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Auroral conjugacy studies based on global imaging

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Abstract

Simultaneous global imaging in the ultraviolet wavelengths by IMAGE and Polar, enable us to examine auroral features in the conjugate hemispheres. With an imaging cadence of 2 and 1 min for IMAGE-FUV and Polar VIS Earth camera, respectively, we have examined dynamic features such as substorm onsets and cusp precipitation as well as slowly varying phenomena such as theta aurora. In this paper, we review the main findings from these studies and present new evidence of the IMF clock angle control of the asymmetric substorm onset locations. Simultaneous images from the opposite hemispheres show asymmetric cusp auroras and their locations are controlled by IMF B_y and dipole tilt angle. Our imaging results demonstrate that theta aurora can be a non-conjugate phenomenon. We suggest that IMF B_x controls in which hemisphere the theta aurora occurs. For substorm onset locations, we have found that there exists a systematic displacement in one hemisphere compared to the other. The relative displacement of onset locations in the conjugate hemispheres is found to be controlled primarily by the IMF clock angle. Compared with some of the existing magnetic field models, the observed asymmetries are an order of magnitude larger than the model predictions. Statistical distribution of substorm onset locations in the southern and northern hemispheres for different clock angles enables us to validate the IMF clock angle control. Based on ~3000 substorm onsets in the northern hemisphere and ~1000 in the southern hemisphere observed by IMAGE we find a remarkable support for our previous findings.

Keywords: Conjugate imaging; Cusp aurora; Theta aurora; Substorm location; Magnetospheric configuration; IMF control

1. Introduction

The general picture of the Earth's magnetic field has been well established and its response to varying solar wind conditions can now be modeled fairly sophisticatedly based on huge statistical data sets (Tsyganenko, 2002a, b). However, to understand *how* the energy transfer from the solar wind into the Earth's magnetosphere, the different types of aurora and the electro-magnetics in the northern and southern hemispheres can be of different intensities, asymmetric or even non-conjugate, we need simultaneous conjugate measurements. In situ conjugate measurements from space are very hard to obtain, because you do not know if you really are on conjugate field lines. Conjugate imaging from

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ground is difficult because you need clear sky and asymmetries that are less than the field of view of the all-sky cameras (Sato et al., 1986). For these reasons, conjugate simultaneous global imaging from space is really what can resolve the degree of conjugacy and non-conjugacy of auroral phenomena. Since the beginning of the space age, only twice have we had two spacecraft with imagers that could provide such data. In the mid-1980s, Viking (Murphree and Cogger, 1988) and Dynamic Explorer 1 (Frank et al., 1981) gave us the very first simultaneous global imaging from space. Despite a large difference in time resolution (12 min and 20 s) these unique observations were very good to study slowly varying aurora, like e.g., the discovery that theta aurora could be a conjugate phenomenon (Craven et al., 1991). Fifteen years passed before the apsidal precession of the Polar spacecraft orbit and the large field of view of the Polar VIS Earth camera (Frank et al., 1995) and the IMAGE-FUV instruments (Mende et al., 2000) offered a new opportunity to observe the aurora simultaneously in the conjugate hemispheres. With an imaging cadence of 2 and 1 min for IMAGE-FUV and Polar VIS Earth camera, respectively, we have examined both dynamic features such as substorm onsets and cusp precipitation as well as slowly varying phenomena such as theta aurora (Østgaard et al., 2003, 2004, 2005a,b). In this paper, we review the main findings from these studies and present new evidence of the interplanetary magnetic field (IMF) clock angle control of the asymmetric substorm onset locations.

2. Observations

While VIS Earth camera is a UV camera (OI emissions at 130.4 nm) to support the visible camera on board Polar, IMAGE-FUV imaging system provides auroral images in three different wavelength bands. The wide-band imaging camera (WIC) covers 140–190 nm, which are N_2 and N emissions and the spectrographic imager (SI) has two channels; one centered at 135.6 nm (SI13) to detect OI emissions and one centered at 121.8 nm (SI12) to image proton aurora. By blocking out the geocorona and measuring the Doppler-shifted Lyman-α, SI12 makes images of energetic proton precipitation only (Mende et al., 2000). As both the VIS Earth camera, the IMAGE-FUV WIC and SI13 are detecting emissions lines that are produced mainly by secondary electrons, the produced intensities are proportional to the total energy flux of protons and electrons. Usually, this means that they are mainly produced by electrons, unless the energy flux of protons is comparable to the energy flux of electrons. Thus, the IMAGE-FUV system enables a determination of the relative importance of proton and electron precipitation. As emissions in the FUV range are differently affected by O_2 absorption the relative intensities of the various emission lines depend on how deep in the atmosphere they are produced. In other words their relative intensities depend on the energy of the incoming electrons. Simultaneous images from WIC and SI13 can therefore be used to estimate the average energy of the precipitating electrons. Exposure times (cadences) are 10 s ($\sim$2 min) and 32.5 s ($\sim$1 min) for IMAGE SI12/13 and VIS Earth camera, respectively. For the mapping to apex magnetic coordinates (Richmond, 1995), i.e., we assume production altitude of 130 km. The apex coordinate system is based on the Definite/International Geomagnetic Reference Field (DGRF/IGRF) and does not take into account any asymmetries imposed by external fields.

2.1. Cusp aurora

Encouraged by the findings of a bright cusp aurora (Milan et al., 2000; Frey et al., 2002, 2003) we searched the IMAGE-FUV and VIS Earth Camera data for conjugate images of this spot. Although, the orbits of the two spacecraft were such that, from 2000 to 2003, imaging of the conjugate hemispheres simultaneously were possible, we only found 15 min of data, where the bright spot from high-latitude reconnection could be identified simultaneously in both hemispheres. The reason for this is that we need sustained northward IMF, high solar wind pressure and the two spacecraft in right locations and finally that the signal from the spot must be distinguishable from day-glow in both hemispheres. These very first simultaneous images (see Fig. 1c) of the cusp aurora (blue circles) in the opposite hemispheres were reported by Østgaard et al. (2005a) and their findings can be summarized as follows; the cusp spot is seen as the ionospheric footprint of high latitude lobe reconnection, giving strong evidence of the IMF and dipole tilt angle effects on the cusp location. The longitudinal asymmetry is controlled by the IMF B_y, while the latitudinal shift is consistent with dipole tilt angle effects (Bobra et al., 2004).

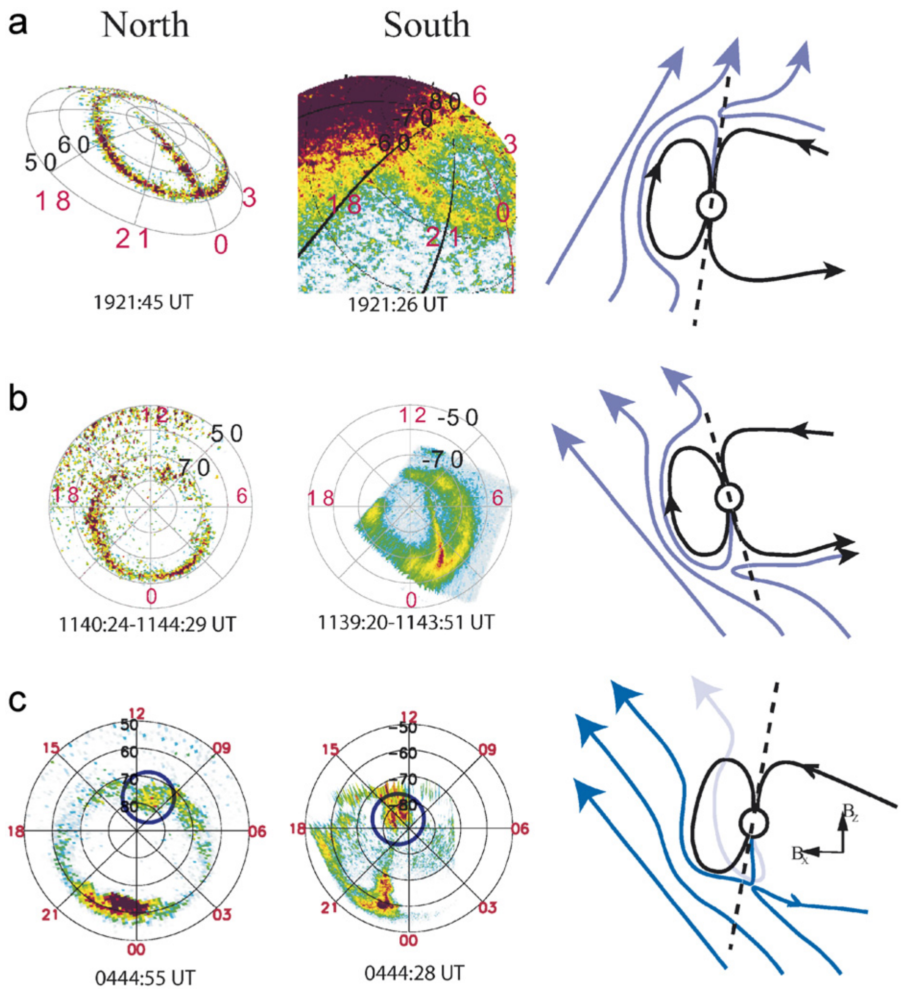

Fig. 1. Three observations of non-conjugate theta aurora. (a) theta only in the northern hemisphere (b)–(c) theta only in the southern hemisphere. (a)–(c) left column: IMAGE-FUV SI13, middle column: VIS Earth Camera, right column: reconnection geometry based on ACE IMF data and actual dipole tilt angle.

2.2. Theta aurora

Based on imaging data from the conjugate hemispheres by DE1 and VIKING Craven et al. (1991) showed that theta aurora could be a conjugate phenomenon. However, our simultaneous IMAGE and Polar images have demonstrated (Østgaard et al., 2003, 2005a) that theta aurora also appears to be a non-conjugate phenomenon. Fig. 1 shows three examples of non-conjugate theta aurora. In the column to the right we have sketched the magnetic reconnection geometries based on data from ACE and the actual dipole tilt angles to indicate in which hemisphere the reconnection would be most efficient. All the three events are associated with polarity changes in IMF B_y. Inferred from DMSP passes the theta arcs in Fig. 1a and b were both observed at the convection reversal boundary of the lobe convection cell in agreement with others (e.g., Cumnock et al., 2002; Carlson and Cowley, 2005). The ion measurements strongly indicate closed field lines. Unfortunately, we have no good DMSP passes for the last case. To explain our observations we have suggested (Østgaard et al., 2003, 2005a) that the flow shears associated with the convection reversal produces electric fields that easily can accelerate electrons to ~1 keV in agreement with DMSP electron data. The driver of the convection cells is the lobe reconnection and the sign of the B_x

component can explain why the flow shears are large enough in one hemisphere but not in the other to produce these electric fields. An alternative explanation is that the theta aurora may be suppressed in one hemisphere due to different exposure to solar EUV radiation. However, the non-conjugate aurora on September 18, 2000 contradicts this explanation. Although both the conjugate theta reported by Craven et al. (1991) and the three non-conjugate thetas reported by us are all consistent with an IMF B_x control of the occurrence of theta aurora we emphasize that more observations of non-conjugate theta are needed to resolve this.

2.3. Substorm onset location

In the open magnetospheric model the IMF is assumed to be an important controlling factor of solar wind-magnetosphere coupling. Theoretical considerations have suggested (Toffoletto and Hill, 1989; Cowley et al., 1991) and observations have indeed shown that the IMF penetrates the outer (Sibeck, 1985) as well as the inner (Wing et al., 1995) magnetotail. The partial magnetospheric penetration (Toffoletto and Hill, 1989) of the IMF has consequently been implemented in the empirical magnetic field models of Tsyganenko; T96 (Tsyganenko, 1995) and T02 (Tsyganenko, 2002a, b). It is also well documented that the IMF orientation affects the location of the night-side aurora (Burns et al., 1990; Elphinstone et al., 1990; Stenbaek-Nielsen and Otto, 1997; Sato et al., 1998; Liou et al., 2001; Frank and Sigwarth, 2003). Based on global imaging data Østgaard et al. (2004) determined more quantitatively how the IMF orientation controls the relative displacement of the aurora in the conjugate hemispheres during substorms. In agreement with predictions (Cowley et al., 1991) we found that, for southward IMF, there exists a systematic hemispherical asymmetry which is strongly correlated with the IMF clock angle (the counter-clockwise angle with respect to the northward direction) and that the relative displacement (ΔMLT) can be expressed as a linear function of IMF clock angle ranging from 90° to 270°(i.e., for southward IMF). We interpreted these findings as the magnetic tensions force acting on open magnetic field lines before reconnecting in the magnetotail or simply the IMF penetration of the magnetosphere. Based on a slightly larger data set, Østgaard et al. (2005b) found that the dipole tilt angle may act as a secondary controlling factor (next to the IMF) of the auroral asymmetries in the conjugate hemispheres. This would be consistent with the field aligned currents (FACs) being stronger in the winter than in the summer hemispheres. Such stronger night-side winter FACs was indeed found by Ohtani et al. (2005) but not in the statistical distribution of FACs based on Iridium measurements (Anderson, 2005). We should emphasize that the correlation coefficient for a possible dipole tilt angle effect was relatively poor (0.56) and further studies are needed to see if this effect is real. Another result reported by Østgaard et al. (2005b) was that the two empirical magnetic field models T96 (Tsyganenko, 1995) and T02 (Tsyganenko, 2002a, b) field models replicate qualitatively the IMF induced asymmetries, but underestimate this effect by an order of magnitude. This is an important results with implications for field-line mapping, either to find conjugate points in the two ionospheres or at different locations in the magnetosphere. In a recent paper Sato et al. (2005) reported north–south asymmetries of the aurora that partly support and partly contradict this simple linear function (ΔMLT versus clock angle). It should be noticed, however, that the asymmetries were small, $\Delta \mathrm{MLT} = 0.02 - 0.2$ and such small fluctuations might have other causes (e.g., FAC) than IMF.

To further investigate this asymmetry we have analyzed the substorm onset locations determined by Frey et al. (2004) from IMAGE-FUV images from year 2000 to 2004. This data set comprises 2760 and 978 substorm onset locations from the northern and southern hemisphere, respectively. For each of these substorms we have determined the 10-min-average IMF clock angle from ACE and Wind data time shifted to $-10R_E$ using the propagation method described Weimer (2004). Cases where the clock angle varied more than 40°within the 10-min averaging interval have been excluded. In order to get sufficient statistics we binned the onset locations (MLT) in 60°intervals of IMF clock angles and calculated the average location for substorm onset in each bin for northern and southern hemisphere separately. The number of substorm locations ranges from 92 (southern hemisphere 30°–90°) to 547 (northern hemisphere 90°–150°). Fig. 2a shows the distribution and average onset location in the northern (black) and southern (red) hemispheres for 5 of the 6 clock angle intervals. In Fig. 2b you can see

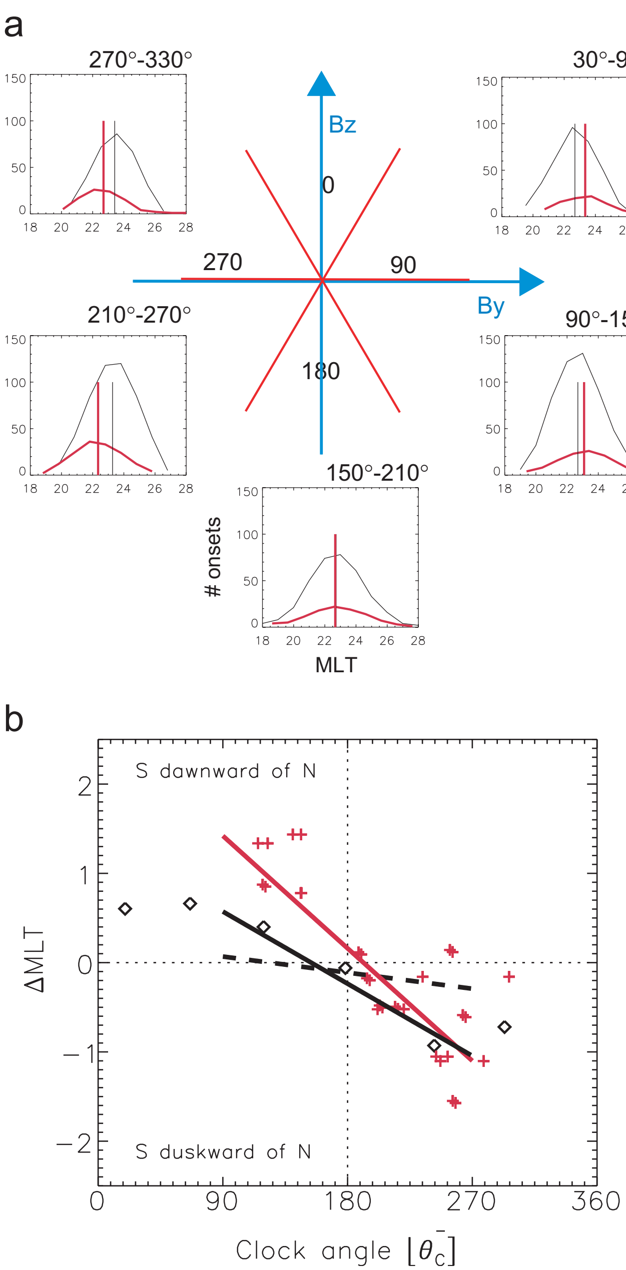

Fig. 2. (a) Statistical distributions and average of substorm onset locations in the northern (black) and southern (red) hemispheres for 5 different clock angle intervals of 60°. IMF coordinates are shown in blue and clock angle is positive in the clockwise direction. (b) ΔMLT versus clock angle. Red line and crosses: simultaneous imaging from Østgaard et al. (2005b), black dashed line: predicted by T02, black diamonds: points derived from (a), i.e., difference between average southern and northern locations, black line: regression line for black diamonds.

the relative asymmetry (southern minus northern average onset location) of the average onset locations. Even if the slope of the regression line (black line) is not as steep as for our simultaneous imaging data (red line), which one should expect from the averaging, these statistical results demonstrate that the asymmetries are still a factor 5 larger than T02 predicts (dashed line).

3. Conclusions

In this paper, we have reviewed and discussed our main results from analyzing simultaneous global imaging by IMAGE and Polar.

(1) The cusp auroras in the opposite hemispheres are asymmetric and their locations are controlled by IMF B_y and dipole tilt angle.
(2) Theta aurora can be a non-conjugate phenomenon and we suggest that IMF B_x controls in which hemisphere the theta aurora occur.
(3) There exists a systematical asymmetry of substorm onset locations in the conjugate hemispheres. The relative displacement of onset locations is found to be controlled primarily by the IMF clock angle. Compared with some of the existing magnetic field models, the observed asymmetries are an order of magnitude larger than the model predictions. These results have been compared with the statistical distribution of substorm onsets observed by IMAGE for different clock angles. Based on ~3000 substorm onsets in the northern hemisphere and ~1000 in the southern hemisphere we find a remarkable support for our previous findings. The asymmetries are at least 5 times larger than model predictions.

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References

Anderson, B.J., 2005. North–south asymmetries in magnetosphere–ionosphere coupling: Simultaneous observations of Birkeland current signatures in both hemispheres. Journal of Geophysical Research, submitted for publication.

Bobra, M.G., Petrinec, S.M., Fuselier, S.A., Claflin, S.S., Spence, H.E., 2004. On the solar wind control of cusp aurora during northward IMF. Geophysical Research Letters 31, L04805.

Burns, G.B., McEwen, D.J., Eather, R.A., Berkey, F.T., Murphree, J.S., 1990. Optical auroral conjugacy: Viking UV imager — south pole station ground data. Journal of Geophysical Research 95, 5781–5790.

Carlson, H.C., Cowley, S.W.H., 2005. Accelerated polar rain electrons as the source of Sun-aligned arcs in the polar cap during northward interplanetary magnetic field conditions. Journal of Geophysical Research 110 (A5), A05302.

Cowley, S.W.H., Morelli, J.P., Lockwood, M., 1991. Dependence of convective flows and particle precipitation in the high-latitude dayside ionosphere and the X and Y components of the interplanetary magnetic field. Journal of Geophysical Research 96, 5557–5564.

Craven, J.D., Murphree, J.S., Frank, L.A., Cogger, L.L., 1991. Simultaneous optical observations of transpolar arcs in the two polar caps. Geophysical Research Letters 18, 2297–2300.

Cumnock, J.A., Sharber, J.R., Heelis, R.A., Blomberg, L.G., Germany, G.A., Spann, J.F., Coley, W.R., 2002. Interplanetary magnetic field control of theta aurora development. Journal of Geophysical Research 107 (A7).

Elphinstone, R.D., Jankowska, K., Murphree, J., Cogger, L., 1990. The configuration of the auroral distribution for interplanetary magnetic field — B_z northward. 1. IMF B_x and B_y dependencies as observed by the VIKING satellite. Journal of Geophysical Research 95, 5791.

Frank, L.A., Sigwarth, J.B., 2003. Simultaneous images of the northern and southern auroras from the polar spacecraft: an auroral substorm. Journal of Geophysical Research 108, 8015.

Frank, L.A., Craven, J.D., Ackerson, K.L., English, M.R., Eather, R.H., Carovillano, R.L., 1981. Global auroral imaging instrument from the dynamic explorer mission. Space Science Instruments 5, 369.

Frank, L.A., Sigwarth, J.B., Craven, J.D., Cravens, J.P., Dolan, J.S., Dvorsky, M.R., Hardebeck, P.K., Harvey, J.D., Muller, D.W., 1995. The visible imaging system (VIS) for the polar spacecraft. Space Science Reviews 71, 297–328.

Frey, H.U., Mende, S.B., Immel, T.J., Fuselier, S.A., Claflin, E.S., Gerard, J.C., Hubert, B., 2002. Proton aurora in the cusp. Journal of Geophysical Research 107 (A7), 1091.

Frey, H.U., Phan, T.D., Mende, S.B., Fuselier, S.A., 2003. Continuous magnetic reconnection at Earth's magnetopause. Nature 426 (6966), 533–537.

Frey, H.U., Mende, S.B., Angelopoulos, V., Donovan, E.F., 2004. Substorm onset observations by IMAGE-FUV. Journal of Geophysical Research 109 (A10), A10304.

Liou, K., Newell, P.T., Sibeck, D.G., Meng, C.I., Brittnacher, M., Parks, G., 2001. Observation of IMF and seasonal effects in the location of auroral substorm onset. Journal of Geophysical Research 106, 5799.

Mende, S.B., Heetderks, H., Frey, H.U., Stock, J.M., Lampton, M., Geller, S.P., Abiad, R., Siegmund, O.H.W., Habraken, S., Renotte, E., Jamar, C., Rochus, P., Gerard, J.C., Sigler, R., Lauche, H., 2000. Far ultraviolet imaging from the IMAGE spacecraft. 3. Spectral imaging of Lyman-α and OI 135.6 nm. Space Science Reviews 91, 287–318.

Milan, S.E., Lester, M., Cowley, S.W.H., Brittnacher, M., 2000. Dayside convection and auroral morphology during an interval of northward interplanetary magnetic field. Annales de Geophysique 18, 436–444.

Murphree, J.S., Cogger, L.L., 1988. The application of CCD detectors to UV imaging from a spinning satellite. Proceedings of SPIE 932, 42–49.

Ohtani, S.-I., Ueono, G., Higuchi, T., Kawano, H., 2005. Annual and semiannual variations of the location and intensity of large-scale field-aligned currents. Journal of Geophysical Research 110 (A1), A01216.

Østgaard, N., Mende, S.B., Frey, H.U., Frank, L.A., Sigwarth, J.B., 2003. Observations of non-conjugate theta aurora. Geophysical Research Letters 30 (21), 2125.

Østgaard, N., Mende, S.B., Frey, H.U., Immel, T.J., Frank, L.A., Sigwarth, J.B., Stubbs, T.J., 2004. Interplanetary magnetic field control of the location of substorm onset and auroral features in the conjugate hemispheres. Journal of Geophysical Research 109 (A7), A07204.

Østgaard, N., Mende, S.B., Frey, H.U., Sigwarth, J.B., 2005a. Simultaneous imaging of the reconnection spot in the opposite hemispheres during northward IMF. Geophysical Research Letters 32 (5), L21104.

Østgaard, N., Tsyganenko, N.A., Mende, S.B., Frey, H.U., Immel, T.J., Fillingim, M., Frank, L.A., Sigwarth, J.B., 2005b. Observations and model predictions of auroral substorm asymmetries in the conjugate hemispheres. Geophysical Research Letters 32 (5), L05111.

Richmond, A.D., 1995. Ionospheric electrodynamics using magnetic apex coordinates. Journal of Geomagnetism and Geoelectricity 47, 191–212.

Sato, N., Fujii, R., Ono, T., Fukunishi, H., Hirasawa, T., Araki, T., Kokubun, S., Makita, K., Saemundsson, T., 1986. Conjugacy of proton and electron auroras observed near $l = 6.1$. Geophysical Research Letters 13, 1368–1371.

Sato, N., Nagaoka, T., Hashimoto, K., Saemundsson, T., 1998. Conjugacy of isolated auroral arcs and non-conjugate auroral break-ups. Journal of Geophysical Research 103, 11,641–11,652.

Sato, N., Kadokura, A., Ebihara, Y., Deguchi, H., Saemundsson, T., 2005. Tracing geomagnetic conjugate points using exceptionally similar synchronous auroras. Geophysical Research Letters 32 (9), L17109.

Sibeck, D.G., 1985. The distant magnetotail's response to a strong interplanetary magnetic field B_y: twisting, flattening, and field line bending. Journal of Geophysical Research 90, 4011.

Stenbaek-Nielsen, H.C., Otto, A., 1997. Conjugate auroras and the interplanetary magnetic field. Journal of Geophysical Research 102, 2223–2232.

Toffoletto, F.R., Hill, T.W., 1989. Mapping of the solar wind electric field to the Earth's polar cap. Journal of Geophysical Research 94, 329–347.

Tsyganenko, N.A., 1995. Modelling the Earth's magnetospheric magnetic field confined within a realistic magnetopause. Journal of Geophysical Research 100, 5599–5612.

Tsyganenko, N.A., 2002a. A model of the near magnetosphere with a dawn-dusk asymmetry 1. Mathematical structure. Journal of Geophysical Research 107 (A8), 1179.

Tsyganenko, N.A., 2002b. A model of the near magnetosphere with a dawn-dusk asymmetry 2. Parametrization and fitting to observations. Journal of Geophysical Research 107 (A8), 1179.

Weimer, D.R., 2004. Correction to predicting interplanetary magnetic field (IMF) propagation delay times using minimum variance techniques. Journal of Geophysical Research 109 (A12), A12104.

Wing, S., Newell, P.T., Sibeck, D.G., Baker, K.B., 1995. A large statistical study of the entry of interplanetary magnetic field component into the magnetosphere. Geophysical Research Letters 22, 2083–2086.