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Importance of the dusk-dawn interplanetary magnetic field component (IMF B_y) to magnetospheric convection in Earth's magnetotail plasma sheet

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The solar wind and its embedded magnetic field, the interplanetary magnetic field (IMF) together with magnetic reconnection power the large-scale plasma and magnetic flux circulation in the Earth's magnetosphere-ionosphere system. This circulation is termed as convection and its strength is controlled by the north-south IMF component (IMF B_z). In recent years, an interest has arisen to investigate the lesser-known role of the dusk-dawn component (IMF B_y) in convection. It has been previously known though that prevailing nonzero IMF B_y can cause plasma flow asymmetries in the high-latitude ionosphere, but how the magnetospheric flows, for instance, in the magnetotail plasma sheet are affected, remains to be investigated. In this article, we introduce the recent progress and the latest achievements in the research of the influence of IMF B_y on tail plasma sheet convection. The research progress has been rapid and it has revealed that both fast and slow convection are affected in a manner that is in accordance with the asymmetries observed in the ionospheric convection. The results indicate the significance of the IMF B_y component on magnetospheric convection and they represent a major advance in the field of solar wind-magnetosphere coupling.

KEYWORDS

solar wind-magnetosphere coupling, interplanetary magnetic field, magnetotail, plasma sheet, magnetospheric convection, interhemispheric asymmetry

1 Introduction

Along with the magnetic reconnection process, the solar wind and the interplanetary magnetic field (IMF) drive a large-scale plasma and magnetic flux circulation, convection, in the Earth's magnetosphere-ionosphere system, the geospace. In a simplified picture, postulated first time already 60 years ago (*Dungey*, 1961), during southward IMF, the southward IMF field lines reconnect with the northward closed geomagnetic field lines at low latitudes on the dayside magnetopause. The newly created open field lines are then dragged antisunward across the polar caps to nightside into the magnetotail by the solar wind. There, in the magnetotail, the magnetic field lines are reconnected again, and subsequently created closed field lines are convected earthward and via dusk or dawn back to the dayside where they become ready to reconnect with the IMF again. In the high-latitude ionosphere, this circulation is seen as two large-scale convection cells, in which plasma flows antisunward from noon to midnight over the polar cap and returns back to the dayside at lower latitudes roughly within the dusk and dawn auroral oval.

During purely northward IMF, the situation is more complicated. Convection is generally much weaker, and plasma and magnetic flux circulation occur preliminary in the magnetotail lobes. The northward directed IMF reconnects with the open magnetic field lines of the high-latitude tail lobes (*Dungey*, 1963). The resulting new open field lines are draped over the dayside magnetopause until they are eventually dragged tailward by the solar wind (*Crooker*, 1992). The corresponding ionospheric convection consists of 2 cells in the polar cap with sunward flow in the centre and antisunward flow just poleward of the dusk- and dawnside auroral oval (*Dungey*, 1963; *Maezawa*, 1976). Most of the time however, the magnitude of the dusk-dawn IMF component (IMF B_y) is larger than the northward directed north-south IMF component (IMF B_z), that is, IMF $|B_y|$ > IMF B_z (*Zhang* et al., 2019). For such a dominant IMF B_y conditions, dayside magnetopause reconnection may occur even in a case of northward IMF B_z (*Nishida* et al., 1998; *Lee* et al., 2010), or the two reconnection modes may co-occur (*Sandholt* et al., 1998). Thus, an essential driver of magnetospheric convection is dayside magnetopause reconnection.

While it is well established that IMF B_z controls the strength of the convection, lesser is known on the role of dusk-dawn IMF B_y. However, we know that a presence of nonzero IMF B_y can cause plasma flow asymmetries in the high-latitude ionosphere, which manifest in that the two-cell convection pattern is distorted (e.g., *Reiff and Burch*, 1985; *Heppner and Maynard*, 1987). In the nightside, depending on the IMF B_y direction, one of the convection cells, either the evening or the morning cell, can extend significantly to the midnight sector (e.g., *Ruohoniemi and Greenwald*, 2005). Such deformations in convection are generally mirrored between the hemispheres along the noon-midnight meridian.

If asymmetry in ionospheric convection under the influence of nonzero IMF B_y exists, the key question is then *how is the corresponding magnetospheric convection affected?* Previous studies have shown that prevailing prolonged nonzero IMF B_y can affect the magnetotail by twisting it: The plasma sheet/cross-tail current sheet can get rotated around its axis (e.g., *Kullen and Janhunen*, 2004; *Tsyganenko* et al., 2015; *Pitkänen* et al., 2021a)) and an additional B_y component collinear to IMF B_y can be induced to the tail field to an extent that the closed tail field lines are bent or twisted from the meridian direction (e.g., *Kaymaz* et al., 1994; *Tenfjord* et al., 2015). These deformations in the magnetotail configuration, along with the observations of asymmetric ionospheric convection suggest that under nonzero IMF B_y, the magnetospheric plasma transport processes in the magnetotail plasma sheet could also be affected.

2 Present knowledge and understanding

First observations-based indications of that nonzero IMF B_y conditions could affect convection also in the magnetotail plasma sheet were observed by *Grocott et al.* (2007) and *Walsh et al.* (2009). Based on simultaneous space-based (ESA's Cluster satellites) and ground-based observations (SuperDARN radars), the authors reported events in which fast earthward ion flows perpendicular to the magnetic field in the near-Earth magnetotail plasma sheet were consistent with the hemispherically asymmetric fast convection in the nightside auroral oval. The perpendicular flows in the dusk-dawn direction in both the magnetotail and in the ionosphere were suggested to be a consequence of a (rapid) untwisting of magnetic field lines, following a reconnection in an IMF B_y-induced twisted magnetotail.

The observations by *Grocott et al.* (2007) and *Walsh et al.* (2009) motivated us to study more the IMF relationship with the magnetotail convection in more detail. In a statistical investigation of Cluster data, *Pitkänen et al.* (2013) discovered that the dusk-dawn component of the fast earthward perpendicular ion flows (>200 km/s) in the midnight near-Earth magnetotail (<20 R_E distance, where R_E is Earth's radius) statistically correlate with the IMF B_y direction and tends to be opposite above and below the neutral sheet (B_x = 0), i.e., in the northern and southern plasma sheet. With an expanded dataset (Cluster + NASA's THEMIS satellites, <30 R_E), *Pitkänen et al.* (2017) further reported that the mechanism that causes the interhemispheric flow asymmetry appears could work at all so-called IMF clock angles, where the IMF B_y direction is the critical deciding parameter.

Convection in terms of occurrence in the magnetotail plasma sheet is dominated by slow flows (<100 km/s, e.g., *Chong* et al., 2022). It is thus equally important to investigate how the slow flows are affected by IMF B_y. *Pitkänen et al.* (2018) addressed this by studying THEMIS measurements from a period of time, which showed clear signatures of an IMF B_y influence on the tail magnetic field. They found that both the earthward and tailward slow (<200 km/s) perpendicular ion flows were affected analogously as previously reported for earthward fast flows. By analyzing Cluster, THEMIS and ISAS's/NASA's Geotail satellite data, *Pitkänen et al.* (2019) statistically demonstrated the existence of interhemispheric asymmetry in average slow perpendicular flows. On the average, under clearly nonzero IMF B_y (IMF $|B_y|$ > 3 nT), one magnetic hemisphere is dominated by a dusk-dawn flow component, which is oppositely directed compared to the other hemisphere. Under clearly positive IMF B_y conditions, the region of the earthward flows with a dawnward velocity component is extending to the midnight sector and expanding more and more to the premidnight sector with increasing tail distance in the northern plasma sheet (See Figure 1 demonstrating this (Figure 4 of *Chong et al.* (2022))). Similarly, the region of the earthward flows with a duskward velocity component is extending to the midnight sector, expanding more and more to the postmidnight sector with increasing tail distance in the southern plasma sheet. An analogous interhemispheric asymmetry but with an opposite sense is found for the flows under clearly negative IMF B_y conditions. Such an asymmetry is also observed for tailward directed ion flows in the near-Earth tail region (<32 R_E distance, Figure 1 (Figure 4 of *Chong et al.* (2022)). Comparison with the magnetic field indicated that the appearance of the dominating dusk-dawn flow component agrees with the appearance of tail *By*, which is interpreted to be induced by IMF *By*.

Research on this topic is progressing rapidly. Recently, *Chong et al.* (2022) investigated the slow perpendicular (to *B*) tail ion flows using a similar dataset as *Pitkänen et al.* (2019), which was

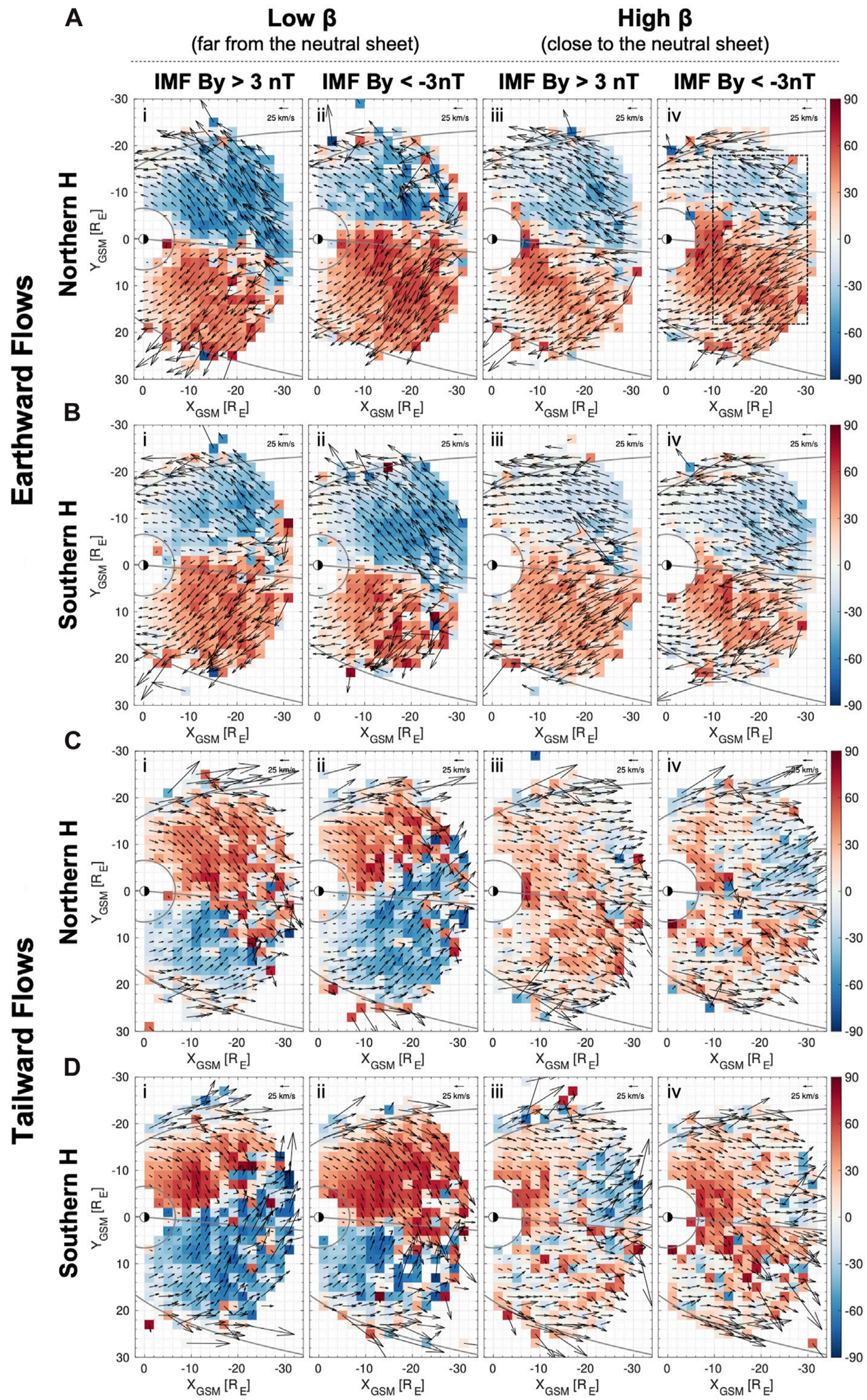

FIGURE 1
The distribution of **(A,B)** earthward and **(C,D)** tailward average ion $\mathbf{V}_\perp$ in the XY plane of the geocentric solar magnetospheric (GSM) coordinate system, for distances far from (i, ii) and close to (iii, iv) the neutral sheet, under clearly positive (IMF B_y > 3 nT, i, iii) and negative (IMF B_y < −3 nT, ii, iv) interplanetary magnetic field (IMF) B_y conditions, in the northern **(A,C)** and southern **(B,D)** plasma sheet respectively. The colour bars show $\tan^{-1}(V_{\perp y}/V_{\perp x})$. From Figure 4 of Chong et al. (2022). Cf. the detailed discussion in *Chong et al.* (2022).

expanded by the NASA's MMS satellite measurements. *Chong et al.* (2022) focused on how the interhemispheric flow asymmetry under the influence of clearly nonzero IMF B_y depends on the distance measured from the neutral sheet. They used plasma ion beta (ratio of ion thermal pressure to magnetic pressure) as a proxy for the distance to the neutral sheet. *Chong et al.* (2022) found that the influence of IMF B_y on both the B_y component of the tail magnetic field and the perpendicular flow is more prominent in the midnight sector (compared to both the pre- and postmidnight sectors) and at distances far from the neutral sheet (compared to the distances close to the neutral sheet). The reason for these differences is not yet fully understood. The differences in the average flow patterns between the distances far from and close to the neutral sheet are demonstrated in Figure 1 (Figure 4 of *Chong et al.* (2022)).

Lane et al. (2022) studied fast earthward perpendicular flows by utilizing a vast dataset of Cluster, THEMIS and Geotail data. They focused on flows that had a velocity component toward the midnight meridian to distinguish them from the flankward diverging "symmetric" flows that are obtained when averaging the flow data without categorizing the magnetic hemispheres and the IMF B_y direction. In this approach, *Lane et al.* (2022) removed the contribution of such flows from their dataset that would formally be consistent with the untwisting hypothesis, but not necessary due to untwisting, something that might have affected the results by *Pitkänen et al.* (2013; 2017). *Lane et al.* (2022) found that ~70% of the fast flow detections exhibit consistency with what would be expected according to the untwisting hypothesis (Agree flows) and ~30% not (Disagree flows). They concluded this to indicate only a rather modest level of IMF B_y control. *Lane et al.* (2022) could infer that Agree (Disagree) flows tended to be accompanied by a localized perturbation to tail B_y in the same sign as (opposite to) the prevailing IMF B_y conditions, which temporarily enhances (overrides) the IMF B_y influence, see their superposed epoch analysis results in Figure 2 (Figure 3 of *Lane et al.* (2022)). Furthermore, Agree (Disagree) flows tended to be observed at larger (smaller) tail B_x, which suggest that they occur farther away from (closer to) the neutral sheet (B_x = 0). This is in accordance with the results by *Chong et al.* (2022) in which the IMF B_y influence on the slow flows was found to be more prominent farther away from the neutral sheet. The average slow "background" flows were found to be consistent with the untwisting hypothesis irrespective of whether the fast flow itself was Agree or Disagree, which is in accordance with the findings by *Pitkänen et al.* (2019) and *Chong et al.* (2022).

The oppositely directed dusk-dawn perpendicular velocity components in the flows in the northern and southern plasma sheet under the influence of nonzero IMF B_y indicate an existence of a reversal in the dusk-dawn velocity somewhere near or at the tail neutral sheet (B_x = 0). While implicitly present in one fast flow event discussed by *Grocott et al.* (2007) and noted in the other event analysed by *Walsh et al.* (2009), the actual velocity reversal has invoked only a very little attention. *Walsh et al.* (2009) discussed that the velocity reversal in their fast flow event could be related to the flows of the untwisting process, but could not draw definite conclusions. *Pitkänen et al.* (2015) reported another fast flow event with direct measurements of a dusk-dawn velocity reversal within the flow. The dusk-dawn velocity directions above and below the neutral sheet in the reversal as well as the tail magnetic field configuration and concurrent ionospheric convection were all consistent with those expected in the magnetotail which is influenced by IMF B_y.

Recently, *Pitkänen et al.* (2021b) investigated such earthward fast flow events measured by MMS, which were associated with clear dusk-dawn velocity reversals. All four analysed fast flow events were associated with signatures of the IMF B_y influence on the tail magnetic field. Three events were associated with dusk-dawn velocity reversals at the neutral sheet whereas one event was associated with reversals without any crossings of the neutral sheet. In those three events, the north-south component (E_z) was the relevant convection electric field component and with the major contribution to both earthward and dusk-dawn perpendicular velocity components, the dusk-dawn components being consistent with velocities expected under the IMF B_y influence. The fourth flow event was a conventional fast flow with the dusk-dawn E_y and Sun-Earth E_x components contributing to X and Y perpendicular velocity components, respectively. It did not show clear consistency with what would be expected in nonzero IMF B_y conditions although the prevailing IMF B_y was strongly nonzero. These results suggest that when IMF B_y is influencing the magnetotail fast convection, then one can expect that the E_z electric field component will play a major role. This is supported by the electric field measurements in slow convection in a clearly twisted tail magnetic field configuration (*Pitkänen* et al., 2018). The reason is that the magnetic field will be twisted or bent from the meridian direction and the convection electric field is by definition perpendicular to the magnetic field.

The relationship between the relevance of the different convection electric field components in fast flows and the IMF B_y influence has further been studied by *Pitkänen et al.* (2023). By investigating MMS measurements, *Pitkänen et al.* (2023) focused on the earthward perpendicular fast flows which fulfilled the frozen-in criterion. They found that the majority of the fast flow events in their dataset (52%) had E_z as the most relevant or dominating electric field component and only 26% of the events were conventional-type fast flows with E_y and E_x as the relevant components. *Pitkänen et al.* (2023) also found the IMF B_y influence on the fast flows to be more efficient as the relevance of E_z in the fast flows increases. This is consistent with the idea that the E_z convection electric field component should play a major role in a twisted magnetotail, as discussed above.

3 Discussion

One related open question is in which time scale the tail responds to changes in the IMF. This has been addressed by using different approaches and methods like direct point measurements (*Motoba* et al., 2011; *Rong* et al., 2015; *Pitkänen* et al., 2016), global magnetospheric simulations (*Tenfjord* et al., 2015; *Eggington* et al., 2022) and auroral observations (*Fear and Milan*, 2012; *Kullen* et al., 2015). However, the inferred estimates span from a few tens of minutes to several hours. In the first statistical studies reporting the interhemispheric asymmetry associated with the fast earthward flows, the IMF conditions were inferred by averaging the IMF over a 130-min time interval prior to a flow event (*Pitkänen* et al., 2013; Pitkänen et al., 2017). The direction of the IMF B_y component

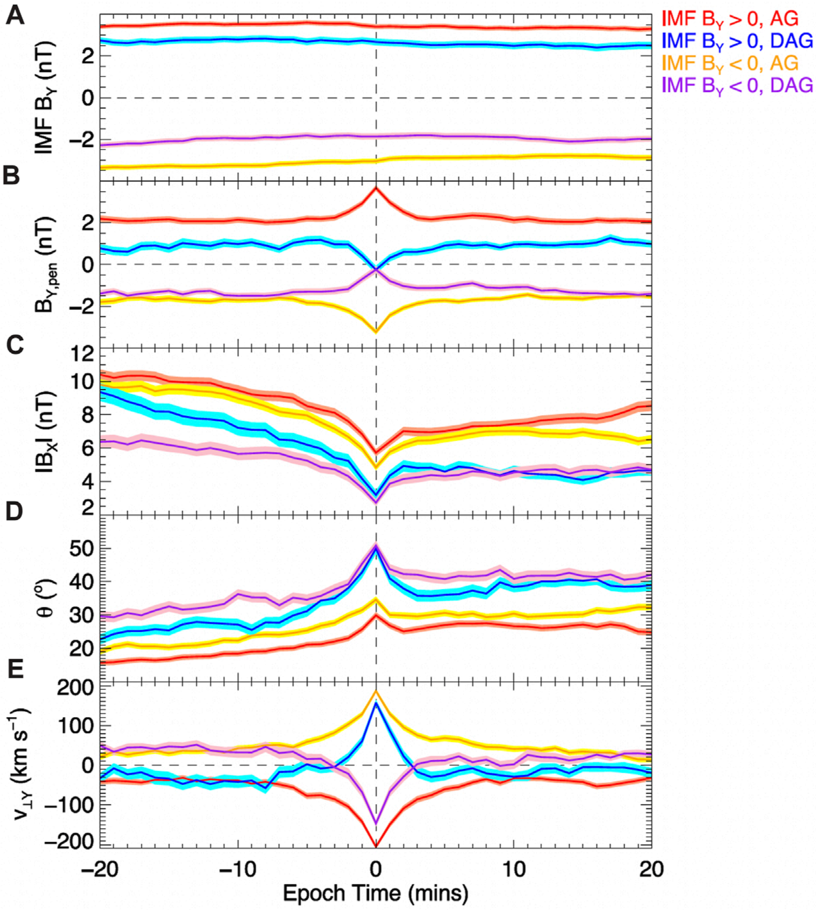

FIGURE 2
Superposed epoch of **(A)** IMF B_y, **(B)** tail B_y induced by IMF B_y, **(C)** tail $|B_x|$ **(D)** the tail magnetic field elevation angle θ, **(E)** $V_{\perp y}$ for the IMF $B_y > 0$, Agree flows (AG, red), IMF $B_y > 0$, Disagree flows (DAG, blue), IMF $B_y < 0$, AG (yellow), IMF $B_y < 0$, DAG (purple) categories (defined relative to Epoch 0, which indicates the time of the fast flow). The shaded region around each curve corresponds to the standard error of the mean. Figure 3 of Lane et al. (2022). Cf. the detailed discussion in *Lane et al.* (2022).

typically varies little compared to that of IMF B_z, and also much shorter IMF averaging windows (e.g., 15 min) have found to be suitable (*Pitkänen* et al., 2019; *Chong* et al., 2022). A prolonged constant nonzero IMF B_y direction may be a prerequisite for clear signatures of the asymmetry. Clear tail responses (e.g., *Pitkänen* et al., 2018) are not often observed in the data and the superposed epoch analysis of the dusk-dawn velocity in IMF B_y reversals by *Case et al.* (2020) support this. Furthermore, from ionospheric observations, we know that at least for the northward IMF with a dominant B_y component, the asymmetry in the two-cell ionospheric convection pattern increases with time (*Grocott and Milan*, 2014), which indicates also an increase of the degree of twisting in the magnetotail.

Another open question is what is the role of the geomagnetic dipole tilt angle in the tail flow asymmetry. Indications that the ionosphere is influenced not only by IMF B_y but a combination of IMF B_y and the Earth's dipole tilt has been reported long ago (e.g., *Friis-Christensen and Wilhjelm*, 1975; *Crooker*, 1992; *Ruohoniemi and Greenwald*, 2005). Recent statistical studies by *Reistad et al.* (2020), *Holappa et al.* (2021), *Ohma et al.* (2021) and Laitinen et al. (2024) indicate that the influence by both IMF B_y and the dipole tilt angle appears, e.g., in the ionospheric field-aligned current pattern, geomagnetic activity, substorm occurrence frequency, Hall conductance and the strength and width of the dawnside auroral electron precipitation region. This implies that the different ionospheric response during positive and negative IMF B_y in combination with different dipole tilt angles may be coupled to tail dynamics as well. In which way a combination of Earth dipole tilt and IMF B_y may affect the tail dynamics and topology, still needs to be examined. It is known though that the dipole tilt angle has a strong effect to the shape of the tail neutral sheet. For positive dipole tilts, the neutral sheet is displaced poleward of the so-called tail equatorial plane, with the neutral sheet flanks being curved below the equatorial plane, such that it has a warped shape (e.g., *Tsyganenko* et al., 2015). For negative dipole tilts the warping has an opposite sense. As discussed in Section 1, a nonzero IMF B_y in turn causes a rotation of the neutral sheet around the Sun-Earth axis (e.g., *Tsyganenko* et al., 2015). How different combinations of the dipole tilt and IMF B_y affect the tail plasma sheet convection is yet to be discovered.

Further research is needed to deepen our understanding of the solar wind-magnetosphere coupling.

Author contributions

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Case, N. A., Grocott, A., Fear, R. C., Haaland, S., and Lane, J. H. (2020). Convection in the magnetosphere-ionosphere system: a multimission survey of its response to IMF B_y reversals. *J. Geophys. Res. Space Phys.* 125, e2019JA027541. doi:10.1029/2019ja027541

Chong, G. S., Pitkänen, T., Hamrin, M., and Kullen, A. (2022). Dawn-dusk ion flow asymmetry in the plasma sheet: interplanetary magnetic field B_y versus distance with respect to the neutral sheet. *J. Geophys. Res. Space Phys.* 127, e2021JA030208. doi:10.1029/2021ja030208

Crooker, N. U. (1992). Reverse convection. *J. Geophys. Res.* 97 (A12), 19363–19372. doi:10.1029/92ja01532

Dungey, J. W. (1961). Interplanetary magnetic field and the auroral zones. *Phys. Rev. Lett.* 6, 47–48. doi:10.1103/physrevlett.6.47

Dungey, J. W. (1963). "The structure of the exosphere or adventures in velocity space," in *Geophysics, the Earth's environment*. Editors C. De Witt, J. Hieblot, and L. Le Beau (New York, NY, USA: Gordon and Breach).

Eggington, J. W. B., Coxon, J. C., Shore, R. M., Desai, R. T., Mejnertsen, L., Chittenden, J. P., et al. (2022). Response timescales of the magnetotail current sheet during a geomagnetic storm: global MHD simulations. *Front. Astron. Space Sci.* 9, 966164. doi:10.3389/fspas.2022.966164

Fear, R. C., and Milan, S. E. (2012). The IMF dependence of the local time of transpolar arcs: implications for formation mechanism. *J. Geophys. Res.* 117, A03213. doi:10.1029/2011ja017209

Friis-Christensen, E., and Wilhjelm, J. (1975). Polar cap currents for different directions of the interplanetary magnetic field in the Y-Z plane. *J. Geophys. Res.* 80, 1248–1260. doi:10.1029/ja080i010p01248

Grocott, A., and Milan, S. E. (2014). The influence of IMF clock angle timescales on the morphology of ionospheric convection. *J. Geophys. Res. Space Phys.* 119, 5861–5876. doi:10.1002/2014ja020136

Grocott, A., Yeoman, T. K., Milan, S. E., Amm, O., Frey, H. U., Juusola, L., et al. (2007). Multi-scale observations of magnetotail flux transport during IMF-northward non-substorm intervals. *Ann. Geophys.* 25, 1709–1720. doi:10.5194/angeo-25-1709-2007

Heppner, J. P., and Maynard, N. C. (1987). Empirical high-latitude electric field models. *J. Geophys. Res.* 92, 4467–4489. doi:10.1029/ja092ia05p04467

Holappa, L., Robinson, R. M., Pulkkinen, A., Asikainen, T., and Mursula, K. (2021). Explicit IMF B_y-dependence in geomagnetic activity: quantifying ionospheric electrodynamics. *J. Geophys. Res. Space Phys.* 126, e2021JA029202. doi:10.1029/2021ja029202

Kaymaz, Z., Siscoe, G. L., Luhmann, J. G., Lepping, R. P., and Russell, C. T. (1994). Interplanetary magnetic field control of magnetotail magnetic field geometry: IMP 8 observations. *J. Geophys. Res.* 99, 11113–11126. doi:10.1029/94ja00300

Kullen, A., Fear, R. C., Milan, S. E., Carter, J. A., and Karlsson, T. (2015). The statistical difference between bending arcs and regular polar arcs. *J. Geophys. Res. Space Phys.* 120 (10), 443–465. doi:10.1002/2015ja021298

Kullen, A., and Janhunen, P. (2004). Relation of polar auroral arcs to magnetotail twisting and IMF rotation: a systematic MHD simulation study. *Ann. Geophys.* 22, 951–970. doi:10.5194/angeo-22-951-2004

Laitinen, J., Holappa, L., and Vanhamäki, H. (2024). A combined effect of the Earth's magnetic dipole tilt and IMF B_y in controlling auroral electron precipitation. *J. Geophys. Res. Space Physics.*

Lane, J. H., Grocott, A., and Case, N. A. (2022). The influence of localized dynamics on dusk-dawn convection in the Earth's magnetotail. *J. Geophys. Res. Space Phys.* 127, e2021JA030057. doi:10.1029/2021ja030057

Lee, D.-Y., Choi, K.-C., Ohtani, S., Lee, J. H., Kim, K. C., Park, K. S., et al. (2010). Can intense substorms occur under northward IMF conditions? *J. Geophys. Res.* 115, A01211. doi:10.1029/2009ja014480

Maezawa, K. (1976). Magnetospheric convection induced by the positive and negative Z components of the interplanetary magnetic field: quantitative analysis using polar cap magnetic records. *J. Geophys. Res.* 81, 2289–2303. doi:10.1029/ja081i013p02289

Milan, S. E., Carter, J. A., Bower, G. E., Imber, S. M., Paxton, L. J., Anderson, B. J., et al. (2020). Dual-lobe reconnection and horse-collar auroras. *J. Geophys. Res. Space Phys.* 125, e2020JA028567. doi:10.1029/2020ja028567

Motoba, T., Hosokawa, K., Ogawa, Y., Sato, N., Kadokura, A., Buchert, S. C., et al. (2011). *In situ* evidence for interplanetary magnetic field induced tail twisting associated with relative displacement of conjugate auroral features. *J. Geophys. Res.* 116, A04209. doi:10.1029/2010ja016206

Nishida, A., Mukai, T., Yamamoto, T., Kokubun, S., and Maezawa, K. (1998). A unified model of the magnetotail convection in geomagnetically quiet and active times. *J. Geophys. Res.* 103, 4409–4418. doi:10.1029/97ja01617

Ohma, A., Reistad, J. P., and Hatch, S. M. (2021). Modulation of magnetospheric substorm frequency: dipole tilt and IMF B_y effects. *J. Geophys. Res.* 126, e2020JA028856. doi:10.1029/2020ja028856

Pitkänen, T., Chong, G. S., Hamrin, M., Kullen, A., Vanhamäki, H., Park, J.-S., et al. (2023). Fast earthward convection in the magnetotail and nonzero IMF B_y: MMS statistics. *J. Geophys. Res. Space Phys.* 128, e2023JA031593. doi:10.1029/2023ja031593

Pitkänen, T., Hamrin, M., Chong, G. S., and Kullen, A. (2021b). Relevance of the north-south electric field component in the propagation of fast convective earthward flows in the magnetotail: an event study. *J. Geophys. Res. Space Phys.* 126, e2021JA029233. doi:10.1029/2021ja029233

Pitkänen, T., Hamrin, M., Karlsson, T., Nilsson, H., and Kullen, A. (2017). "On IMF B_y-induced dawn-dusk asymmetries in earthward convective fast flows," in *AGU monograph*. Editors S. Haaland, A. Runov, and C. Forsyth (Washington, D. C., USA: American Geophysical Union), 95–106.

Pitkänen, T., Hamrin, M., Kullen, A., Maggiolo, R., Karlsson, T., Nilsson, H., et al. (2016). Response of magnetotail twisting to variations in IMF B_y: a THEMIS case study 1–2 January 2009. *Geophys. Res. Lett.* 43, 7822–7830. doi:10.1002/2016gl070068

Pitkänen, T., Hamrin, M., Norqvist, P., Karlsson, T., and Nilsson, H. (2013). IMF dependence of the azimuthal direction of earthward magnetotail fast flows. *Geophys. Res. Lett.* 40, 5598–5604. doi:10.1002/2013gl058136

Pitkänen, T., Hamrin, M., Norqvist, P., Karlsson, T., Nilsson, H., Kullen, A., et al. (2015). Azimuthal velocity shear within an Earthward fast flow – further evidence for magnetotail untwisting? *Ann. Geophys.* 33, 245–255. doi:10.5194/angeo-33-245-2015

Pitkänen, T., Kullen, A., Cai, L., Park, J.-S., Vanhamäki, H., Hamrin, M., et al. (2021a). Asymmetry in the Earth's magnetotail neutral sheet rotation due to IMF B_y sign? *Geosci. Lett.* 8, 3. doi:10.1186/s40562-020-00171-7

Pitkänen, T., Kullen, A., Laundal, K. M., Tenfjord, P., Shi, Q., Park, J.-S., et al. (2019). IMF B_y influence on magnetospheric convection in earth's magnetotail plasma sheet. *Geophys. Res. Lett.* 46, 11698–11708. doi:10.1029/2019gl084190

Pitkänen, T., Kullen, A., Shi, Q. Q., Hamrin, M., De Spiegeleer, A., and Nishimura, Y. (2018). Convection electric field and plasma convection in a twisted magnetotail: a THEMIS case study 1-2 January 2009. *J. Geophys. Res. Space Phys.* 123, 7486–7497. doi:10.1029/2018ja025688

Reiff, P. H., and Burch, J. L. (1985). IMF B_y-dependent plasma flow and Birkeland currents in the dayside magnetosphere 2. A Global model for northward and southward IMF. *J. Geophys. Res.* 90, 1595–1609. doi:10.1029/ja090ia02p01595

Reistad, J. P., Laundal, K. M., Ohma, A., Moretto, T., and Milan, S. E. (2020). An explicit IMF B_y dependence on solar wind-magnetosphere coupling. *Geophys. Res. Lett.* 47, e2019GL0860062. doi:10.1029/2019gl086062

Rong, Z. J., Lui, A. T. Y., Wan, W. X., Yang, Y. Y., Shen, C., Petrukovich, A. A., et al. (2015). Time delay of interplanetary magnetic field penetration into Earth's magnetotail. *J. Geophys. Res. Space Phys.* 120, 3406–3414. doi:10.1002/2014ja020452

Ruohoniemi, J. M., and Greenwald, R. A. (2005). Dependencies of high-latitude plasma convection: consideration of interplanetary magnetic field, seasonal, and universal time factors in statistical patterns. *J. Geophys. Res.* 110, A09204. doi:10.1029/2004ja010815

Sandholt, P. E., Farrugia, C. J., Moen, J., and Cowley, S. W. H. (1998). Dayside auroral configurations: responses to southward and northward rotations of the interplanetary magnetic field. *J. Geophys. Res.* 103, 20279–20295. doi:10.1029/98ja01541

Tenfjord, P., Østgaard, N., Snekvik, K., Laundal, K. M., Reistad, J. P., Haaland, S., et al. (2015). How the IMF B_y induces a B_y component in the closed magnetosphere and how it leads to asymmetric currents and convection patterns in the two hemispheres. *J. Geophys. Res. Space Phys.* 120, 9368–9384. doi:10.1002/2015ja021579

Tsyganenko, N. A., Andreeva, V. A., and Gordeev, E. I. (2015). Internally and externally induced deformations of the magnetospheric equatorial current as inferred from spacecraft data. *Ann. Geophys.* 33, 1–11. doi:10.5194/angeo-33-1-2015

Vennerstrøm, S., and Friis-Christensen, E. (1987). On the role of IMF B_y in generating the electric field responsible for the flow across the polar cap. *J. Geophys. Res.* 82, 195–202. doi:10.1029/JA092iA01p00195

Walsh, A. P., Fazakerley, A. N., Lahiff, A. D., Volwerk, M., Grocott, A., Dunlop, M. W., et al. (2009). Cluster and Double Star multipoint observations of a plasma bubble. *Ann. Geophys.* 27, 725–743. doi:10.5194/angeo-27-725-2009

Zhang, L. Q., Wang, C., Wang, J. Y., and Lui, A. T. Y. (2019). Statistical properties of the IMF clock angle in the solar wind with northward and southward interplanetary magnetic field based on ACE observation from 1998 to 2009: dependence on the temporal scale of the solar wind. *Adv. Spac. Res.* 63, 3077–3087. doi:10.1016/j.asr.2019.01.023