GEOPHYSICAL RESEARCH LETTERS, VOL. 25, NO.16, PAGES 3083-3086, AUGUST 15, 1998

Conjugacy of geomagnetic disturbances and the substorm current wedge

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Abstract. The conjugacy of geomagnetic phenomena at high latitudes in the northern and southern hemispheres is investigated using observations of the geomagnetic field variations. Similar the magnetic disturbances at the poleward edge of the auroral oval night sector were observed in both hemispheres. These results show that magnetic field lines at the periphery of the plasma sheet are closed and that processes leading to the appearance of magnetic disturbances are similar in conjugate regions. Modeling of geomagnetic field line structure has shown that field lines are closed up to a distance of several dozens of Earth radii during the existence of the tail current wedge. The region of closed field lines maps to the nightside ionosphere up to ~ 80° geomagnetic latitude.

Introduction

Akasofu [1968] has summarized observations of aurorae and magnetic disturbances at auroral latitudes in geomagnetically conjugate regions during magnetospheric substorm intervals. Conjugate discrete aurorae have similar forms and movements, brightening and decaying simultaneously. The magnetic field variations are strikingly similar, too. These observations indicate that energetic electron precipitate along magnetic field lines into the upper atmosphere and auroral electrojets in geomagnetically conjugate regions are caused by the same magnetospheric source. Moreover, geomagnetic field lines mapping to the night sector of the auroral oval are closed.

Simultaneous auroral observations in the high latitudes of both hemispheres have become possible with the advent of global far ultraviolet (FUV) images from the Viking and Dynamics Explorer-1 satellites. The first results of such a comparison, for the transpolar band observed on August 3, 1986, were presented by *Craven et al.* [1991]. *Vorobjev et al.* [1995] described this band's dynamics and showed that the band had a complicated structure consisting of three parallel arcs. These arcs were connected with the main auroral oval by continuous precipitation [*Feldstein et al.*, 1995]. The interpretation of the polar arcs as the result of the expansion of plasma sheet precipitation into the very high latitudes has been obtained by [*Meng*, 1981; *Makita et al.*, 1991]. Multisatellite observations of auroral energy plasma precipitation show that the transpolar band is located on closed magnetic field lines.

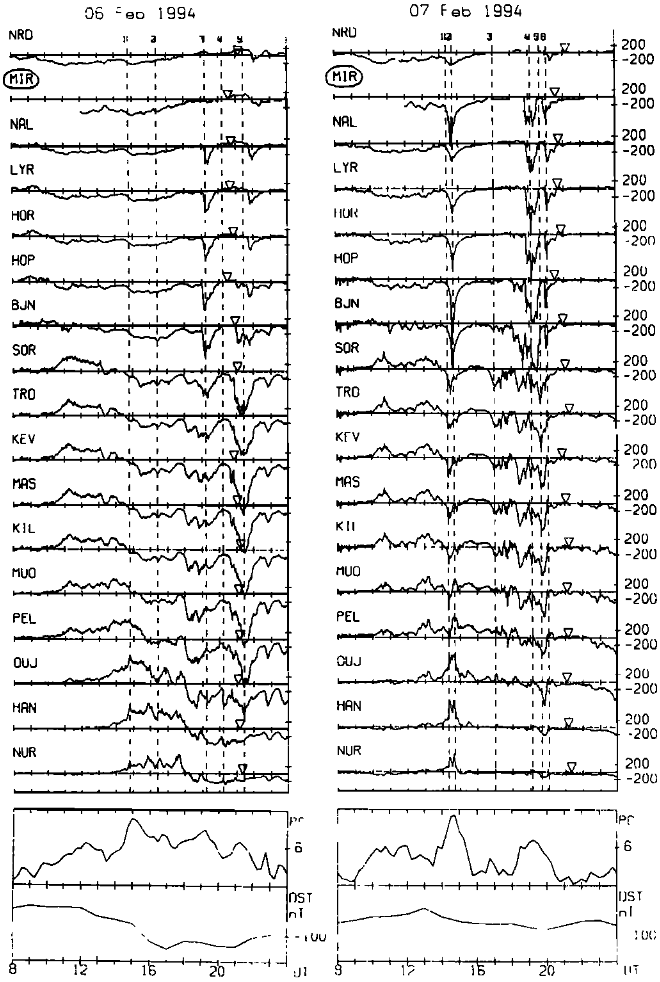

Figure 1. Variations of the magnetic field X' component along the IMAGE chain during the storm main phase on February 6-7, 1994 (at the top). Dotted vertical lines correspond to UT's with latitudinal cross-sections of the X' and Z components presented further in the text. The Dst and the PC indices of the magnetic field variations for the same storm are shown at the bottom. The Antarctic station is marked by circle. The time of MLT midnight at each station is marked by a triangle.

Paper number 98GL02323.
0094-8534/98/98GL-02323$05.00

There is also additional data that shows a correlation of the auroral luminosity in one hemisphere and precipitating auroral electrons in the other hemisphere. For example, *Mizera et al.* [1987] and *Obara et al.* [1988] found that polar arcs in the northern hemisphere are located in the same time sector and at the same geomagnetic latitude as auroral precipitation in the southern hemisphere.

The aim of this investigation is to analyze the magnetic disturbances at the poleward edge of the auroral oval during a magnetic storm in the northern hemisphere and to compare their intensity with magnetic disturbances in the conjugate region of the southern hemisphere. We used data from the IMAGE (International Monitor Auroral Geomagnetic Effects) meridian chain of magnetometers (near geomagnetic meridian 110°) in Scandinavia extending from Nurmijarvi (corrected geomagnetic latitude $\Phi \sim 57°$) to Ny Ålesund ($\Phi \sim 76°$) and Nord station in Greenland ($\Phi \sim 81°$) and from Mirny station in the southern hemisphere ($\Phi \sim 77°$) which is located on nearly the same geomagnetic meridian as the IMAGE chain.

Results of the observations

Figure 1 shows variations in the X' component of the geomagnetic field (the northward component in the geomagnetic meridian direction) along the IMAGE chain and for Mirny station during the magnetic storm of February 6-7, 1994. Vertical dotted lines mark the latitudinal cross-sections for which the quantitative comparisons of the intensity of geomagnetic field variations were made. The hourly *Dst* index and the fifteen-minute *PC* index variations are plotted in the bottom panel of Figure 1. From these magnetograms one can see that the geomagnetic variations at Mirny are similar to the expected variations at the conjugate latitudes of the northern hemisphere between Ny Ålesund and Nord stations. One should also note that there is a time delay of the magnetic disturbance peak at the high latitudes with respect to the auroral zone.

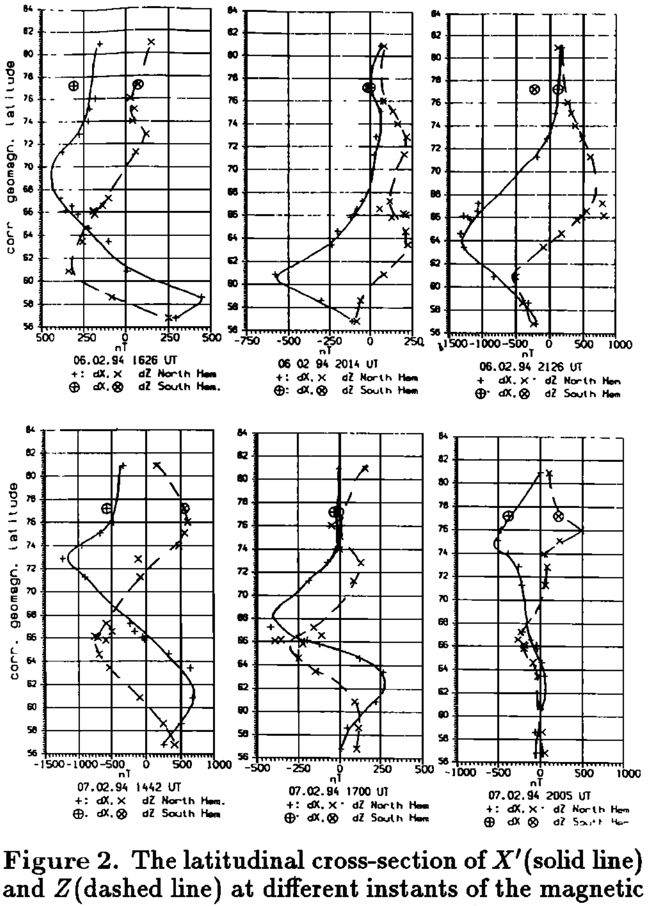

Figure 2. The latitudinal cross-section of X'(solid line) and Z(dashed line) at different instants of the magnetic storms: 1626, 2014, and 2126 UT on February 6, 1994 (top panel), and through different types of the westward electrojet: 1700 and 2005 UT on February 7, 1994.

Figure 2 shows the latitudinal cross-sections of X' and Z (solid and dashed lines correspondingly) at the key times during the magnetic storm:

- at the maximum of the storm at 1626 UT on February 6;
- during the quiet interval between substorms at 2014 UT;
- at substorm maximum at 2126 UT.

Southern hemisphere station is marked by circle.

The cross-sections at 1700 UT and 2005 UT on February 7 characterize the intensity distribution of the magnetic field disturbances for two different types of westward electrojet, namely, only at auroral zone latitudes (1700 UT) or at higher latitudes (2005 UT). The intensity of magnetic variations at Mirny is the same as at the conjugate latitudes in the northern hemisphere.

Therefore, substorm development is practically similar in both the northern and the southern hemispheres up to geomagnetic latitudes 78°–82°, the poleward limit of the region to which disturbances from auroral oval latitudes propagate. We can say that conjugacy of geomagnetic phenomena is observed even up to the poleward edge of the auroral ovals in both hemispheres.

Results of magnetic field modeling

The similarity in the magnetic field variations and the good correlation of their intensity in both hemispheres at latitudes 77°–82° suggest that the magnetic field lines are closed even at these high latitudes.

Because magnetic field lines at auroral latitudes are definitely closed, the poleward expansion of disturbances is usually interpreted as a consequence of reconnection of initially open magnetic field lines in the tail and the further dipolarisation of closed field lines, i.e., the sudden change from a stretched magnetospheric tail configuration to a quasi-dipolar one. Thus the field lines mapping to Mirny latitudes are probably closed.

Figure 3 presents results of modeling using two external magnetic field models: *Tsyganenko's* [1995] model (top panel) and the paraboloidal model of *Alexeev et al.* [1996] (bottom panel). Input parameters of Tsyganenko's model are the solar wind dynamic pressure (P_{dyn}), index *Dst*, the interplanetary magnetic field components B_y and B_z, and the geodipole tilt angle ψ. For Alexeev's model, input parameters include the geocentric distances to the subsolar point on the magnetopause (R_1) and to the inner edge of the current sheet in the magnetospheric tail (R_2), the magnetic flux in the magnetospheric tail lobe (Φ_∞), and the geodipole tilt angle ψ. For the latitudinal cross-section at 2126 UT on February 6, 1994, the geomagnetic latitudes of the equatorward (61°, "1") and poleward (68°, "3") boundaries and the center (64°, "2") of the electrojet were obtained. The magnetic field lines from these lat-

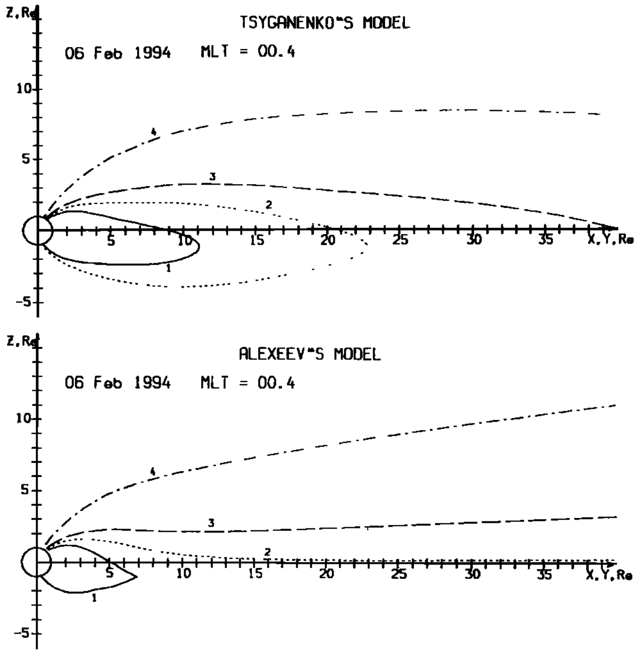

Figure 3. Mapping of the equatorial (1) and poleward (3) boundaries of the westward electrojet and its center (2) into the magnetosphere using the models of *Tsyganenko* [1995] (top panel) and *Alexeev et al.* [1996] (bottom panel); the magnetic field line mapping from $\Phi = 77^\circ$ is marked as (4). The electrojet parameters are defined from the 2126 UT cross-section on February 6, 1994.

itudes and the point conjugate to Mirny station in the northern hemisphere (77°, "4") were mapped into the magnetosphere.

The magnetic field line mapping from the poleward boundary of the westward electrojet is open according to both models, as is also the magnetic field line mapping from $\Phi = 77^\circ$. Hence, neither model confirms magnetic field lines closing at such high latitudes during disturbances.

This result can be the consequence either of the absence of geomagnetic conjugacy at $\Phi \sim 77^\circ$, or of the inadequacy of the models in representing real magnetospheric conditions during disturbances. In particular, the character of field lines in the nightside magnetosphere can change drastically as a result of the emergence of the current wedge. Figure 4 shows magnetic field structure on February 6, 1994, based on *Tsyganenko's* [1997] model for the same UT as Figure 3. Field lines were modeled allowing for the magnetic field of the current wedge with an integrated current magnitude of 10^6 A, initial radius of the current loop $r_0 = 4.85R_e$, and ratio between r_0 and the radius of the current loop during the substorm r_s equal to 0.2. It follows from Figure 4 that the whole electrojet maps to the tail in the closed magnetic field line region at $\leq 16R_e$ geocentric distance. Even the field line with footprint at 77° is closed, although it maps into the tail out to $68R_e$. Thus, the emergence of a current wedge during disturbances allows us to interpret the observed conjugacy of geomagnetic disturbances up to very high latitudes in the framework of existing magnetospheric magnetic field models.

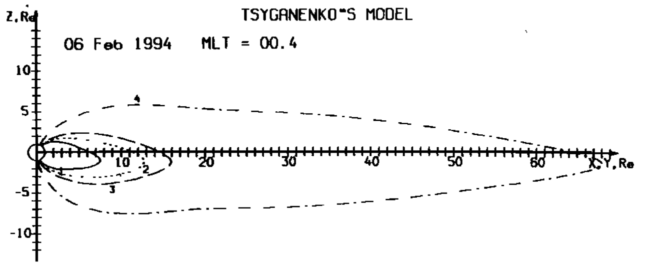

Figure 4. Magnetic field lines structure on February 6, 1994, based on *Tsyganenko's* [1997] model for the same UT as Figure 3, but taking into account the emergence of the current wedge with integral current magnitude of 10^6A.

The dynamics of the magnetic field line mapping of the westward electrojet boundaries and center during substorm development has been studied for the February 7, 1994, substorm in which the geocentric distance of the current wedge r_s increases from $6.2R_e$ to $25R_e$. Figure 5 shows the results of modeling of the magnetic field line structure. These two static models characterize the change in the structure of the nightside magnetosphere during the shift of westward electrojet center from auroral latitudes to $\Phi \sim 75^\circ$ during the substorm active phase. The sequence of these models with changing input parameters may represent a considerably detailed description of the geomagnetic field structure dynamics. Figure 5 shows that the geocentric distance of the electrojet equatorial boundary does not effectively change. The center of the westward electrojet moves to the distant magnetospheric tail but it is still located on closed magnetic field lines.

This paper does not aim to demonstrate the possibility of using geomagnetic variations for the determination of Λ_c (the outer boundary of the region with closed but stretched downtail field lines). Our purpose has been to show the existence of conjugacy up to very high latitudes and to show that field lines should be closed at such high latitudes according to existing models. Determinations of Λ_c with considerable accuracy may be obtained using satellite observations of auroral electron precipitation into the upper atmosphere.

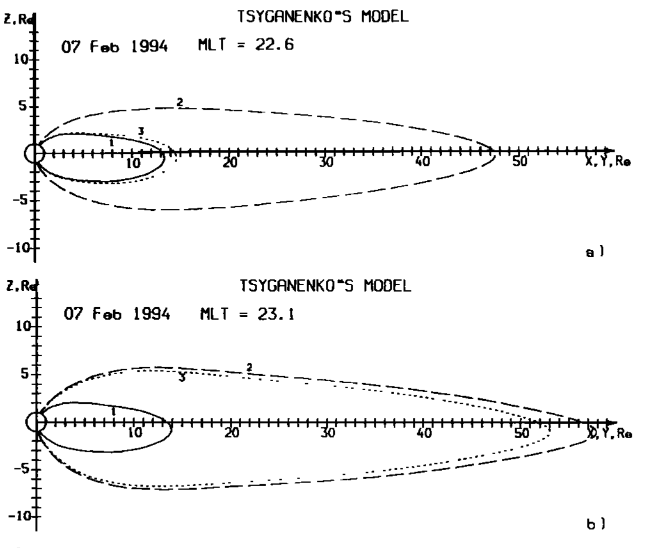

Figure 5. Magnetic field line structure on February 7, 1994, based on *Tsyganenko's* [1997] model, taking into account the emergence of the current wedge at (a) 1940 UT , $r_s = 6.2R_e$; (b) 2005 UT, $r_s = 25R_e$

Such precipitation structures and the method of identifying the boundaries of different plasma domains have been studied by *Galperin and Feldstein* [1991, 1996] and *Newell et al.* [1996].

Conclusions

1. The character and the intensity of geomagnetic variations at the poleward boundary of the auroral ovals in the northern and southern hemispheres are similar.

2. This similarity suggests that magnetic field lines are closed at these high latitudes. However, according to the contemporary models of magnetospheric magnetic fields by *Tsyganenko* [1995] and *Alexeev et al.* [1996], the magnetic field lines mapping from these high latitudes are open.

3. Magnetic field lines in the nightside magnetosphere can become closed up to very high geomagnetic latitudes, if the emergence of the current wedge during disturbances is taken into account using the model of *Tsyganenko [1997]*.

Acknowledgments. This work has been supported by grants RFBR 96-05-65067 and 96-05-66279, INTAS- RFBR-95-0932. We are thankful to T. Lui for discussions of the problem of closed magnetic field lines, N. Tsyganenko for current wedge software, V. Papitashvili for sharing data from the stations Komsomolskaya and Mirny, and DMI for Nord station data. We appreciate very much fruitful discussions with H. Luehr. We are grateful to the IMAGE magnetometer chain teams. We are very thankful to the volunteer copyeditor Dr. J. Rodriguez.

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(Received March 22, 1998; revised June 01, 1998; accepted June 05, 1998.)