Observations and model predictions of substorm auroral asymmetries in the conjugate hemispheres

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Received 6 December 2004; revised 24 January 2005; accepted 18 February 2005; published 15 March 2005.

[1] Based on imaging data from the Polar VIS Earth camera and the IMAGE-FUV instruments we have documented how the IMF orientation and the dipole tilt angle act as the main and the secondary controlling factors of the relative displacement of the aurora in the conjugate hemispheres. Comparing our results with the asymmetries predicted by recent empirical magnetospheric models, we show that the assumed partial penetration of the IMF into the magnetosphere is clearly supported by observations, but the modeled conjugate shifts were found to be an order of magnitude smaller than the observed ones.
Citation: Østgaard, N., N. A. Tsyganenko, S. B. Mende, H. U. Frey, T. J. Immel, M. Fillingim, L. A. Frank, and J. B. Sigwarth (2005), Observations and model predictions of substorm auroral asymmetries in the conjugate hemispheres, *Geophys. Res. Lett.*, *32*, L05111, doi:10.1029/2004GL022166.

1. Introduction

[2] In the open magnetospheric model, first suggested by *Dungey* [1961], 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; *Cowley and Lockwood*, 1992] and observations have indeed shown that the IMF penetrates the outer [*Sibeck*, 1985] as well as the inner [*Wing et al.*, 1995] magnetotail and that the IMF orientation affects the location of the nightside aurora [*Burns et al.*, 1990; *Elphinstone et al.*, 1990; *Stenbaek-Nielsen and Otto*, 1997; *Sato et al.*, 1998; *Liou et al.*, 2001; *Vorobjev et al.*, 2001; *Frank and Sigwarth*, 2003]. Based on imaging data from Polar VIS Earth camera and the IMAGE-FUV instruments *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; *Cowley and Lockwood*, 1992] we found that, for southward IMF, there exists a systematic hemispherical asymmetry which is strongly correlated with the IMF clock angle (the clockwise angle with respect to the northward direction when viewed from the sun) and that the relative displacement (ΔMLT) can be expressed as a linear function of IMF clock angle. We interpreted these findings as the magnetic tensions force acting on open magnetic field lines before reconnecting in the magnetotail or alternatively as the IMF penetrating the magnetosphere.

[3] In this paper, we further investigate the hemispherical asymmetry of the nightside aurora during substorms. Based on a slightly larger data set, we studied (1) the relative role of the dipole tilt in the asymmetry, and (2) to what extent that asymmetry can be predicted by two empirical magnetic field models [*Tsyganenko*, 1995, 1996, 2002a, 2002b] (hereinafter referred to as T96 and T02).

2. Data

[4] During 2001 and 2002, the Polar and IMAGE spacecraft offered a unique opportunity to study the aurora simultaneously in the conjugate hemispheres. Due to the apsidal precession of the Polar spacecraft orbit and the large field of view of the Polar VIS Earth camera and the IMAGE-FUV instruments, substorms and auroral features were imaged on a global scale from the southern (VIS Earth camera) and the northern (IMAGE-FUV) hemispheres simultaneously. Comparing data from the two instruments we assume the emission height to be 130 km and map the images onto magnetic apex coordinates [*Richmond*, 1995]. This 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. Both the VIS Earth camera images and the IMAGE SI13 are detecting OI emission lines from the aurora, 130.4 nm and 135.6 nm, respectively. In this analysis we have also used IMAGE WIC images (140–180 nm), due to their higher count rates, after checking that the locations of onset and auroral features in the WIC images do not differ from what is observed in the SI13 images. Exposure times are 10 s and 32.5 s for IMAGE WIC and VIS Earth camera, respectively.

[5] The IMF measurements are provided by the Wind and ACE satellites. In order to examine any IMF influence on the inner nightside magnetosphere we have assumed a planar propagation of the solar wind and then added 10 min for the inner nightside magnetosphere to respond to the IMF [*Cowley and Lockwood*, 1992]. The time-shift, which was performed point by point, can be considered as a minimum time shift. For all the events we have therefore checked that a larger time-shift to e.g., $-10\ R_E$ (as used by *Østgaard et al.* [2004]) and even $-20\ R_E$ gives approximately the same IMF values. To further remove uncertain-

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0094-8276/05/2004GL022166$05.00

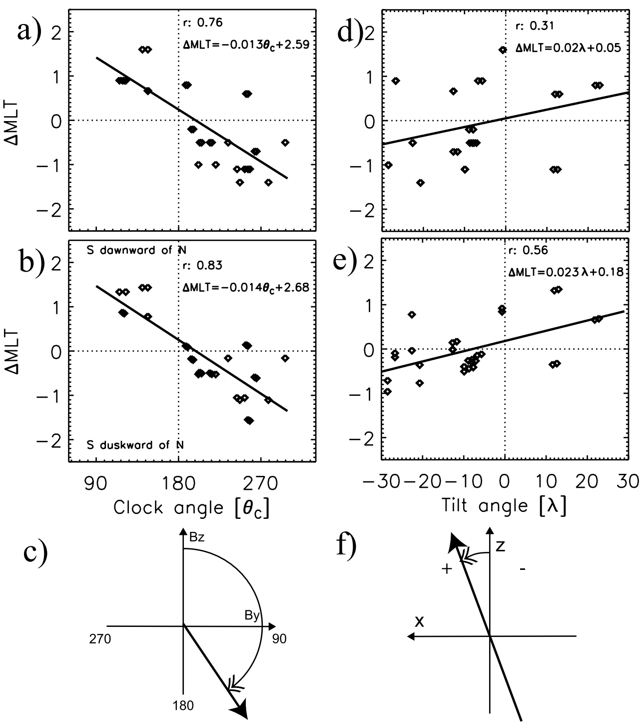

Figure 1. The relative displacement of substorm auroral features in the two hemispheres. (a) ΔMLT versus IMF clock angle, (b) ΔMLT versus IMF clock angle after removing the linear tilt angle dependence, (c) clock angle definition, (d) ΔMLT versus tilt angle, (e) ΔMLT versus tilt angle after removing the linear IMF clock angle dependence and (f) Tilt angle definition. In panel a,b,d and e, positive ΔMLT means that the feature in the southern hemisphere was dawnward of the feature in the northern hemisphere.

ties due to small variations in IMF we have used a 10 min average of the time-shifted IMF data centered around the time of the observed auroral features. The uncertainties of the time shifts are in the range of 0–10 min [*Collier et al.*, 1998], consistent with the 10 min averaging of the IMF data. Finally, we have excluded events where IMF B_z and/or B_y show significant fluctuations within a ±10 min interval.

[6] In addition to the 11 events presented by *Østgaard et al.* [2004], their Figure 6 we have identified 4 more events giving a total of 15 events for this analysis. As Wind data are excluded when the satellite is more than 40 R_E off the Sun-Earth line or within the magnetosphere, Wind data could be used for 11 of the events, while ACE data were available for all the 15 events. In order to utilize all the data and weigh them equally, we have given the 4 events with only ACE data double weight, giving a total of 30 data points.

3. Results

[7] In Figure 1a we show the hemispherical asymmetry of substorm onsets and auroral features as a function of IMF clock angle, as defined in Figure 1c. Positive ΔMLT means that the feature in the southern hemisphere was observed dawnward of the feature in the northern hemisphere. For bright spots the center of the features was used to determine location, while the steep intensity gradient was used for features like the westward bulge [see also *Østgaard et al.*, 2004]. The linear fit based on these 30 data points gives a correlation coefficient of 0.76. Figure 1d shows the displacements as a function of tilt angle, as defined in Figure 1f. The poor correlation coefficient of 0.3 indicates that the tilt angle is not a dominant controlling factor. However, if we only consider the residuals after removing the IMF clock angle dependence, i.e., for each data point in Figure 1a the value of the linear fit for that specific clock angle is subtracted, we obtain a larger correlation coefficient of 0.56. This indicates that the tilt angle acts as a secondary controlling factor (next to the IMF).

[8] As energetic electrons travel from the source region in the magnetotail to the ionosphere in a second or so, any motion of field lines due to convection can be considered to be negligible. It should therefore be reasonable to assume that the locations of substorm onset and auroral features in the conjugate hemispheres are the illuminated footprints of the magnetic field line connecting the two hemispheres. This means that the asymmetry of the auroral features is the observational evidence of the twisted magnetotail field configuration.

[9] Both the T96 and T02 models assumed a partial penetration of the IMF into the magnetosphere, with the empirical penetration coefficient ε being derived from the data and varying within the range 0.4–0.8. The main differences between the T02 and T96 models are as follows: (1) much more flexible and realistic approximations for the fields of principal sources in T02, including the symmetric and partial ring current, scalable Birkeland currents, tilt-dependent cross-tail current, and (2) entirely new set of data used in the derivation of the T02 model parameters (Geotail, Polar, AMPTE CCE, and others, including Wind and ACE interplanetary data). Regarding the interhemispheric asymmetries induced by the IMF, the two models differed in the way of taking into account the IMF penetration: in the T96 model, the penetrated field was assumed to decrease tailward, while in the T02 model that field did not depend on X, but varied with the IMF clock angle. The penetration coefficient (ε) in both models was treated as an empirical parameter, whose magnitude was derived from data by least squares.

[10] In Figure 2, the asymmetries for the 15 events, using both ACE and Wind data (giving 30 data points), as predicted by the T96 and T02 models are seen. The same IMF time shift procedure as applied for the observations is used to get the IMF input needed for the model predictions.

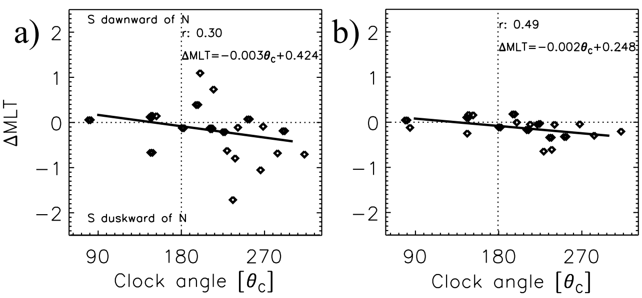

Figure 2. The relative displacement, ΔMLT, of substorm auroral features in the two hemispheres versus IMF clock angle as predicted by the Tsyganenko models, (a) T96 and (b) T02.

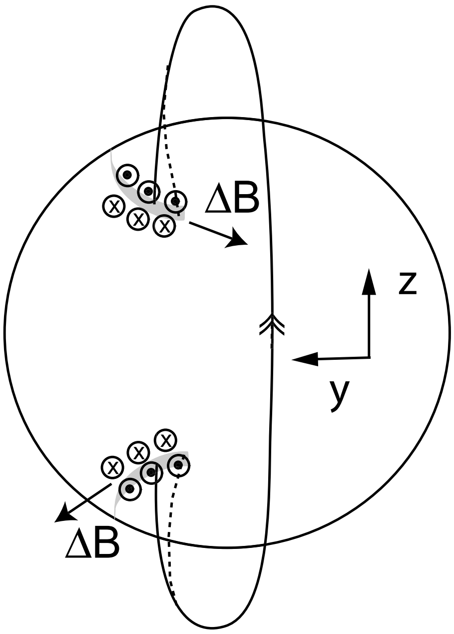

Figure 3. Sketch of the magnetic effects of a pair of upward (region 1) and downward (region 2) field aligned currents in the pre-midnight sector.

For each event we identified the location of the aurora in the northern hemisphere and used the model to trace the field line to its footpoint in the southern hemisphere. While the T96 model shows more scatter and a poorer correlation coefficient than the T02 model, they both indicate an IMF clock angle dependence. However, this effect is only 1/10 of what is observed.

4. Discussion and Summary

[11] Based on a slightly larger data set than reported by *Østgaard et al.* [2004] the results presented in this paper indicates that the tilt angle seems to play a secondary role in defining the asymmetry of auroral features in the conjugate hemisphere. This can be interpreted as being the result of the seasonal dependent field aligned current (FAC) intensity in the pre-midnight sector. As sketched in Figure 3, consider a pair of region 1 and 2 currents in the pre-midnight sector of equal intensities in the conjugate hemispheres. In such a case the ΔB from the two pairs of FACs should be in the opposite direction in the conjugate hemispheres resulting in a symmetric displacement of the magnetic field footpoints, as shown by the dashed lines. However, if the FAC is stronger in the winter than in the summer hemisphere, the ΔB effect will be larger in winter than summer. With our definition of tilt angle, a positive angle defines summer in the northern hemisphere. If there is a stronger FAC, giving a larger ΔB in the southern winter hemisphere, the southern hemisphere aurora will be observed dawnward of the northern aurora, in nice agreement with our observations. This result is consistent with the seasonal dependence of upflowing electron beams reported by *Cattell et al.* [2004]. Our results are also partly supported by a statistical study of 19 year of DMSP data [*Ohtani et al.*, 2005]. While the dayside FAC was found to be far more intense in the summer than winter, the opposite seems to be true for the FAC in the 19–23 MLT sector. All our auroral features are from the pre-midnight sector with 14 event in the 19–23 MLT sector and 1 event at 24 MLT.

[12] The results presented in this paper also indicate that the implementation of the partial penetration [*Toffoletto and Hill*, 1989] of the IMF in the T96 and T02 models has a strong observational support, although the models only predict 1/10 of the observed effect. Such a large discrepancy may indicate interesting physical features missing in the models. At least three factors can be envisioned in this regard, providing a possible explanation of the observed large shifts of the conjugate points. First, the distortion of the magnetospheric magnetic field line geometry by the penetrated IMF By is inversely proportional to the strength of the ambient geomagnetic field. All events used in this study corresponded to active auroral forms, implying that the corresponding field lines, most likely, mapped into the transient regions of low magnetic field (e.g., local neutral points, magnetic islands, etc.). These transient and spatially localized substorm-related depressions of B are not adequately reproduced by the models. Second, the cumulative longitudinal shift between the conjugate footpoints of a field line is proportional to the total length of the line. Because of the highly turbulent nature of the magnetic field inside the plasma sheet, the actual total length of the field line can be much larger than that in the model with a regular and smooth distribution of B. Third, the empirical models assume a spatially uniform penetration of the IMF By. However, statistical studies of the tail magnetic structure have demonstrated that the penetration is significantly larger inside the plasma sheet, in comparison with that in the tail lobes [*Lui*, 1986; *Sergeev*, 1987; *Kaymaz et al.*, 1994]. Theoretically, the penetrated IMF By can be amplified inside the plasma sheet up to the values of the order of the lobe field, due to the formation of magnetic flux ropes [*Kivelson and Khurana*, 1995; *Hesse et al.*, 1996]. A more detailed quantitative treatment of this interesting issue is beyond the scope and size of this work, and will be given elsewhere.

[13] To summarize, in this paper we have reported the following:

[14] 1) Adding more events confirms the strong IMF control of the relative displacements of substorm onset and auroral features in the conjugate hemispheres.

[15] 2) The dipole tilt angle seems to be a secondary controlling factor (next to the IMF) of the auroral asymmetries in the conjugate hemispheres. This is consistent with the FACs being stronger in the winter than in the summer hemispheres.

[16] 3) The T96 and T02 field models replicate qualitatively the IMF induced asymmetries, but underestimate this effect by an order of magnitude.

[17] **Acknowledgments.** This study was supported by the Norwegian Research Council, project 165487, and by NASA through SwRI subcontract number 83820 at UC Berkeley under contract number NAS5-96020 and through the contract NAG5-11528 at the University of Iowa. Most of this study was accomplished when N. Ø. was working at the Space Sciences Laboratory at UC Berkeley. The research by N. T. was supported by NSF grant ATM-0207248. We want to thank J. G. Patel at UC Berkeley for helping identifying the auroral events. We thank R. Lepping for the WIND magnetic field data, A. Lazarus for the WIND solar wind data, C. Smith for the ACE magnetic field data and D. McComas for the ACE solar wind data.

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