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IMF By effects in the magnetospheric convection on closed magnetic field lines

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[1] Using data from the Super Dual Auroral Radar Network (SuperDARN) and the ultraviolet imager on the Polar satellite, we have earlier shown that the IMF By-related electric field can penetrate into the closed magnetosphere and produce convection changes in the region of the postnoon auroral oval [*Kozlovsky et al.*, JGR, N12, 2002]. In such a case, contra-directed azimuthal (East–West) plasma flows should be expected in the conjugated hemispheres. In this paper we present a theoretical model, which can well explain these observations. Due to the solar wind-magnetosphere dynamo, IMF By generates a voltage between the two polar caps, so that field-aligned currents flow between the two hemispheres within some layer just equatorward of the open polar cap boundary. In this region a field-aligned potential difference (i.e., a magnetic field line discontinuity) can occur when the field-aligned current exceeds a threshold value. The IMF By-related contra-directed ionospheric plasma flows can co-exist in the northern and southern hemispheres within the region of the inter-hemispheric field-aligned currents. The latitudinal width of this region depends on the IMF By and the ionospheric conductance, and can be of the order of 1–2 degrees. *INDEX TERMS:* 2463 Ionosphere: Plasma convection; 2708 Magnetospheric Physics: Current systems (2409); 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions. **Citation:** Kozlovsky, A., T. Turunen, A. Koustov, and G. Parks, IMF By effects in the magnetospheric convection on closed magnetic field lines, *Geophys. Res. Lett.*, *30*(24), 2261, doi:10.1029/2003GL018457, 2003.

1. Introduction

[2] In the course of solar wind-magnetosphere interaction, the interplanetary magnetic field Y-component (IMF By) generates a voltage between the two polar caps (Figure 1) [e.g., *Leontyev and Lyatsky*, 1974]. The IMF By-related plasma flows are opposite in the northern and southern hemispheres, such that a negative IMF By produces an eastward (westward) plasma flow in the northern (southern) polar cap. In a steady-state case, such oppositely directed flows should not co-exist in the closed magnetic field line regions of the conjugate hemispheres because of the high conductivity along the magnetic field lines. Hence it is commonly believed that the IMF By - related plasma flows occur within the open polar caps forming lobe convection cells [e.g., *Burch et al.*, 1985].

[3] However, Super Dual Auroral Radar Network (SuperDARN) observations have shown that the IMF By-related electric field can penetrate into the closed magnetosphere and influence ionospheric convection in the morning sector [*Rash et al.*, 1999] and in the region of the postnoon auroral oval [*Kozlovsky et al.*, 2002]. From analysis of EISCAT radar measurements it was found that significant flow variations with IMF By occur on closed magnetic field lines, predominantly in the midnight sector, but also in the pre-dusk (1600–1700MLT) sector [*Khan and Cowley*, 2001]. These observations are consistent with the seasonal dependence of IMF By-related convection reported earlier [*Ruohoniemi and Greenwald*, 1995; *Milan et al.*, 2001].

[4] Attempting to explain their observations, *Khan and Cowley* [2001] investigated whether a “penetrating” IMF component can change the mapping to the ionosphere. Their model has been found to account well for the observed IMF By-related flow perturbations in the midnight sector, however it does not account for the effects observed in the postnoon sector. *Kozlovsky et al.* [2002] proposed that the IMF By effects might be due to a seasonal (winter-summer) asymmetry between the hemispheres, however no model was suggested. Thus, the IMF By effects on the dayside ionospheric convection patterns have not been explained. The aim of the present paper is to suggest a mechanism for how the IMF By component may influence the convection pattern on closed magnetic field lines, using the experimental results obtained in [*Kozlovsky et al.*, 2002] to validate the model.

2. Inter-Hemispheric Field-Aligned Currents

[5] Due to the solar wind motion with respect to the Earth, an IMF By component is associated with a north-south oriented electric field in the undisturbed solar wind (on open field lines). Through the well-conducting ionosphere, footprints of the open field lines are connected to footprints of closed magnetic field lines, so that an electric connection occurs between the open field lines over the southern polar cap and the open field lines over the northern polar cap. Thus, IMF By generates a voltage between the two polar caps [e.g., *Leontyev and Lyatsky*, 1974; *Trondsen et al.*, 1999], which drives field-aligned currents between the hemispheres (Figure 1). The relative position of the up- and downward field-aligned currents depends on the IMF By sign: for positive IMF By, upward FACs in the northern hemisphere are located poleward of the downward FACs, for negative IMF By, the positions of the currents are

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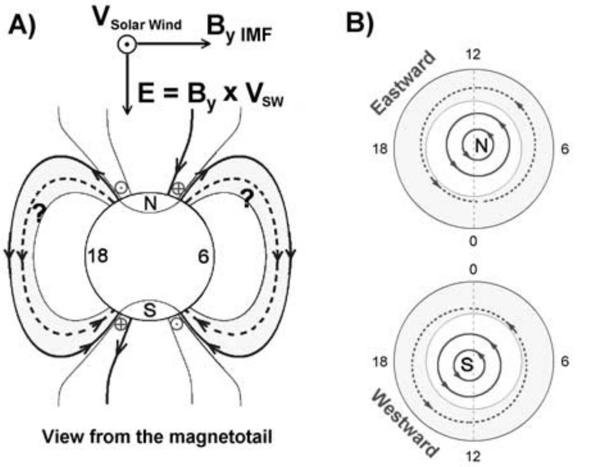

Figure 1. (a) Due to the solar wind dynamo, IMF By generates an electric field **E** = **By** × **Vsw** in the Earth-associated framework, which drives inter-hemispheric field-aligned currents (indicated by question marks). (b) The IMF By-related ionospheric plasma flows are opposite in the northern and southern hemispheres (e.g., IMF By < 0 produces eastward (westward) plasma flow in the northern (southern) polar cap).

reversed. The field-aligned currents flow from the solar wind to the open polar cap ionosphere, then at the boundary of open/closed field lines (in a thin layer of the closed magnetosphere) they transfer into the opposite hemisphere (Figure 1), and exit the ionosphere from the opposite polar cap. Thus, the inter-hemispheric FACs occur inside a layer just equatorward of the polar cap boundary. When the field-aligned current exceeds a threshold value of the order of 10^{-6} A/m^2, a field-aligned potential difference is developed [e.g., *Knight*, 1973; *Lyons and Williams*, 1984]. Thus, in the field-aligned current region the electric potential distributions in conjugate hemispheres can be different, which implies different ionospheric convection patterns. A rough estimate of the possible latitudinal width of the FAC layer is given below (see also Figure 2).

[6] Using the ionospheric electric field model by *Heppner and Maynard* [1987], *Volkov* [1993] obtained the following relationship for the polar cap potential versus IMF By:

$$\Delta\varphi[\mathrm{kV}] = \pm 6\ By[\mathrm{nT}]. \tag{1}$$

Here $\Delta\varphi$ is the potential difference between the center and the boundary of the polar cap, and "+" and "−" are related to the northern and southern hemispheres, respectively (Figure 2). Assuming the polar cap radius (R_{pc}) to be of the order of 1500 km, one obtains a meridional electric field of about $E_N \approx \Delta\varphi/R_{\mathrm{pc}} \approx 20$ mV/m for IMF By = 5 nT, which corresponds to an azimuthal ionospheric plasma drift of 400 m/s, a typical value from observations [*Kozlovsky et al.*, 2002]. For a Pedersen conductance of $\Sigma_{\mathrm{P}} = 4$ mho, this electric field produces a meridional Pedersen current of $J_P = E_N\,\Sigma_{\mathrm{P}} \approx 80$ mA/m in magnitude. This current should flow to the opposite hemisphere through a thin field-aligned current layer just equatorward of the polar cap (Figure 2). The field-aligned current density is limited by a critical value, $j_{\|\mathrm{c}}$, of the order of 10^{-6} A/m^2 [e.g., *Knight*, 1973; *Lyons and Williams*, 1984]. Thus, the width of the field-aligned current layer can be estimated as

$$\Delta x_{By}[\mathrm{km}] = 6\,\frac{\sum_p[\mathrm{mho}]}{R_{pc}[\mathrm{m}]\,j_{\|c}\left[\mathrm{A/m^2}\right]}\,|B_y[\mathrm{nT}]|. \tag{2}$$

Kozlovsky et al. [2002] obtained a maximum of the postnoon large-scale FAC of about $0.6\cdot10^{-6}$ A/m^2, which, for the values of Σ_{P} and By given above corresponds to a FAC layer with a width of about 1.2 degrees (130 km).

[7] This width agrees with the distance of about 1–2° between the polar cap boundary (identified from DMSP particle precipitation data) and the postnoon convection reversal (CR), which has been observed for an IMF By value of −5 nT [*Kozlovsky et al.*, 2002]. For this case the convection on the closed magnetic field lines was anti-sunward adjacent to the polar cap boundary. In contrast, for the case of positive IMF By (+2 nT) the convection on the closed magnetic field lines was sunward. Thus, the IMF By can affect the ionospheric electric field at 1–2° equatorward of the open polar cap boundary. In this region the ionospheric plasma flows in the conjugate hemispheres will have opposite directions due to the field-aligned potential difference associated with field-aligned currents.

3. Ionospheric Convection

[8] In this section we shall use the above consideration to explain the IMF By effects in the ionospheric convection reported by *Kozlovsky et al.* [2002]. In that study the SuperDARN radar and the ultraviolet imaging from the Polar satellite (UVI) observed the postnoon auroral ionosphere during the rotation of the IMF vector in the Y-Z plane from a positive to a negative By value (IMF Bz had a value of about −5 nT both before and after the rotation, except a short positive deflection at the moment of the By change). This case is presented in Figure 3. For positive IMF By the convection reversal was poleward of the auroral oval (left panel in Figure 3). In response to the IMF By turning negative, the position of the maximum of the auroral

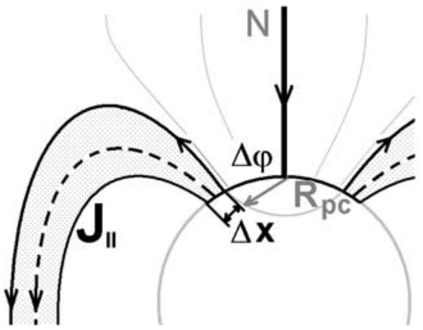

Figure 2. Sketch explaining field-aligned currents generated due to IMF By. The FACs flow from the solar wind to the open polar cap ionosphere, then along a thin layer of the closed magnetosphere to the opposite hemisphere, and finally (not drawn here) exit from the opposite polar cap.

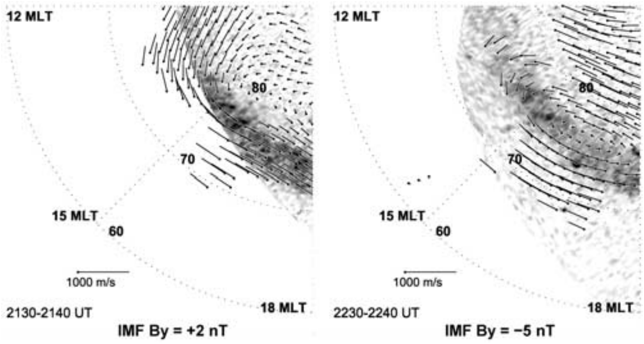

Figure 3. The postnoon auroral oval (Polar UVI) and ionospheric convection (SuperDARN) observed on January 17, 1997 before (left panel) and after (right panel) an IMF By transition from a positive to a negative value. The IMF Bz was about −5 nT for the both diagrams (see [*Kozlovsky et al.*, 2002] for more details).

luminosity did not change noticeably, but the convection changed considerably. For negative IMF By, the convection reversal moved equatorward and became roughly co-located with the center of auroral oval (right panel in Figure 3).

[9] Figure 4 illustrates schematically a way to explain the convection patterns presented in Figure 3. For small (near-zero) values of IMF By (top panel in Figure 4), the ionospheric electric field and position of CR is determined by solar wind-magnetosphere interaction processes, such as reconnection and viscous interaction and by the effects of hot magnetospheric plasmas. In this case the CR is close to the polar cap boundary. For IMF By >0, an additional westward plasma flow is generated in the polar cap and immediately equatorward of the polar cap boundary so that the CR appears at a higher latitude (left part of Figure 4). If IMF By <0, the additional plasma flow is eastward, so the CR is shifted to lower latitudes toward the core of the auroral oval (right panels in Figure 3). The width of the penetration region where IMF By may produce convection changes on closed magnetic field lines can be estimated by equation (2). Note that the schematic convection patterns in Figure 4 are very similar to the experimental observations shown in Figure 3, which give support to the suggested model.

4. Discussion

[10] The key element of the proposed model is the high-latitude inter-hemispheric FACs driven by the IMF By generated voltage drop between the northern and the southern polar caps. We would like to mention two important phenomena associated with this, the IMF By control of the auroral activity and the seasonal effects in the IMF By-related electrodynamics.

[11] In the FAC region the ionospheric plasma flows in the conjugate hemispheres may have opposite directions due to the field-aligned potential difference associated with the field-aligned currents. The field-aligned potential drop increases the energy of the precipitating auroral electrons, which implies that IMF By has an influence on the high-latitude dayside auroral activity. On the basis of Viking UV imager data *Trondsen et al.* [1999] concluded that negative IMF By conditions are preferable for the occurrence of dayside aurora in the northern hemisphere. This experimental result agrees well with the predictions by our model, namely that enhanced auroral activity occurs in that hemisphere where the IMF By produces an upward FAC (i.e., a downward electron flow) on the closed magnetic field lines associated with the auroral oval.

[12] The voltage between the polar caps is due to the solar wind dynamo, which operates as a voltage generator, $\Delta\varphi_{NS} \propto |\mathbf{V}_{SW} \times \mathbf{B}_Y|$. Associated ionospheric and field-aligned currents depend on the ionospheric conductivity, which can control the width and location of the region of the IMF By-associated inter-hemispheric FACs. Since the ionospheric conductivity depends on season, one may expect a seasonal dependence of the IMF By effect on the convection pattern on closed magnetic field lines. Indeed, such effects have been observed [*Ruohoniemi and Greenwald*, 1995; *Milan et al.*, 2001], but no explanation was given of the cause. *Benkevich et al.* [2000] suggested a model for the ionospheric control of inter-hemispheric FACs, however this model does not account for the field-aligned potential

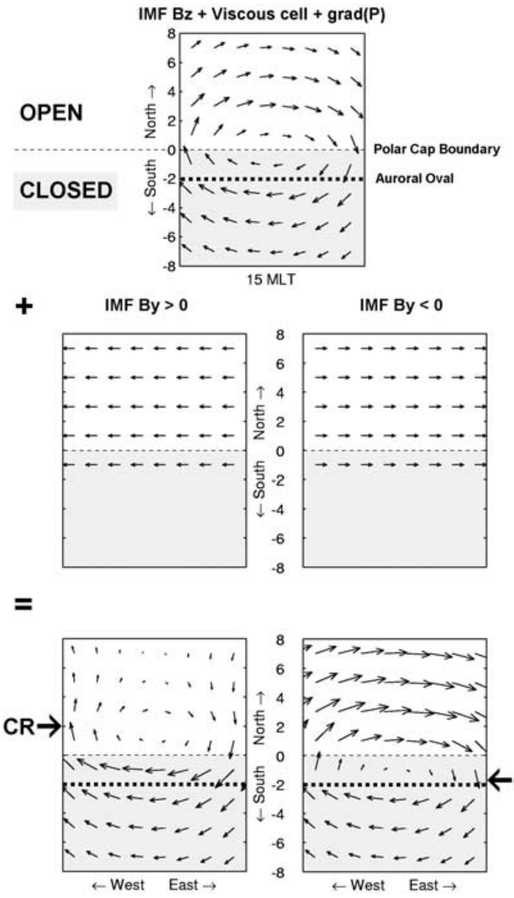

Figure 4. Sketch illustrating the IMF By control of ionospheric convection patterns. Top panel shows convection for small (near-zero) values of IMF By. Middle panels show azimuthal plasma flows generated due to IMF By > 0 (left) and IMF By < 0 (right). Bottom panels show the sums of the top and middle patterns. Shaded areas indicate regions related to the closed magnetosphere.

drop. Thus, the seasonal effect can be a matter of future studies, both experimental and theoretical.

5. Conclusions

[13] IMF By has an important influence on the ionospheric convection on closed magnetic field lines. Due to the solar wind-magnetosphere dynamo, IMF By generates an electric potential difference between the two polar caps, so that field-aligned currents flow between the hemispheres within a layer equatorward of the open polar cap boundary. In this region a field-aligned potential difference (i.e., a magnetic field line discontinuity) can occur when the field-aligned current exceeds a threshold in magnitude. The IMF By-related ionospheric plasma flows are opposite in the northern and southern hemispheres, however they can co-exist within the region of the inter-hemispheric field-aligned currents. The latitudinal width of this region depends on the IMF By and the ionospheric conductance, and can be of the order of 1–2 degrees in latitude. Predictions of the suggested model agree well with the SuperDARN observations of the ionospheric convection patterns presented by *Kozlovsky et al.* [2002]. The field-aligned potential drop can result in electron acceleration and precipitation, and therefore IMF By also controls the high-latitude dayside auroral activity.

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