This is the published version of a paper published in *Geophysical Research Letters*.

Citation for the original published paper (version of record):

Pitkänen, T., Hamrin, M., Kullen, A., Maggiolo, R., Karlsson, T. et al. (2016)
*Geophysical Research Letters*, 43(15): 7822-7830
https://doi.org/10.1002/2016GL070068

Access to the published version may require subscription.

N.B. When citing this work, cite the original published paper.

Permanent link to this version:
http://urn.kb.se/resolve?urn=urn:nbn:se:umu:diva-126750
Response of magnetotail twisting to variations in IMF $B_y$: A THEMIS case study 1–2 January 2009

T. Pitkänen$^1$, M. Hamrin$^1$, A. Kullen$^2$, R. Maggiolo$^3$, T. Karlsson$^2$, H. Nilsson$^4$, and P. Norqvist$^1$

1Department of Physics, Umeå University, Umeå, Sweden, 2Space and Plasma Physics, School of Electrical Engineering, Royal Institute of Technology, Stockholm, Sweden, 3Belgian Institute for Space Aeronomy, Brussels, Belgium, 4Swedish Institute of Space Physics, Kiruna, Sweden

Abstract

Theoretical considerations, observations, and simulations have shown that the $B_y$ component of the interplanetary magnetic field (IMF) may cause twisting of the magnetotail. However, the fundamental issues, the temporal and spatial responses of the magnetotail in the twisting process, are still unresolved. We report unique multpoint observations of the response of the magnetotail to the variations in IMF $B_y$ on 1–2 January 2009. For the first time, estimates of the tail twisting response time at different (Time History of Events and Macroscale Interactions during Substorms, THEMIS) distances in the same event are inferred. Using cross-correlation and timing analyses, we find that the tail twisting propagates from farther out toward the Earth and the response time increases significantly to the inner magnetosphere.

1. Introduction

The dawn-dusk, i.e., the $B_y$ component of the interplanetary magnetic field (IMF), may affect the large-scale structure and topology of the Earth’s magnetotail causing a twisting of the tail [e.g., Fairfield, 1979; Cowley, 1981; Kaymaz et al., 1994; Owen et al., 1995; Kullen and Janhunen, 2004a, 2004b; Tsyganenko et al., 2015]. For nonzero IMF $B_y$, the plasma sheet and cross-tail current/neutral sheet can get rotated along the Earth-Sun axis, and an additional IMF $B_y$ component appears in tail lobes and the plasma sheet that has the same sign as IMF $B_y$. The additional $B_y$ component in the plasma sheet is connected to a twisting of the closed field lines out of the meridional symmetry.

It is, however, not established how long it takes for the magnetotail to respond to changing IMF conditions; i.e., what is the timescale associated with the tail twisting process. McComas et al. [1986] have discussed one cross-tail current sheet crossing of the ISEE satellites in the postmidnight sector (ISEE 1: [XGSM, YGSM] $\sim [−18, −3] R_E$, where GSM yields for geocentric solar magnetic). The crossing occurred during strongly northward IMF $\sim 1$ h after the IMF had completed a long excursion of strong negative $B_y$ (at $[−2, 22] R_E$) and plasma sheet $B_y$ measured by ISEE spacecraft was still collinear with IMF $B_y$ of the excursion.

Motoba et al. [2011] inferred $\sim 1$ h tail twisting response time to IMF in the postmidnight plasma sheet boundary layer (XGSM $\sim −11$ to $−14 R_E$, YGSM $\sim −4$ to $−1 R_E$), measured from the bow shock nose during southward IMF. Even though some of the Cluster spacecraft had a separation of a couple of $R_E$, the response times estimated from the measurements by different spacecraft were practically the same. Recently, Rong et al. [2015] have presented two events when an IMF effect was observed by Cluster in the postmidnight tail lobes after $\sim 1$ h ($[−18, −4] R_E$) and $\sim 1.5$ h ($[−16, −5] R_E$), respectively, measured from the bow shock nose. These were associated with northward IMF.

Based on correlation results between IMF $B_y$ and the initial magnetic local time location of transpolar arcs, two independent statistical studies [Fear and Milan, 2012; Kullen et al., 2015] found similar time delays, indicating a response time of the initial arc location on IMF $B_y$ of at least $\sim 1–2$ h. It is generally assumed that the formation of a transpolar arc is tightly connected to changes in the magnetotail due to IMF $B_y$ effects [e.g., Kullen and Janhunen, 2004a, 2004b; Milan et al., 2005]. As transpolar arcs are a predominantly northward IMF phenomenon, the results of the two studies give a good estimate of the tail response time on new IMF $B_y$ conditions during northward IMF.

The tail twisting response time can also be studied using magnetospheric models. To our knowledge, first, such a study has been carried out by Walker et al. [1999], who used an MHD simulation and found that the
plasmasheet twist at XGSM ∼−20 Re occurred 45–60 min after an IMF By sign reversal during southward IMF at the dayside magnetopause. In addition, Kullen and Janhunen [2004a, 2004b] have investigated magnetotail twisting using the GUMICS-4 MHD code [Janhunen et al., 1996, 2012]. From their Figure 5, which corresponds to northward IMF, one can infer the equatorial tail By to change its direction in the central tail (XGSM ∼−12 to −20 Re) ∼22 min after the IMF has reversed its sign at the dayside magnetopause. Recently, Tenfjord et al. [2015] suggested few tens of minutes response time for the nightside near-Earth closed field lines, based on a model run using the Lyon-Fedder-Mobarry MHD model [Lyon et al., 2004; Merkin and Lyon, 2010]. Tenfjord et al. [2015] changed IMF By from zero to positive after 30 min during southward IMF.

Kullen and Janhunen [2004a, 2004b] and Walker et al. [1999] suggest that the twisting propagates from the tail flanks inward and from near-Earth tailward. Tenfjord et al. [2015] propose a propagation from near-Earth tailward, but the tail closed field line twist would be induced asymmetrically determined by the IMF By direction (section 3).

In this letter, we report unique multipoint observations of the response of the magnetotail to the variations in IMF By on 1–2 January 2009. For the first time, estimates of the tail twisting response time at different (Time History of Events and Macroscale Interactions during Substorms, THEMIS) distances in the same event are inferred.

2. Observations

The time interval studied extends from 15:00 UT 1 January to 09:00 UT 2 January 2009. For the solar wind data, we use OMNI data at 1 min time resolution and propagated to the bow shock nose (http://omniweb.gsfc.nasa.gov/). The magnetotail data are provided by the five satellites of the Time History of Events and Macroscale Interactions during Substorms (THEMIS) mission [Angelopoulos, 2008]. Magnetic field data from the fluxgate magnetometer (FGM) [Auster et al., 2008] and particle data from the electrostatic analyzer (ESA) [McFadden et al., 2008] on board the satellites are studied. In section 2.2, the THEMIS data are presented in the ∼3 s resolution, but in the latter sections the data have been averaged to 1 min resolution to make it comparable with the IMF data. Throughout the study, we will present data in the geocentric solar magnetic (GSM) coordinates.

2.1. Solar Wind and Geomagnetic Activity

During the time interval of interest, the solar wind speed mostly stays between 400 and 450 km/s, with minimum and maximum excursions of 369 and 453 km/s, respectively (data not shown). The solar wind proton density varies between 1.1 and 3.7 cm$^{-3}$. The proton density maximum is measured during a period of enhanced density between ∼02:30 and 05:00 UT. This includes a transient major change in IMF By between ∼02:30 and 04:10 UT with an excursion from negative IMF By values to positive at ∼03:17–03:59 UT (Figure 1a). The generally low proton density with typical solar wind speed lead to a prevailing low ≲1 nPa solar wind dynamic pressure with a maximum of ∼1.2 nPa at the proton density maximum. IMF By is relatively weak and fluctuates around zero with a maximum amplitude of ∼3.4 nT (Figure 1a). IMF Bx shows two major negative incursions, one shorter and more rapid ∼16:48–18:16 UT and one longer and more gradual ∼21:04–21:13 UT (Figure 1b). In the following, we will focus on the gradual negative incursion of IMF Bx. Before 17:00 UT, the AE indices indicate an occurrence of a small substorm (AE maximum ∼300 nT). After that geomagnetic activity remains low.

2.2. Overview of THEMIS Observations

Figures 1g and 1h show the orbits of the THEMIS satellites during the time interval of interest. After 01:03 UT, all the five spacecraft have moved to the nightside and are traversing toward dawn and the apogee of the orbits in the postmidnight sector. For clarity, the trajectory of THEMIS D (thd) is not shown since THEMIS A (tha) and thd have a small separation. The red and green solid lines indicate the time intervals 19:04–06:01 UT and 21:25–07:21 UT for THEMIS B (thb) and THEMIS C (thc) spacecraft, respectively. These time intervals are used in the cross-correlation analysis between the IMF and THEMIS data in section 2.3. The two markers for each spacecraft indicate the positions of the spacecraft at 02:55 UT and 03:52 UT when thb and thc measure a beginning of a significant increase of Bz associated with the preceding IMF Bx change, respectively. These findings will be discussed in detail in section 2.4.

In Figures 1c and 1d magnetic field data measured by thb are displayed. The thb-Bz data show that before ∼18:30 UT, the component is relatively strong and decreases with geocentric distance as the satellite moves...
Figure 1. (a, b) IMF components, (c, d) THEMIS B (thb), and (e, f) THEMIS C (thc) $B$ field components during the time interval of interest. (g) Dashed lines: orbits of the THEMIS spacecraft in the GSM $XY$ plane between 15:00 UT 1 January to 09:00 UT 2 January 2009 (trajectories only for four of five satellites drawn). Solid lines: the THEMIS B (thb) and C (thc) spacecraft trajectories during the time intervals used in the cross-correlation analysis (see details in section 2.3). The markers indicate the time 02:55 UT (03:52 UT) when thb (tha) observed the beginning of the significant increase of $B_y$ associated with the latter IMF $B_y$ change (see section 2.4). The estimates for the propagation delay of the tail twisting change from thb toward the inner magnetosphere obtained in this study are given with arrows indicating associated distances. (h) Same as Figure 1g but for the GSM $XZ$ plane.
away from the Earth (Figure 1d). After that, a more tail-like field is measured with a smaller \( B_z \) contribution. The \( \text{thb-} B_y \) data indicate that the spacecraft stays during most of the time above the neutral sheet. A striking feature in the \( \text{thb} \) magnetic field data is that after \( \sim 19:00 \) UT, the \( B_y \) component (\( \text{thb-} B_y \)) closely follows the behavior of the IMF \( B_y \) component with some delay. As IMF \( B_y \) gradually changed from positive to negative, \( \text{thb-} B_y \) behaved similarly. The occasional high-frequency variations with large amplitudes seen in the \( \text{thb-} B_y \) data, e.g., the one occurring right after \( 21:30 \) UT, are associated with flow burst activity seen in the bulk velocity data (not shown). The magnitudes of \( \text{thb-} B_y \) (Figure 1d) and the ion beta (not shown) indicate that \( \text{thb} \) was in the plasma sheet. The magnetic pressure observed by \( \text{thb} \) stays quasi-stable between \( \sim 20:00 \) UT and \( \sim 04:50 \) UT suggesting the field compression is not playing a role with the decrease and increase trends of \( \text{thb-} B_y \).

Figures 1e and 1f display the magnetic field data measured by \( \text{thc} \). The satellite is interpreted to exit the significantly dipolar inner-magnetospheric field lines at \( \sim 01:00 \) UT. However, \( \text{thc-} B_y \) begins to follow IMF \( B_y \) already after \( \sim 23:00 \) UT, similarly as \( \text{thb-} B_y \). As well as for \( \text{thb} \), the abrupt high-frequency disturbances in \( \text{thc-} B_y \), like the one just before \( 01:30 \) UT, are associated with flow burst activity and the measurements are made in the plasma sheet (not shown). Similarly, no indication of the field compression driving the \( \text{thc-} B_y \) change trends is seen.

Tsyganenko and Fairfield [2004] found that the geomagnetic dipole tilt angle may affect tail plasma sheet \( B_y \). However, the dipole tilt effects on \( B_y \) appear only in certain regions in the tail. According to Petrukovich [2009, Figure 7], the dipole tilt effects should be negligible (in the region passed by \( \text{thb} \)) or cause a constant, small additional \( B_y \) component (in the region passed by \( \text{thc} \)), which cannot explain the transition from negative to positive \( \text{thc-} B_y \) measurements.

### 2.3. Tail Twisting Response From Cross Correlation

To study the magnetotail response to the variations of IMF \( B_y \), we have carried out a cross-correlation analysis between IMF \( B_y \) and the THEMIS \( B_y \) components. The cross-correlation analysis is made for the two outermost spacecraft, \( \text{thb} \) and \( \text{thc} \), since no clear and long analogous response in \( \text{thb-} B_y \), \( \text{thc-} B_y \) is seen. The sample cross-correlation [e.g., Chatfield, 2004] computed using 658 data point pairs peaks at a 98 min lag for \( \text{thb-} B_y \) independently of the IMF time series (correlograms not shown). The corresponding cross-correlation coefficients are 0.63 and 0.65 for IMF \( B_y \) and the clock angle, respectively. The peak lags for \( \text{thc-} B_y \) measurements.

The IMF \( B_y \) time interval for the cross-correlation is 19:20–02:48 UT between the two local \( B_y \) maxima (yellow shading in Figure 3a). For \( \text{thb} \) and \( \text{thc} \), we similarly selected the time intervals 19:04–06:01 UT and 21:25–07:21 UT, respectively, from the residual \( \Delta B_y \) data (yellow shading in Figures 2d and 2f). Note that the IMF and THEMIS time intervals have different lengths. For cross correlation, we made the IMF time series equal to the length of the THEMIS time series. For \( \text{thb} \), this was done by adding zeros on the both sides of the IMF \( B_y \) and the clock angle series to make them span the same time interval as the \( \text{thb} \) time series. In the case of \( \text{thc} \), zeros were added in the end of the IMF and in the beginning of the \( \text{thc} \) time series. The sample cross correlation [e.g., Chatfield, 2004] computed using 658 data point pairs peaks at a 98 min lag for \( \text{thb-} B_y \) independently of the IMF time series (correlograms not shown). The corresponding cross-correlation coefficients are 0.63 and 0.65 for IMF \( B_y \) and the clock angle, respectively. The peak lags for \( \text{thc-} B_y \) measurements.
Figure 2. (a) IMF $B_y$ and (b) clock angle. (c) The solid line is the $B_y$ component of the tail magnetic field measured by thb. The black (red) dash-dotted line indicates the T96 model $B_y$ (with zero input IMF $B_y$) when the model input parameters have been averaged over the preceding 60 min period. (d) The residual thb $\Delta B_y$ after subtracting the T96 model with zero input IMF $B_y$. (e, f) Same as Figures 2c and 2d but for thc. The yellow shading marks the time intervals used in the cross-correlation analysis.

using 722 data point pairs are 118 min (IMF $B_y$) and 116 min (the clock angle). The two-min difference arises due to a longer period of high clock angles compared to the corresponding period of large negative IMF $B_y$ 00–02 UT. The corresponding cross-correlation coefficients are 0.67 and 0.68, respectively.

The results imply that the magnetotail farther out responds first to variations in IMF $B_y$. Note that during the time intervals used in the cross-correlation analysis, thb and thc moved from $\sim -11 R_E$ to $-20 R_E$ and from $\sim -5 R_E$ to $-13 R_E$ in XGSM, respectively (Figures 1g and 1h). The associated time intervals are long and the
spacecraft positions vary over a large range, which is expected to have an effect on the timing accuracy. However, as thc is always located at shorter geocentric distances than thb, it is clear that the magnetotail farther out responds first.

### 2.4. Tail Twisting Response From \( B_y \) Increase

We also investigated the magnetotail response by comparing the onset times of the significant increases in the THEMIS \( B_y \) components after the latter IMF \( B_y \) change from negative back to positive. Figure 3 shows from top to bottom IMF \( B_y \), the IMF clock angle, and the \( B_y \) components measured by thb, thc, and tha. Also, the T96 model fields are shown for a comparison with the actual tail measurements. The onset times have been identified from the \( \Delta B_y \) curves (e.g., Figures 2d and 2f) and are marked into Figures 3c–3e by green vertical

![Figure 3](image-url)
dashed lines and arrows. No clear onset time of the increase in IMF $B_y$ can be seen (Figure 3a), but instead, one can identify an onset in the clock angle data at 01:17 UT (Figure 3b).

The first onset is observed first by thb at 02:55 UT (Figures 3c and 1g), 98 min after the IMF clock angle onset, which matches with the delay obtained by the cross-correlation analysis. Spacecraft thc observes the onset 13 min later at 03:08 UT (Figure 3d). The 13 min delay between the onsets at thb and thc (111 min between the IMF clock angle onset and the thc onset) is of the order of the 20 min (116 min) delay obtained using the cross-correlation analysis. These correspondences suggest that the timing uncertainties arising from the long time interval and associated large satellite location change may not significantly influence the cross-correlation analysis.

The thb satellite in the inner magnetosphere observes a signature of an onset of the $B_y$ increase at 03:52 UT. If the increase in thb-$B_y$ is associated with the same process causing the $B_y$ changes measured by thb and thc, the disturbance reaches the thb spacecraft in the inner magnetosphere 57 min after thb (44 min after thc). This is a significant longer delay compared to the delay between thb and thc. We have also checked the delay to the satellite, which followed thb (Figures 1g and 1h). We found a possible, even though weaker, signature of an onset of the-$B_y$ increase at 04:06 UT, i.e., 71 min after thb (data not shown). Also, thc shows similar magnetic field signatures as thb, as the two spacecraft have a small separation (not shown).

The negative bay observed by thb between ~05:20 and 06:00 UT is also seen by the other THEMIS inner-magnetosphere satellites. It is associated with small amplitude (10–20 km/s) velocity oscillations in the earthward-dawnward to tailward-duskward direction and could be an inner-magnetospheric signature of oscillatory flow braking of fast earthward flows [e.g., Panov et al., 2010, 2013].

3. Summary and Discussion

We have presented unique multipoint observations of the response of the magnetotail to variations of IMF $B_y$ on 1–2 January 2009, during which the THEMIS satellites are aligned well inside the magnetospheric tail at different geocentric distances in the midnight-postmidnight sector. For the first time, both the temporal and spatial magnetotail response to IMF $B_y$ during one single event can be inferred.

During the event, IMF $B_y$ showed a gradual negative incursion from the positive direction lasting ~5 h. This IMF behavior was conveyed to the tail plasma sheet $B_y$ with a delay depending on the tailward distance from the Earth, as measured by the THEMIS satellites. The IMF $B_z$ was weak and fluctuated around zero.

By using both the cross-correlation analysis and the comparison of the onset times of magnetic field changes at the bow shock nose and in the tail, we have inferred the response times of the $B_y$ component to the IMF $B_y$ changes at different tail distances. We interpret the tail $B_y$ changes as changes in the field line twisting in the magnetotail. The results indicate that the magnetotail responded in ~100 min, 110–120 min, and 160–170 min at thb, thc, and thb/the distances, respectively, to the IMF lagged to the bow shock nose (OMNI data) (Figures 1g and 1h). These results suggest that the magnetotail farther out responds first and the response time increases significantly as geocentric distance decreases to inner-magnetospheric distances.

The 100 min and 110–120 min delays in tail $B_y$ response for thb and thc, respectively, are longer than the 60 min delay estimate deduced from McComas et al. [1986] and the 60–90 min delays inferred by Rong et al. [2015], the latter obtained in the tail lobes. The 60 min delay by Motoba et al. [2011] lies in the same range as the previous estimates. Notably, the measurements analyzed in all these studies have been made during more active geomagnetic conditions than the measurements analyzed in the present study. Thus, the quiet geomagnetic conditions may explain the longer time responses in the present study. Specifically, the observational evidence presented by Rong et al. [2015] that stronger convection is associated with shorter response time in the lobes supports this explanation.

Also, as discussed in detail by Kullen et al. [2015], there exists a very high correlation between IMF $B_y$ and the initial transpolar arc location with a delay of about 1–2 h up to many hours back in time (which appears due to the statistically rather constant IMF $B_y$ values the hours before transpolar arc events). As the transpolar arcs appear during predominantly northward IMF [Fear and Milan, 2012; Kullen et al., 2015, and references therein] and their formation is strongly controlled by IMF $B_y$-induced changes in the magnetotail [Kullen and Janhunen, 2004a, 2004b], the time delay of at least 1–2 h should correspond to the tail response time on new IMF $B_y$ conditions during quiet times. However, it is not known whether the way how IMF $B_y$ affects the tail is the same for northward and southward IMF as tail reconnection is predominantly a southward IMF phenomenon.
Between 23 and 03 UT, we find that the fraction of induced tail $B_y (\Delta B_y/IMF B_y)$ varies between 200 and 500% for both thb and thc (data not shown). It is known that the induced $B_y$ is nonuniformly distributed within the plasma sheet with highest values at the neutral sheet [e.g., Kaymaz et al., 1994; Kullen and Janhunen, 2004a, 2004b]. However, the induced-$B_y$ values found in the present study are still a magnitude higher than in previous observational and simulation studies even at the neutral sheet [e.g., Kaymaz et al., 1994; Kullen and Janhunen, 2004a, 2004b; Cao et al., 2014, and references therein]. In the inner magnetosphere at the geosynchronous orbit, the proportionality between magnetospheric $B_y$ and IMF $B_y$ has statistically shown to reach ~80% in the midnight sector [Wing et al., 1995]. At ~22:00 UT, thc is located at about that region and we find thc-$\Delta B_y \sim \sim 2.1$ nT and IMF $B_y \sim \sim +0.2$ nT, when using the 118 min lag for IMF $B_y$. Even using a longer, 160–170 min lag for the IMF, which was deduced using the inner-magnetospheric THEMIS data, the signs remain opposite. However, the results by Wing et al. [1995] show large scattering for both positive and negative IMF $B_y$, suggesting that observations of a lack of an opposite extra $B_y$ in the inner-magnetospheric distances are not totally unusual. In conclusion, the present event may represent a somewhat extreme event during which the mechanism generating the twisted closed tail field lines is working effectively. A more plausible contributing factor to the high efficiency could be the limited ability of T96 to model the reference, non-IMF $B_y$-affected field. The values of the solar wind and IMF parameters are not found to be extreme.

The IMF $B_y$ “penetration” into the tail lobes can be understood to be caused by dawn–dusk asymmetric dayside reconnection under nonzero, favorably strong or dominating IMF $B_y$. On the contrary, the question how does additional $B_y$ convey into the closed tail field lines is yet unanswered. While the propagation of the IMF-induced $B_y$ from outside (flanks)-in (central tail) appears in the MHD simulations by Walker et al. [1999] and Kullen and Janhunen [2004a, 2004b], the results of the present study regarding the propagation in the Sun-Earth direction suggest contrarywise. The strong northward IMF conditions in the simulation study by Kullen and Janhunen [2004a, 2004b] (high-latitude lobe reconnection and no tail reconnection seen in the simulations) could be part of the explanation why the propagation of the IMF-induced new $B_y$ direction is directed in a different direction in the present event as compared to their simulations.

Hau and Erickson [1995] have proposed that IMF-induced plasma sheet $B_y$ could be generated by the differential azimuthal shear motion of magnetic field lines and that the earthward convection could also enhance $B_y$ (in the direction of IMF $B_y$). Khurana et al. [1996] have presented an analogous model according to which the shear flows between the northern and the southern halves of the plasma sheet are driven by opposite cross-tail flows in the northern and southern lobe/mantle regions generating $B_y$ on the closed field lines. The cross-tail flows in the lobes/mantles would be driven by magnetic pressure gradients generated by asymmetric addition of the magnetic flux into the tail lobes during dawn-dusk asymmetric dayside reconnection. The results studied by Tenford et al. [2015] are in accordance with this scenario and suggest that the timescale in which the nightside near-Earth closed field lines respond to IMF $B_y$ is faster than the convection time from the dayside magnetospheric boundaries to the tail reconnection site. On the other hand, an indication of a correlation between the IMF $B_y$ and the YGSM component of the earthward convective fast flows has been found, which is consistent with untwisting rather than twisting of the tail magnetic field lines [e.g., Grocott et al., 2007; Pitkänen et al., 2013, 2015]. A guide field reconnection determined by the IMF $B_y$ direction could play a role in conveying the IMF $B_y$ effects into the plasma sheet.

The present THEMIS observations invoke further questions like why should the response time of the tail twisting delay from farther out from the tail to inner-magnetospheric distances? What is the mechanism generating the tail twist? To answer these questions, the associated plasma flows must be investigated. The analysis of the magnetospheric flows associated with this event is beyond the scope of the present study, but it is planned for a future study.