Interhemispherical asymmetry of substorm onset locations and the interplanetary magnetic field

N. Østgaard,1 K. M. Laundal,2 L. Juusola,1 A. Åsnes,3 S. E. Håland,1,4 and J. M. Weygand5

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1. Introduction

The auroral substorm display in the conjugate hemispheres offers a unique tool to understand how the Earth’s plasma and magnetic environment respond to changes in the solar wind and the interplanetary magnetic field (IMF). Earlier studies have demonstrated that substorm onset locations in the two hemispheres are systematically displaced due to the orientation of the IMF, but it is still a controversy which IMF parameter is most important. We have analysed more than 6600 substorms identified from global auroral images by Polar UVI from years 1996−2000 plus 2007 and IMAGE FUV from years 2000−2005. We find very strong statistical support for earlier conjugate auroral imaging observations, according to which the IMF clock angle, θy, organizes the average substorm onset locations in both hemispheres. The IMF θy control is a manifestation of dayside/lobe reconnection geometry and magnetic tension on open field lines before tail reconnection resulting in closed field lines with asymmetric footpoints for all θy angles. By organizing the average substorm locations by the IMF By component only we also find statistical significance. The relation is not linear, as reported earlier, but reveals saturation effects that can be explained by the non-uniform penetration of IMF By into the closed magnetosphere. Citation: Østgaard, N., K. M. Laundal, L. Juusola, A. Åsnes, S. E. Håland, and J. M. Weygand (2011), Interhemispherical asymmetry of substorm onset locations and the interplanetary magnetic field, Geophys. Res. Lett., 38, L08104, doi:10.1029/2011GL046767.

[1] The identification of a large number of substorms in both hemispheres from IMAGE FUV data [Frey et al., 2004] provided an opportunity to confirm statistically the results of previous event studies. Based on more than 3700 substorms identified from 2000 to 2004, Østgaard et al. [2005] showed that the IMF clock angle control of the asymmetry of substorm onset location is indeed statistically significant. Wang et al. [2007] analysed an extended version of this list [Frey and Mende, 2006] of substorms from IMAGE including the year 2005, giving a total of 4192 substorms. Although they mainly focused on the IMF By and the solar zenith effect, they also reported that no IMF θy control of substorm onset location could be found in the data. Unfortunately, no results were shown and they did not explain how they performed the unsuccessful search for a IMF θy control.

[2] When and why the auroras are asymmetric in the two hemispheres are key questions that need to be answered to obtain a more complete knowledge on how the Earth’s plasma and magnetic environment interacts and responds to changes in the solar wind and the interplanetary magnetic field (IMF).

[3] As a contribution to this effort Østgaard et al. [2004, 2005] have previously reported, based on simultaneous conjugate auroral images, that the locations of the auroral substorm onset in the conjugate hemispheres are usually not symmetric. Although these studies were based on a limited number of events (15) they indicated clearly that the degree of asymmetry is well correlated with the orientation of the IMF. Comparing the degree of asymmetry with the IMF clock angle (θy) and the IMF By component, they found that IMF θy gives a slightly higher correlation coefficient than comparing with the IMF By only. θy is defined as the angle between the IMF and Z-axis in the YZ plane of the Geocentric Solar Magnetospheric (GSM) reference system. The observed asymmetry was also found to be larger than predicted by the empirical magnetic field models [Østgaard et al., 2005].

[4] We suggested that the IMF θy control can be understood as the magnetic stress imposed by the IMF on the Earth’s magnetic field from the moment the field lines are opened on the dayside, draped down the tail and until they eventually close through reconnection in the mid-tail before substorm onset. The result of this tension force on open field lines is that only the ones with asymmetric footpoints will reconnect in the mid-tail forming closed field lines with interhemispherically asymmetric footpoints [Østgaard et al., 2005]. To explain how IMF By affects the substorm onset location one would rather consider the asymmetric cross-tail pressure resulting from a non-zero IMF By that non-uniformly penetrates into the closed magnetosphere [Cowley, 1981; Khurana et al., 1996].

[5] The IMF θy control is a manifestation of dayside/lobe reconnection geometry and magnetic tension on open field lines before tail reconnection resulting in closed field lines with asymmetric footpoints for all θy angles. By organizing the average substorm locations by the IMF By component only we also find statistical significance. The relation is not linear, as reported earlier, but reveals saturation effects that can be explained by the non-uniform penetration of IMF By into the closed magnetosphere. Citation: Østgaard, N., K. M. Laundal, L. Juusola, A. Åsnes, S. E. Håland, and J. M. Weygand (2011), Interhemispherical asymmetry of substorm onset locations and the interplanetary magnetic field, Geophys. Res. Lett., 38, L08104, doi:10.1029/2011GL046767.

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[6] In a recent paper Liou and Newell [2010] analysed a new set of substorms identified from Polar UVI data [Liou, 2010]. This substorm list is complementary to the IMAGE list and covers the years from 1996 to 2000 and 2007. Their main result is that substorm onset locations have a dependence on the pairing of IMF Bz/tilt angle, which is a confirmation of what was suggested by Østgaard et al. [2005, Figure 1], where θy = 90° (positive Bz) and positive tilt angle (northern summer) gives the largest positive ΔMLT which implies the earliest substorms in northern hemisphere. Liou
and Newell [2010] found a similar dependence on the pairing of IMF $B_y$/solar zenith angle, consistent with the results from Wang et al. [2007]. They also found a weak IMF $\theta_y$ control of substorm onset location, but still argue that this is not a strong controlling parameter for substorm onset location.

Motivated by the findings (or the lack thereof) in these two studies [Wang et al., 2007; Liou and Newell, 2010] and the release of a new and complementary substorm list based on Polar UVI data [Liou, 2010], we find it important to revisit this problem and try to settle the controversy. We will first compare the results from the two substorm lists applying exactly the same method to both data sets. Then we will use the entire data set of more than 6600 substorms to investigate how the relation between the IMF parameters, $\theta_y$ and $B_y$, and substorm onset location can give us a better understanding of how the IMF interacts with the Earth’s magnetic fields and plasma. To make our results as transparent as possible, we have uploaded a file with all the substorm times, MLT locations and the corresponding IMF data as auxiliary material.\(^1\)

2. Data

We have used the extended substorm list from IMAGE FUV data comprising 4192 substorms from years 2000 to 2005 and the new substorm list from Polar UVI data comprising 2539 substorms. The solar wind data are mainly from ACE but using Wind when ACE is not available. The data have been time shifted to $X = 17R_E$ using the propagation method described by Weimer [2004]. These data can be downloaded from measure.igpp.ucla.edu. The data have been further time shifted using planar propagation from $X = 17R_E$ to $X = -10R_E$ (average of ±5 min and 40 minutes prior to onset time) and $X = -20R_E$ (average of ±5 min) to investigate different possible impact times from the solar wind to the magnetosphere.

3. Results

For each of the data sets we have grouped the substorm locations in 60° bins of IMF $\theta_y$, and calculated the average substorm onset location in each bin, as well as the standard deviation of each bin-average. Throughout this paper average refers to the arithmetic mean. The results are shown in Figure 1 where the data from IMAGE and Polar are shown in black and red, respectively. A sine function with three free parameters, $Y = A_y \sin(\theta_y + A_y) + A_y$, is fitted to the data, where $Y = \text{MLT}$ in Figures 1a–1c and $Y = \Delta\text{MLT}$ in Figure 1d. From the IMAGE data one can clearly see that the average substorm location in the northern (Figure 1a) and southern (Figure 1c) hemisphere are in anti-phase and that the relative asymmetry (Figure 1d) follows a sine function. The Spearman correlation coefficients ($R_S$) for these fits are 0.96 (north), 0.81 (south) and 0.98 (relative).

\(^{1}\text{Auxiliary materials are available at ftp://ftp.agu.org/apend/gl/} \text{2011g046767.}\)
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c values differ more than 30° (60°) from the UCLA values.

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< 0.05 leaving little doubt that the c0 values for 2007 control is L08104 

L08104 [2010] (R = 0.86).

0.3. Time shifts to estimates are not the same as

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in the northern hemisphere, where the number of data points are comparable, giving a high correlation coefficient of 0.92. Due to the much smaller data set from Polar in the southern hemisphere we do not see a clear sine function in anti-phase to the northern hemisphere. However, as less than 1/3 of the data points are outside the standard deviation, the distributions from Polar are still statistically in agreement with the IMAGE distributions in this hemispheres as well. We have also shown that the sine distribution for the substorms in northern hemisphere from Polar is statistically significant when using similar bins as Liou and Newell [2010] (R = 0.86).

Our average IMF \( \theta_c \) estimates are not the same as reported by Liou and Newell [2010, Figure 1D] and may indicate that the time-shifted OMNI data and the UCLA data are not the same.

As a check, we have compared the \( \theta_c \) values for 2007 (~540 substorms) and found that 39% (21%) of the OMNI \( \theta_c \) values differ more than 30° (60°) from the UCLA values. There might be other differences in analysis performance as well. However, we find it extremely unlikely that errors in data processing on our side should coincidentally show up as a statistically significant correlation. We would rather think that errors in the procedure would scramble the data and remove statistical significance.

When analysing the combined data set the IMF \( \theta_c \) control becomes even clearer, with R_S > 0.96, probability, \( p < 0.2\% \), and \( \chi^2_{red} < 0.05 \) leaving little doubt that the average onset locations and interhemispheric asymmetry are organized as a sine function of IMF \( \theta_c \). Although different time shifts and averaging (red and blue diamonds in Figures 2a–2c) give almost similar results, the correlation is significantly poorer for 40 min averaging with R_S down to 0.75, \( p \) as high as 1.8% and \( \chi^2_{red} \) of 0.3. Time shifts to \(-10\) give slightly better correlation than for \(-20\). The IMF \( \theta_c \) control (black diamonds in Figures 2a–2c) can be summarized in the following three equations (subscripts refer to north and south).

\[
MLT_n = 0.32 \times \sin(\theta_c - 201) + 22.9,
\]

\[
MLT_s = 0.24 \times \sin(\theta_c + 16.3) + 22.8
\]

\[
\Delta MLT(MLT_n - MLT_s) = 0.53 \times \sin(\theta_c - 4.8) - 0.17
\]

If only values with total IMF larger than 5 nT are included the amplitudes increase to 0.41 (north), 0.35 (south) and 0.73 (relative), while the phase shifts and constants are unchanged. Due to fewer data points the errors are larger.

These results give a very strong support to the results reported by Østgaard et al. [2004, 2005]. These studies were limited to only southward IMF and we explained the IMF \( \theta_c \) control by the magnetic stress imposed by the IMF on the Earth’s magnetic field from the moment the field lines are opened on the dayside, draped down the tail and until they eventually close through reconnection in the mid-tail before substorm onset. Now we observe that the IMF \( \theta_c \) control is also apparent for substorms during northward IMF, under which conditions no magnetic flux is opened by lobe reconnection. However, open field lines can still be closed by tail

The best correlations are found for \(-10R_E\) and ±5 min, with R_S of 0.98 (north), 0.96 (south) and 0.99 (relative).

Finally we show (Figures 2d–2f) how the average substorm locations are related to IMF \( B_n \) using the combined data set from Image and Polar. Despite the larger number of substorms the sampling for large \( B_n \) values are poor. We have therefore used 4 nT bin resolution and integral \(< -10 R_E \) and \( >10 \) nT, giving number of substorms in each bin that ranges from 61 to 1427 in the northern hemisphere and 24 to 753 in the southern hemisphere. Neither the northern or the southern hemisphere reveals a linear relation, but rather a linear relation for negative (positive) \( B_n \) in the northern (southern) hemisphere and a constant value (saturation effect) for positive (negative) \( B_n \) in the North (South), giving R_S = 0.93 (north) and R_S = 0.82 (south). The asymmetry between hemispheres is very well fitted with a sine function (R_S = 0.99).

4. Discussion and Summary

Our results (Figure 1) show clearly that the average substorm onset locations in the two hemispheres based on the IMAGE FUV list of substorms follow a sine function of IMF \( \theta_c \) and that the two hemispheres are in anti-phase. When analysing the new and complementary substorm list based on Polar UVI data we find that the distribution of average substorm onset location follows a similar sine function in the northern hemisphere, where the number of data points are comparable.
reconnection [Cowley and Lockwood, 1992; Grocott et al., 2005]. Thus, due to the tension force imposed by IMF before tail reconnection the resulting closed field lines will, also in this case, have asymmetric footpoints. The sine behavior with maxima at \( \theta_c = 90^\circ/270^\circ \) (Figure 2c) is exactly what one would expect considering the plasma sheet and lobe reconnection geometry and tension force on open field lines.

[15] Our results are based on average values and cannot be used to predict the location of one single substorm. However, the relative displacement \((\text{equation } 3)\) is probably a more robust result that can be used when the location in one hemisphere is known [e.g., Motoba et al., 2010]. Although unbinned data have a large spread they can be still fitted by sine functions (not shown).

[19] The comparison between average substorm location and IMF \( B_y \) also gives results that are statistically significant and provides additional information about the interaction between the IMF and the closed magnetosphere. The relation is not linear, as previously reported [Østgaard et al., 2005; Wang et al., 2007; Liou and Newell, 2010], but reveals a saturation effect for positive (negative) \( B_y \) values in the North (South).

[20] This effect can be explained by considering how magnetic flux is added non-uniformly to the magnetotail for negative and positive \( B_y \) values [Khurana et al., 1996], and assuming that this non-uniform penetration of IMF \( B_y \) extends into the closed magnetosphere. We have illustrated this in Figure 3a by sketching the cross section of the magnetotail and how magnetic flux is added (+) in the northern dawn and the southern dusk for IMF \( B_y > 0 \). This means that a positive \( B_y \) will penetrate only in the southern dusk and a negative \( B_y \) will only penetrate into the northern dusk. Considering also that substorms on average are located in the pre-midnight region, the closed magnetic field lines (arrows) will be affected by \( B_y > 0 \) in the southern hemisphere and not in the northern, where we observe the saturation effect for \( B_y > 0 \). For \( B_y < 0 \) (Figure 3b) it is opposite. The flux is not added to the southern dusk, consistent with the saturation we observe in the southern hemisphere for \( B_y < 0 \). This idea is supported by results from the semi-empirical Tsyganenko 96 model (Figures 3c and 3d). The interhemispherical asymmetry is related to \( B_y \) as

\[
\Delta \text{MLT} (\text{MLT}_y - \text{MLT}_n) = 0.88 \times \sin \left( \frac{B_y}{12^n} \right) \text{ (4)}
\]

To summarize, based on more than 6600 substorm onset locations identified by Polar UVI and IMAGE FUV covering the years from 1996 to 2005 plus 2007 we have found the following:

[21] 1. The IMF \( \theta_c \) controls the average substorm locations in both hemispheres and explains the asymmetry of onset locations between the hemispheres. This is a manifestation of dayside and lobe reconnection geometry and magnetic tension on open field lines before tail reconnection resulting in closed field lines with asymmetric footpoints and is valid for all \( \theta_c \) angles.

[22] 2. The relation between IMF \( B_y \) and the average substorm locations is also statistically significant. It is not linear, but reveals a saturation effect due to the non-uniform penetration of IMF \( B_y \) into the closed magnetosphere. The interhemispherical asymmetry is very well correlated with \( B_y \).

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References


A. Åsnes, Bergen Oilfield Services, Nedre Åstveit 12, N-5106 Bergen, Norway.

S. E. Håland, L. Juusola, and N. Østgaard, Department of Physics and Technology, University of Bergen, Allegt. 55, N-5007 Bergen, Norway. (nikolai.ostgaard@ift.uib.no)


J. M. Weygand, Institute of Geophysics and Planetary Physics, University of California, 3845 Slichter Hall, 405 Charles E. Young Dr., Los Angeles, CA 90095-1567, USA.