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EFFECT OF B_Y IMF IN SUBSTORM CURRENT WEDGE FORMATION

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Abstract. Based on the data of longitudinal chain of midlatitude stations in the northern hemisphere, substorm-associated field-alighned currents (FACs) are examined. A comparison of IMF component variations with surface FAC characteristics in substorm sites is performed. It is shown that the ratio between the upward and downward surface FAC intensities depends on B_y IMF. In this regard, the conditions are discussed that favor currents flowing from the dayside cusp to nightside auroral region. These currents, which position is dependent on B_y IMF direction, can be responsible for difference between the upward and downward current-wedge-associated FACs.

Introduction

Substorm current wedge (SCW) is intensification of magnetosphere-ionosphere current system in the night-time auroral region. According to [1], SCW originates due to magnetic reconnection process in the near-Earth plasma sheet. In this framework it remains unclear, why the westward azimuthal current in the magnetosphere diverts to the ionosphere via SCW-associated FACs. There are also difficulties in interpretation of the magnetospheric currents, flowing perpendicularly to the cross-tail current, though in [2] these currents are shown to exist under stationary conditions.

The above problems evidently have the same underlying physics and can be also referred to the magnetopause currents. According to [3–5], a possibility of current flowing normally to the magnetopause is a principle point in boundary layer – ionosphere electrodynamic coupling.

We believe that in both stationary and non-stationary cases, current diversion is a widely spread magnetospheric process, which, in particular, can be related to generation of inductive or static field-aligned electric fields.

In the present work we treat SCW formation scenario, in which explosive reconfiguration of the plasma sheet current is controlled by inductive electric field. Within this framework, as distinct from electrostatics, we can correctly relate the electric field to the electric current without invoking to anomalous processes associated with violation of ideal MHD.

Taking into account that substorm is mostly initiated under southward IMF, of major interest are cases when this phenomenon proceeds against strong azimuth IMF component, meaning that substorm onset develops under electric field associated in a definite manner with IMF sector structure [6].

We note, that in case $|B_y / B_z| > 1$, B_y, B_z being IMF components in the GSM coordinate system, according to [7], it is E_z that transfers most efficiently from the solar wind to the magnetosphere, in particular, to the polar cap

$$E_z \sim - V_0 B_y,$$

where V_0 is the solar wind velocity. Then, according to views of [6,8], the field with a component perpendicular to the neutral sheet plane penetrates into the plasma sheet.

To verify this concept experimentally, we seek for the above electric field effect in the distribution of SCW currents and for consequences of associated current diversion.

By now, similar problems have been treated using low-altitude satellite detected magnetic field variations [9]. But we start with analysis of the ground magnetic observations. Based on a method of distant diagnostics of SCW-associated FACs proposed in [10], we have studied their magnetic effects under different directions of B_y IMF.

Data analysis

Here we consider disturbances in the course of six isolated substorms under B_Z IMF< 0 and $|B_y$ IMF / B_z IsMF $| > 1$ (see also [7,11]). Substorm onset T_0 is determined by H-component at auroral zone stations.

It was shown in [12,13] that longitudinal distribution of geomagnetic D-component amplitude variation $\Delta D(t,\lambda)$

$$\Delta D(t,\lambda) = D(t,\lambda) - D(T_0,\lambda) \qquad (1)$$

can be used to determine a longitudinal extent of substorm expansion phase FACs.

Within this framework the longitudinal extent of FAC sheets was determined from midlatitude chain magnetic data in [14], where the longitudinal dependence of $\Delta D(t,\lambda)$ was approximated by a cube function and (1) took the form

$$\Delta D3(T_0 + \Delta t, \lambda) = 0,$$

Three roots of this equation (Δt being fixed time intervals equal to 5, 10, and 15 minutes) are λ_W, λ_E and λ_0, which mark the central longitude of the downward FAC sheet, upward FAC sheet and central longitude of substorm site. Correspondingly, longitudinal extent of the downward FAC is

$\Lambda_W = \lambda_W - \lambda_0$,

and that of the upward FAC is

$\Lambda_E = \lambda_E - \lambda_0$.

The above results suggested that SCW-associated FACs are distributed in the manner, which is sketched in Fig.1.

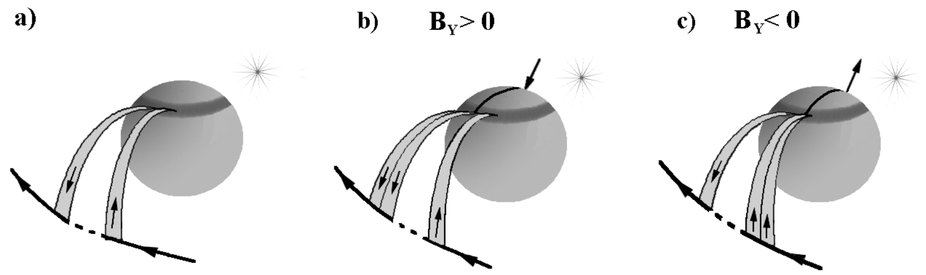

Fig. 1 Sketch illustrating distribution of SCW-associated field-aligned currents under different directions of B_Y IMF.

In Fig. 1 SCW-associated FACs are a superposition of purely anti-symmetric part (Fig.1 a) and an additional FAC, which direction is controlled by B_Y IMF sign (Fig.1 b, c).
Observations performed at magneto-conjugate stations suggest that there is asymmetry in substorm development in the northern (N) and southern (S) hemispheres [15], the ratio $|\Delta H|_{max\ N}$ / $|\Delta H|_{max\ S}$ of substorm perturbation maximums being dependent on the sign of B_Y IMF.
With the above north-south asymmetry taken into account (see [16]), we present in Fig. 2 superposition of purely anti-symmetric and associated with B_Y IMF FACs for substorms developing in the northern and southern hemispheres under either positive or negative B_Y IMF.

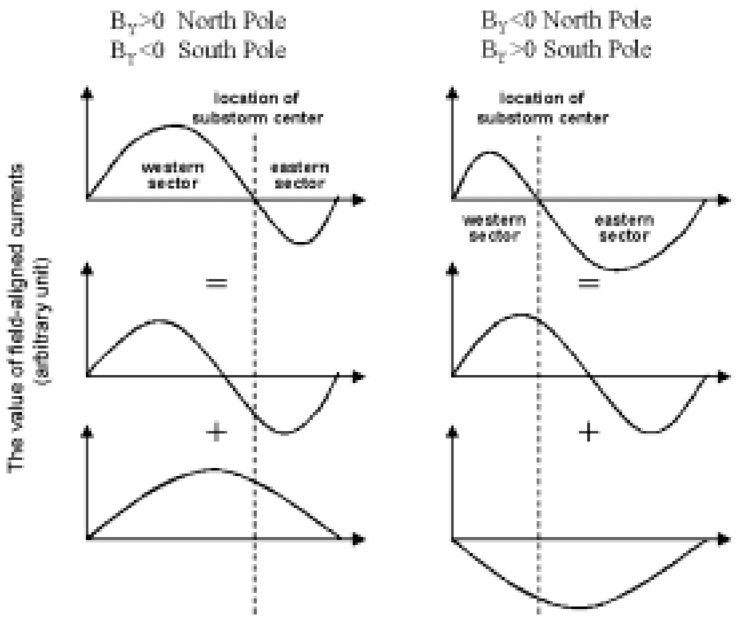

Fig. 2 Longitudinal distribution of SCW-associated FACs in the northern/southern hemispheres under positive/negative B_Y IMF.

The results of the above consideration allow us to construct a more complete picture of substorm currents in association with different IMF sector structure than that depicted in Fig. 1. In Fig. 3 we present a generalized SCW scheme, including an additional source in the magnetopause flowing-around region, substorm cross-tail current, and auroral electrojet distribution in the northern and southern hemispheres under different sign of B_Y IMF. The dashed line indicates the boundary between FACs of different direction. One can see that substorm sites in the northern and southern hemispheres appear to be longitudinally displaced, a principle feature that has to be interpreted in any model of the substorm.

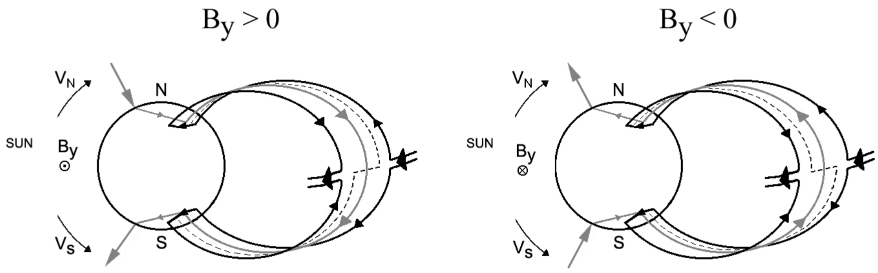

Fig. 3 The current associated with IMF sector structure (thin) and substorm current wedge (thick) in the northern and southern hemispheres under different sign of B_Y IMF.

Discussion

In the previous sections we demonstrated the effect of B_Y IMF direction in distribution of SCW-associated FACs, leading to both pre midnight/post midnight and northern hemisphere/southern hemisphere asymmetry in substorm development. We note, that the manner of how the northern /southern asymmetry matches the pre midnight/post midnight one in the present study is different from [18,19], in which the effect of B_Y IMF in auroral magnetic activity was treated. This inconsistency can be understood, since the geomagnetic indexes indicate Hall current behavior rather than that of magnetospheric FACs. This point makes ground-based distant diagnostics of FAC intensities more preferable [10].

Further, one should take into account that the current generator associated with the IMF sector structure is located in daytime magnetopause cusp region. In consistence with ionospheric conductivity distribution, the electric field is transferred to the polar caps. The ratio of electric field amplitudes in the dawn and dusk sectors can be estimated as

$E_{dawn} / E_{dusk} \approx (r-d) / (r+d)$

where r is the polar cap radius, and d is the cusp displacement from the noon-midnight meridian plane. For simplicity, we neglect cusp displacement in this plane and consider that $d > 0$ if the cusp is displaced to the morning side from this plane.

For B_Y IMF > 0 (B_Y IMF < 0), according to [20], the cusp is positioned in the evening (morning) sector in the northern (southern) hemisphere, and, correspondingly, $d < 0$ ($d > 0$). Thus $E_{dawn} / E_{dusk} > 1$ ($E_{dawn} / E_{dusk} < 1$) in the northern (southern) hemisphere, which is in agreement with [18, 20]. Thus one can see that the current system associated with IMF sector structure, being added to SCW current system keeps this feature unchanged.

Having determined the current direction from (6), one can conclude that under B_Y IMF > 0 (B_Y IMF < 0) it flows into (out of) the magnetosphere in the evening (morning) sector of the northern (southern) hemisphere, and current of the same value flows out of (into) the magnetosphere in the morning (evening) sector of the southern (northern) hemisphere. Naturally, the expected equality of these currents should be verified, provided all other current sources are excluded. This is quite a complicated problem, so we first consider a simplified method of current direction verification.

Direction of FACs in the region of the dayside cusps is determined by their relation to the Lorentz force component perpendicular to the magnetopause

$$J_{\|} \sim [\mathbf{V}\, \mathbf{B}_Y]_{\perp}$$

It is suggested that this force action is from the side of the magnetized solar wind, which flows around the magnetopause, with the velocities V in the cusp regions directed as shown in Fig. 3. The currents in the cusp regions associated with different IMF sector structure are shown in this Figure by the arrows near the poles N and S.

Change of magnetospheric current direction (Fig. 3) corresponds to redistribution of the FACs in the models [16], in which the effect of B_Y IMF is taken into account. This consistency permits to discuss quantitative characteristics of dynamical coupling between FAC distribution and diversion of diamagnetic or inertial currents in both the magnetosphere-ionosphere system and magnetosheet.

By using relations from [16] for the total current flowing into the magnetosphere in one cusp and out of it in the other, we can get the following estimate

$$J \approx B_n\, d_j / \mu \approx 200 \text{ A},$$

where $B_n \approx 1$ nT is the perpendicular to the magnetopause magnetic field component in the region of open magnetic field lines, $d_j \approx 200$ km is the thickness of the current sheet and $\mu = 4\pi \cdot 10^{-7}$ H/m is the magnetic permeability of vacuum. The order of J in the above estimate is much smaller than it is needed to interpret peculiarities in distribution of SCW FACs (their total values are $\geq 10^6$ A [1]) in terms of B_Y IMF influence.

Based on generalized Ohm's law, one can apply MHD approach to describe B_Y IMF effect on the magnetospheric boundary layer. By suggesting that in cusp region the transverse to the magnetopause conductivity currents are mostly parallel to the magnetic field inside the magnetosphere, we can estimate the upper limit of the current flowing in the high latitude region (the mantle)

$$J_{\|} < V\, B_Y\, d_V / R$$

This yields ≈ 10^6 A, for the velocity V ≈ 200 km/s, magnetic field B_Y ≈ 10 nT, thickness of the velocity shift layer d_V ≈ 6 · 10^3 км (see [21]) and effective resistivity R = 10^{-2} Ohm. The resistivity is adopted to be close to the ionospheric resistivity R_i, the latter for the SCW condition being taken from [1]. We note, that as in an ordinary electric circuit, under R = R_i the upper limit for the conductivity current in the circuit 'mantle-ionosphere' is close to the self-discharge current i.e. $J_s = E / R$ in the electrostatic field $\mathbf{E} \sim -[\mathbf{V}\ \mathbf{B}_Y]$ of plasma flowing around the magnetopause. Along with the equality $J_{||} = J_s$, we can use that the sum of these currents is equal to the upper limit of the total current. In result, one can obtain that $J_{||} \approx 0{,}5 \cdot 10^6$ A.
Thus, under the assumption that B_Y IMF penetrates inside the magnetosoheric mantle, the magnitude of $J_{||}$ appears to be quite comparable to SCW-associated FACs, so that $J_{||}$ can affect their distribution.

Conclusions
1. B_Y IMF effect in the SCW is due to the currents associated with IMF sector structure passing by the Earth.
2. In addition to pre midnight/post midnight asymmetry in distribution of substorm-associated FAC, IMF sector structure causes northern/southern hemisphere asymmetry.
3. The above asymmetrical distributions in field-aligned and ionospheric currents form a special class in globally asymmetrical geomagnetic disturbances.

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