The Connection Between Transpolar Arcs and Magnetotail Rotation

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Abstract. Recent observations show that the evolution of transpolar arcs (TPA's) are often associated with a sign change of the dawn-dusk component of the interplanetary magnetic field (IMF). It is known that a nonzero IMF B_y causes a twist of the tail plasma sheet. In this study it is assumed that a sign change of IMF B_y causes the magnetotail to rotate until the entire tail is twisted in the opposite direction. To examine a possible connection between TPA's and tail rotation the Tsyganenko 1989 model is modified such that the near-Earth tail and the far tail are twisted in opposite directions. Mapping from the tail current sheet to the ionosphere shows a separated region of closed field lines that extends into the polar cap. This separated part may be interpreted as the mapped region of a TPA.

Introduction

Since the first global observation of transpolar arcs (TPA's) [*Frank et al.*, 1982] there have been many studies on this subject. While the source region of small-scale polar arcs remains unclear [e.g., Bonnell et al., 1999] TPA's are commonly believed to map to the tail plasma sheet or its boundary layer [e.g., *Frank and Craven*, 1988]. Different topologies of the magnetotail have been proposed for TPA events. The plasma sheet has been suggested to be bifurcated [*Frank and Craven*, 1988], to have filamentary extensions into the lobes [*Huang et al.*, 1987] or to be asymmetrically expanded [*Meng*, 1981]. Alternatively, a significant 'distortion' in the mapping along B-field lines has been suggested [*Blomberg and Marklund*, 1993].

Observations indicate that the evolution of a TPA depends strongly on the direction of the IMF. Polar arcs are predominantly a northward IMF phenomenon [e.g., *Valladares et al.*, 1994]. In the statistical study by *Valladares et al.* [1994] it is shown that the dawn-dusk motion of polar arcs is strongly dependent on the sign of IMF B_y. This result is in agreement with observations which report that TPA's move in the direction of IMF B_y [e.g., *Cumnock et al.*, 1997]. There is some evidence that TPA's occur simultaneously in the northern and southern polar cap but with opposite dawn-dusk motion [*Craven et al.*, 1991]. Different IMF initial conditions have been suggested to generate TPA's [*Chang et al.*, 1998]. In the model of *Kan and Burke* [1985] that describes TPA's which evolve from midnight to noon, a purely northward IMF is required. TPA's splitting from the dawnside or duskside of the oval have been observed to occur after a sign change of IMF B_y during northward IMF [*Cumnock et al.*, 1997] or, alternatively, a southward turning of an initially northward IMF during changing IMF B_y [*Newell and Meng*, 1995].

In this paper the IMF configuration proposed by *Cumnock et al.* [1997] is addressed. Based on their results, a different topology of the magnetotail is suggested which may help to explain the evolution of TPA's appearing after a sign change of IMF B_y.

Observations

The latest results by Cumnock [private communication] are that a sign change of IMF B_y during northward IMF often triggers the evolution of a TPA (Figure 1) which lasts for several hours. The evolution of the TPA can be described in four steps: (1) A dawnward (duskward) IMF is connected to a dawnward (duskward) expansion of the auroral oval. (2) A sign change of IMF B_y causes a TPA to separate from the side of the oval which is expanded poleward. (3) In case the IMF B_y remains constant the TPA moves poleward. (4) Often, the TPA fades away after having crossed the noon-midnight line. In the final configuration, the opposite side of the oval is expanded poleward.

It has been shown that IMF B_y partially penetrates the magnetotail and causes a twist of the entire tail [e.g., *Kaymaz et al.*, 1994]. The tail is positively twisted (counter-clockwise in the yz-plane looking from the Earth downtail) for positive IMF B_y and negatively twisted for negative IMF B_y. Positive and negative IMF B_y have qualitatively similar but anti-symmetrical effects on the magnetotail topology. Thus, the difference of type and occurrence frequency of polar arcs for dawnward and duskward IMF [*Gussenhoven*, 1982] perhaps does not have its cause in the topology of the tail. The model presented in this study produces symmetric mapping results for positive and negative IMF B_y as it shows only those ionospheric regions which map to the tail plasma sheet. For simplicity only the IMF sign change from dawnward to duskward is considered in this work but the result is also valid for the opposite case.

Assumptions

This work is based on the assumption that a sign change of IMF B_y affects the magnetotail to change its twist first in the near-Earth region and then farther down the tail (Figure 2). The process can be described in four steps: (1) For negative IMF B_y the tail is negatively twisted. (2) A sign change of IMF B_y from negative to positive influences first the near-Earth tail. The near-Earth tail rotates to a positive twist whereas the far tail remains negatively twisted. (3) With time the rotation of the tail propagates tailward. The region of the tail having a positive twist thus expands. (4) Finally the entire tail becomes positively twisted. The change of the tail topology during a sign change of IMF B_y is assumed to correspond to the evolution of a TPA in the ionosphere (above described). The TPA persists as long as the tail twist changes polarity. The tailward propagation of the twist reversal region is supposed to be connected to a dawn/dusk movement of the TPA. As the tail rotation is completed the TPA should fade away.

The model

To examine the connection between TPA's and tail rotation the *Tsyganenko* [1989] model (T89) is modified such that the near-Earth tail is twisted positively whereas the far tail is twisted negatively representing an IMF B_y sign change from negative to positive. An extension of the T89 model to include the effects of constant IMF B_y has already been done by *Kullen and Blomberg* [1996]. They demonstrated that the poleward expansion of the auroal oval is connected to a twist of the magnetotail by adding nonuniform B field components (B_x^*, B_y^*, B_z^*) to the T89 model B-field to represent the penetration B-field and the twist of the plasma sheet, respectively:

$$B_x^* = B_y^{\mathrm{IMF}}[-c_3 y - \tfrac{2c_2 b_3}{b_2^2} y e^{-(\frac{y}{b_2})^2} e^{\frac{x}{b_3}}]$$
$$B_y^* = B_y^{\mathrm{IMF}}[c_1 e^{-(\frac{z}{b_1})^2} + c_2(1 - e^{-(\frac{y}{b_2})^2})] e^{\frac{x}{b_3}}$$
$$B_z^* = 0$$

The coefficients $b_1 = 8\mathrm{R_E}$, $b_2 = 20\mathrm{R_E}$, $b_3 = 20\mathrm{R_E}$, $c1 = 1.3$, $c2 = 0.7$ and $c_3 = 0.04\mathrm{R_E^{-1}}$. were chosen to fit the tail twist and the B_y penetration field of the model to the results of a data study by *Kaymaz et al.* [1994]. For further details see *Kullen and Blomberg* [1996]. To get opposite twists of the near-Earth tail and the far tail the added B-field components have to change polarity at some point x_0 in the tail. *Akasofu and Roederer* [1983] showed that an abrupt change of IMF B_y would lead to a splitting of the polar cap into two regions. Since they modeled only a uniform B_y penetration field and not a tail twist, they needed an unrealistically strong IMF B_y. Including a tail twist in the model of this study excludes an abrupt change of the superimposed B-field. The tail would be twisted differently on both sides of the discontinuity sheet (div $\mathbf{B} \neq 0$). Thus, the added B-field components are changed smoothly from positive to negative over a given area, Δx. We represent this smooth change by a tanh function:

$$\begin{aligned}
B_x^{'} &= B_x^{*} \tanh(\tfrac{2(x-x_0)}{\Delta x}) \\
B_y^{'} &= B_y^{*} \tanh(\tfrac{2(x-x_0)}{\Delta x}) + \tfrac{2}{\Delta x}[1 - \tanh^2(\tfrac{2(x-x_0)}{\Delta x})] \times \\
&\quad B_y^{\mathrm{IMF}}[\tfrac{c_3}{2} y^2 - c_2 b_3 e^{-(\frac{y}{b_2})^2} e^{\frac{x}{b_3}}] \\
B_z^{'} &= 0
\end{aligned}$$

where x_0 represents the center of the area over which the sign change takes place and Δx the width of it. Since B_x now has a second x-dependence an additional term has to be added in the yz-plane to obtain a divergence free B-field. Independent of the choice of this extra term a splitting of the oval occurs. The splitting is only significant for reasonably low IMF B_y values if the B_y component dominates. Hence, the extra term has been assumed to lie in the y-direction (last term in $B_y^{'}$).

Figure 3 shows plots of the ionospheric regions which are connected to the tail plasma sheet, for different model parameters. The plots are produced by mapping B-field lines from the tail current sheet (defined here as the surface where B_x changes sign) back to Earth. The poleward boundary of this region in the ionosphere represents the approximate location of the poleward boundary of the auroral oval. In order to simulate the conditions of a quiet magnetosphere with a plane neutral sheet, the K_p index and the dipole tilt are set to zero in the model. Figure 3a (right plot) shows the tail current sheet from $-10\mathrm{R_E}$ to $-60\mathrm{R_E}$ (the T89 model is not valid farther downtail) which is color coded to help identify the corresponding areas in the ionosphere. Near the current sheet flanks, only parts of the colored areas belong to the magnetosphere and map to the ionosphere. In Figure 3a (left plot) the mapping to the ionosphere for the unmodified T89 model is shown. Since the mapping is only done from the tail at $x = -10\mathrm{R_E}$ and farther downtail, the dayside part of the oval does not appear in the mapping plots. Also, the far-tail flanks and the far-tail center map to too low latitudes in the ionosphere. The T89 model does not contain a defined magnetopause and the added extra terms in the modified version are not limited in the y or z direction. Thus the model is realistic only inside the magnetosphere.

Results

The mapping plots of Figure 3b, 3c and 3d are obtained for opposite twists of the near-Earth tail and the far tail. All ionospheric plots show a clear splitting of the polewardly expanded oval region. The flank boundaries have been moved 1.5 R_E into the tail to minimize distortions where the TPA connects to the oval. This has a neglectable effect on the location of the open-closed field line boundary. The region of closed field lines which is separated from the main oval may be interpreted as the mapped source region for a TPA, however, the TPA does not necessarily extend over the entire separated part. The topological connection to the plasma sheet is not a sufficient condition for aurora to occur. The main limitation of this model is that the TPA does not stretch over the entire polar cap. This is caused by the mapping from the current sheet for a tailward limited model. Mapping from a surface parallel but above the current sheet produces a deformed 'TPA' which stretches nearly to the dayside oval. Since it is difficult to define a plasma sheet boundary in this model, the current sheet mapping gives more reliable results.

In Figure 3b mappings for different IMF B_y values are plotted. A comparison of these plots with the third plot of Figure 3c shows the influence of the input parameters IMF B_y and Δx on the mapping results. Both a small Δx and a strong IMF B_y lead to a clearer splitting of the TPA from the oval. While strong IMF B_y is connected to a more polewardly located TPA, the influence of Δx on the location of the TPA is negligible. Assuming that Δx is dependent on the time period over which IMF B_y changes sign, the model results indicate that the duration of a TPA event is not influenced by the magnitude of $\partial B_y^{\mathrm{IMF}}/\partial_t$.

In each plot of Figure 3c the region over which the twist reversal takes place is located farther downtail. These mapping plots demonstrate that the separation from the oval and the poleward motion of the TPA can be connected to a tail rotation propagating tailward. The TPA should disappear when the rotation of the tail is completed and the entire tail has returned to the topology typical for a uniform nonzero IMF B_y. This is implicated by the model. The TPA gets thinner and shorter when the twist reversal region is located farther downtail. The tailward propagation of the twist reversal region is assumed to be caused by the tailward progression of the IMF B_y sign change. Since TPA's can last up to several hours either the magnetotail would have to respond extremely slowly to a sign change of IMF B_y or the plasma sheet regions from even the very distant tail would contribute to the TPA.

To get a better understanding of how the splitting of the oval is connected to the tail topology, Figure 3d shows mapping plots of a tail cross section at $x = -20\mathrm{R_E}$ for different locations of x_0. The plots correspond to the ionospheric mapping plots of Figure 3c and show those field lines which map from the current sheet to the northern hemisphere. The splitting of the dawnside oval is connected to a 'bifurcation' of the region of current sheet field lines. The current sheet field lines from the far tail map to much higher latitudes than field lines from the near-Earth tail because the near-Earth and far-tail plasma sheet regions are oppositely twisted.

Some additional features can be found from studying the mapping plots of Figure 3 in more detail. The regions between the TPA and the dawnside and duskside of the auroral oval lie on open field lines. Field lines originating Earthward of x_0 map to the auroral oval whereas field lines originating tailward of x_0 map to the TPA. Since the tail is symmetric about the current sheet, TPA's occur in the model simultaneously in the northern and southern hemisphere but on opposite sides of the noon-midnight line.

Although this model gives only qualitative results it shows that opposing tail twists are likely to play an important role in the development of those TPA's which occur after a sign change of IMF B_y.

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References

Akasofu, S.-I., and M. Roederer, Polar cap arcs and the open regions, *Planet. Space Sci., 31*, 193, 1983.

Blomberg, L.G., and G. T. Marklund, High-latitude electrodynamics and aurorae during northward IMF, *Auroral Plasma Dynamics, Geophys. Monogr. Ser., 80*, 55, 1993.

Bonnell, J. et al., Observations of polar cap arcs on FAST, *J. Geophys. Res., 104*, 12:669, 1999.

Chang, S.-W. et al., A comparison of a model for the theta aurora with observations from Polar, Wind and Super-DARN, *J. Geophys. Res., 103*, 17:367, 1998.

Craven, J.D. et al., Simultaneous optical observations of transpolar arcs in the two polar caps, *Geophys.Res.Lett., 18,* 2297, 1991.

Cumnock, J.A. et al., Evolution of the global aurora during positive IMF Bz and varying IMF By conditions, *J. Geophys. Res., 102*, 17:489, 1997.

Frank, L.A. et al., Polar view of the Earth's aurora with dynamic explorer, *Geophys. Res. Lett., 9*, 1001, 1982.

Frank, L.A., and J.D. Craven, Imaging results from Dynam-

ics Explorer 1, *Rev. Geophys., 26*, 249, 1988.
Gussenhoven, M.S., Extremely high latitude auroras, *J. Geophys. Res., 87*, 87, 2401, 1982.
Huang, C.Y. et al., Filamentary structures in the magnetotail lobes, *J. Geophys. Res., 92*, 2349, 1987.
Kan, J.R., and W.J.Burke, A theoretical model of polar cap auroral arcs, *J. Geophys. Res., 90*, 4171, 1985.
Kaymaz, Z. et al., Interplanetary magnetic field control of magnetotail magnetic field geometry: IMP 8 observations, *J. Geophys. Res., 99*, 11:113, 1994.
Kullen, A., and L.G. Blomberg, The influence of IMF By on the mapping between the Earth's magnetotail and its ionosphere, *Geophys. Res. Lett., 23*, 256, 1996.
Meng, C.-I., Polar cap arcs and the plasma sheet, *Geophys. Res. Lett., 8*, 273, 1981.
Newell, P.T., and C.-I. Meng, Creation of theta-auroras: The isolation of plasma sheet fragments in the polar cap, *Science, 270*, 1338, 1995.
Tsyganenko, N.A., A magnetospheric magnetic field model with a warped tail current sheet, *Planet. Space Sci., 37*, 5, 1989.
Valladares, C.E., H.C. Carlson Jr. and K. Fukui, Interplanetary magnetic field dependency of stable Sun-aligned polar cap arcs, *J. Geophys. Res., 99*, 6247, 1994.

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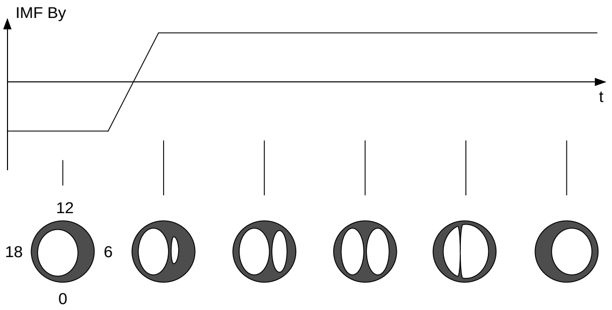

Figure 1. TPA evolution for a sign change of IMF B_y.

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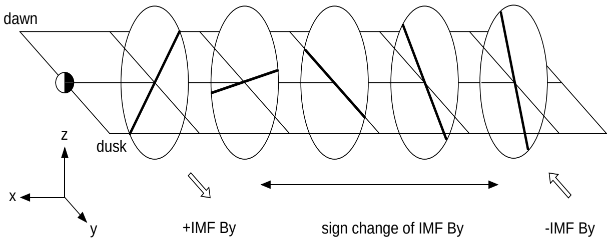

Figure 2. Tail rotation for a sign change of IMF B_y.

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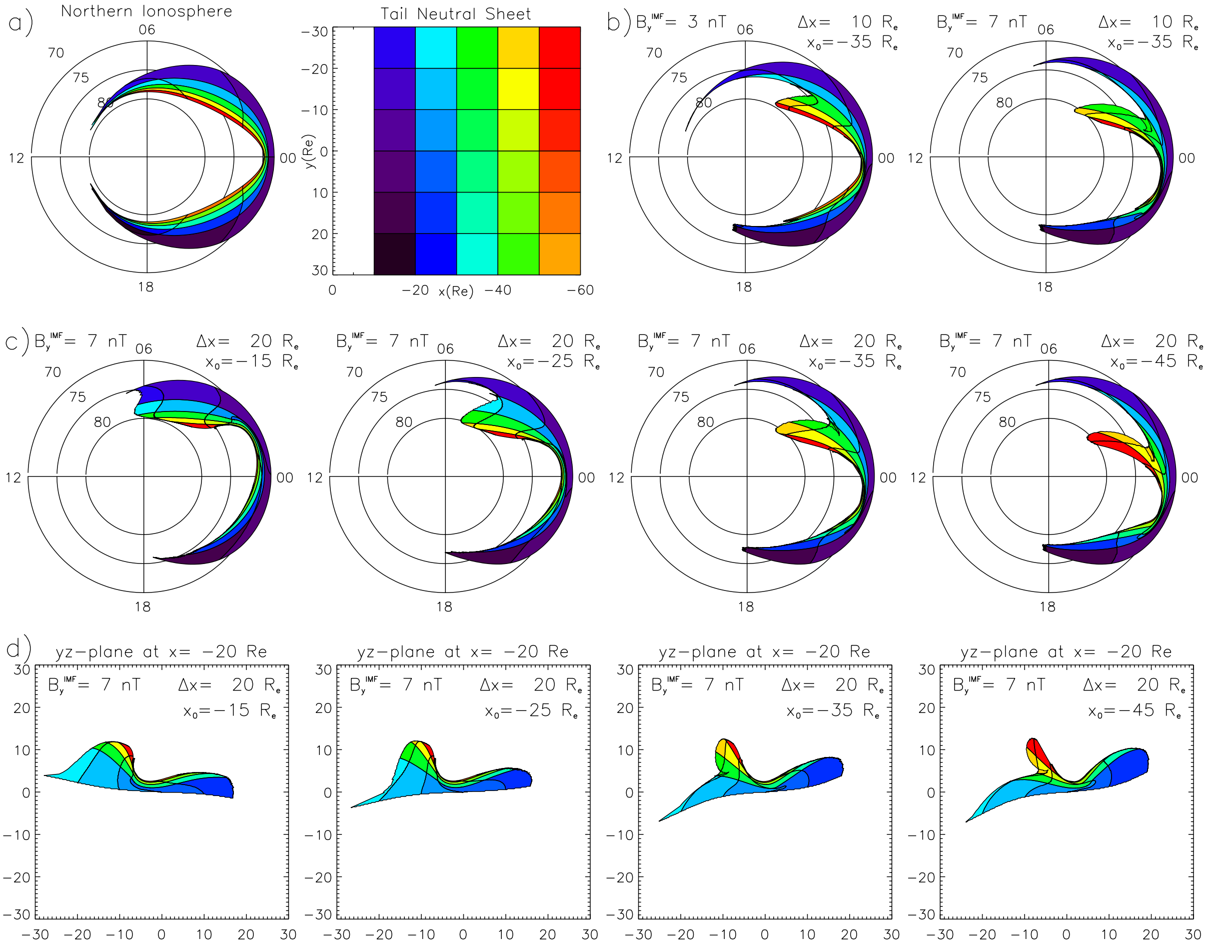

Figure 3. Field line mapping from the tail current sheet (B_x sign reversal) to the ionosphere for a) the unmodified T89 model (IMF $B_y = 0$), b) different strengths of IMF B_y for a narrow twist reversal region Δx, c) the twist reversal region being located farther downtail at each plot with a medium Δx and d) field line mapping from $x = -20\mathrm{R_E}$ and downtail to the tail cross section at $x = -20\mathrm{R_E}$ for those field lines which map to the northern ionosphere (the cross section plots correspond to the ionosphere plots of Figure 3c).

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