the shear B_Y field existing in the magnetotail due to the partial IMF penetration.

1. Introduction

The problem of origin of a shear magnetic field component in the Earth magnetotail has been studied during several decades. In the Geocentric Solar Magnetospheric (GSM) coordinate system a shear magnetic component is directed along the Y-axis, which is defined as the cross product of the X-axis (directed along the Earth-Sun line) and the magnetic dipole axis (Z). The B_Y magnetic field can appear in the magnetotail due to many reasons. The flaring of the magnetotail field lines results in the appearance of the B_Y field proportional to the local B_X. In the neutral sheet the twisting effect creates the B_Y proportional to the local B_Z (e.g. Tsurutani et al., 1984; Kaumaz et al., 1994; Petrukovich et al., 2009). Another widely discussed mechanism is the penetration of the Interplanetary Magnetic Field (IMF) into the magnetotail (e.g. Fairfield, 1979). Many statistical studies reported a good correlation between the Y-component of the IMF (B_{Y_IMF}) and the B_Y field observed in the Earth's magnetotail (e.g. Sergeev, 1987; Kaumaz et al., 1994). However the different estimations of the penetration factor of the B_{Y_IMF} were reported: 13% by Lui (1984), 9–21% by Tsurutani et al. (1984), 60% by Sergeev (1987), 76% by Borovsky et al. (1998). Petrukovich (2011) also reported a good correlation between the IMF and the Plasma Sheet (PS) B_Y field, but the authors showed that the B_Y in the PS is often substantially larger than the statistically expected value. They explained this effect by the "amplification" due to internal PS dynamics.

Many theoretical studies were devoted to the problem of generation of a shear magnetic field in the magnetotail and its influence on the global tail configuration. Birn (1990) obtained equilibrium solution for the tail PS with a net constant B_Y field. Cowley (1979, 1981) considered

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two-dimensional non-planar field line system and obtained the intensification of the net B_Y field at the center of the CS. These models considered an isotropic thick CS, in which the magnetic tension of curved field lines is balanced by the radial plasma pressure gradient. Such models cannot describe the kinetic effects in particle dynamics arising in a thin CS with the thickness of the order of a few ion gyroradii or less. Contrary to the case of isotropic CS, in a thin CS, which sizes along the directions tangential to the sheet plane are much larger than the size along the normal to the CS plane, the magnetic field tension is balanced by the anisotropy of plasma pressure tensor. This consideration is based on the existence of the so-called Speiser particles which experience quasi-adiabatic dynamics in the CS. Such CSs are very often observed in the Earth magnetotail within Cluster and THEMIS orbits (e.g. Sharma et al., 2008 and references therein).

Malova et al. (2012; 2015), Mingalev et al. (2012) performed the simulations of self-consistent evolution of a thin CS with initial net B_Y component. They showed that due to the kinetic features of quasi-adiabatic ion interactions with the sheet the system evolves to the magnetic configuration with the amplification of the B_Y field near the neutral plane. Thus, the resulting spatial profile of the B_Y field in the direction perpendicular to the CS plane has a "bell-like" shape.

Multipoint Cluster observations confirmed the existence of such spatial profiles of the B_Y field in the magnetotail (e.g. Rong et al., 2012; Grigorenko et al., 2013, 2015). The strongest $|B_Y|$ was observed near the neutral plane of the CS (i.e. in the plane where $B_X = 0$) and it decreased towards the edges of the CS. The sign of a shear B_Y at the CS neutral plane generally coincides with the sign of the B_{Y_IMF}, but, in many cases, the absolute value of a shear B_Y field in the CS was significantly larger than the corresponding IMF component (e.g. Grigorenko et al., 2015).

Grigorenko et al. (2013) studied the spatial distribution of the B_Y field tailward of a near-Earth X-line. By using Cluster observations the authors showed that the spatial distribution of B_Y changed with the distance from the X-line. In the close vicinity of the X-line the B_Y field changes its sign across the CS in the agreement with the expected "quadrupole" B_Y distribution formed by the Hall current system tailward of the X-line. The "quadrupole" distribution was obtained in simulations (e.g. Lottermoser and Scholer, 1997; Nakamura et al., 1998; Hesse et al., 2001; Pritchett, 2001) and confirmed by observations (e.g. Nagai et al., 2001; Runov et al., 2003; Eastwood et al., 2007). With the increase of the distance from the X-line the asymmetric quadrupole B_Y field distribution transforms into the symmetric "bell-shaped" spatial profile.

The last can be formed by the mechanism discussed by Grigorenko et al. (2013, 2015); Malova et al. (2015). Under the presence of even small initial B_Y field, which can be originated from the IMF penetration into the magnetotail, the "north-south" asymmetry in the quasi-adiabatic ion interaction with the CS appears. This kinetic effect is caused by the differences in the reflection/refraction of ions arriving to the CS from the northern/southern parts of the PS. Due to the presence of a shear B_Y of a given sign ions arriving from one hemisphere are forced to move oppositely to the dawn-dusk E_Y field Such ions experience strong scattering and are partially reflected to the same hemisphere from which they arrived. At the same time, ions arriving from the other hemisphere are moving along the magnetic field lines in the same direction as the E_Y. All such ions are ejected to the opposite hemisphere after the interaction with the CS. As a result, in the particular part of the PS (either northern or southern one) there is a surplus of the ejected ions in comparison with the opposite part of the PS. Fig. 1 shows a cartoon of the "northern" and "southern" ion trajectories in the CS with a positive shear B_Y field. For the negative B_Y field the pattern of ion interactions with the CS is opposite. These kinetic effects lead to the generation of the oppositely directed electric currents J_X at the edges of the CS, which, in turn, can support and enhance the B_Y field of a given sign at the neutral plane.

Summarizing the results of these studies one may conclude that the internal CS particle dynamics can significantly modulate a shear B_Y field arising in the magnetotail PS due to the IMF penetration. These effects may explain the difference in estimations of the IMF B_Y penetration factors obtained in the statistical studies. In this paper by using multipoint THEMIS (Angelopoulos, 2008) and Cluster (Escoubet et al., 2001) observations we discuss the spatial distributions of a shear B_Y field in the magnetotail PS observed both in the direction perpendicular to CS plane and in the radial direction (along the X). We also estimate the characteristic time scales of the B_Y field variations in the CS. Everywhere in the paper the GSM coordinate system is used.

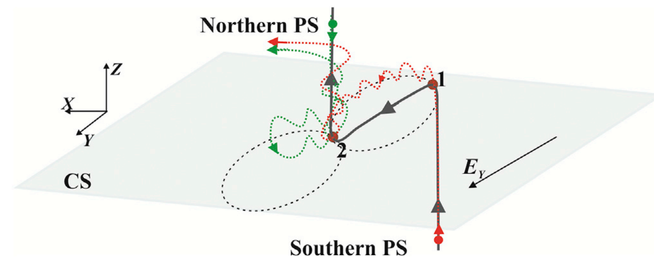

Fig. 1. An illustration of the peculiarities of the quasi-adiabatic ion interactions with the CS under the presence of a positive shear BY field. The magnetic field line si shown by the solid grey line. An ion coming from the southern PS (its trajectory is shown by red dotted line) crossed the separatrix at point "1" and experienced a quasi-larmor gyration in the CS around the finite positive BZ field so that the field line lies inside the ion gyration circle (shown by the black dotted line), and, then at the point "2" of the separatrix crossing it is ejected to the opposite (northern) part of the PS. Thus, in such magnetic field geometry all "southern" ions are ejected into the northern hemisphere. On the contrary, ions coming to the CS from the northern hemisphere (shown by the green dotted line) starts to rotate in the CS plane, so that their original magnetic field lines do not lie inside the quasi-larmor circles. The partial magnetization of the ions by a shear B_Y field impedes their duskward motion. Such ions pass smaller distances in the duskward direction because of strong scattering and are partially ejected back into the northern hemisphere. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. THEMIS observations of the radial distribution of a shear B_Y field during quiet and active PS periods

To study the radial distribution of a shear B_Y field in the magnetotail PS we use 9 intervals of THEMIS observations in February–March 2009 (the list of intervals is presented in Table 1). During these intervals five THEMIS probes were distributed in the radial direction at $-30\ R_E \leq X \leq -9\ R_E$ while their separation along the Y was $\leq 3\ R_E$. To select the intervals of the PS crossing we use the condition $|B_X| \leq 10$ nT. All analyzed intervals were located within the midnight sector, $|Y| \leq 5\ R_E$, where the flaring-related magnetic component is not significant (Petrukovich, 2009).

2.1. *An example of the quiet PS interval*

Fig. 2 shows an overview of the period of a shear B_Y field observation in the magnetotail PS by four THEMIS probes (P1 — P4) on 03.02.2009 between 05:00 and 09:00 UT. THEMIS probes had close Y-coordinates ($Y_{P1} = -3.8\ R_E$; $Y_{P2} = -4.8\ R_E$; $Y_{P3} = -5.0\ R_E$; $Y_{P4} = -4.0\ R_E$) and were distributed in the radial direction as it is shown in Fig. 4a. It was quiet geomagnetic period: during the entire interval the $|AL| < 50$ nT.

Table 1
The PS intervals observed by THEMIS probes, which are used in the analysis of the B_Y variations.

PS Intervals	PS state
03.02.2009 05:00–09:00	quiet
07.02.2009 03:00–07:00	active
08.02.2009 04:00–08:00	quiet
09.02.2009 03:00–12:00	quiet
11.02.2009 02:00–09:00	active
15.02.2009 02:00–09:00	active
19.02.2009 03:00–10:00	quiet
27.02.2009 02:00–12:00	active
03.03.2009 04:00–12:00	active