

Statistical Limitations on Detecting Diamagnetic Suppression of Reconnection at Earth's Magnetopause

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The occurrence of magnetic reconnection is of pivotal importance regarding the evolution of many magnetized astrophysical systems. Among others, the mechanism known as “diamagnetic suppression” can prevent reconnection from developing. Over the last decade, many studies evidenced a statistical correlation of the magnetic shear and plasma beta for current sheets interpreted as reconnecting or not, consistent with predictions of the diamagnetic suppression theory. The strength of the observed correlations has suggested that diamagnetic suppression is the dominant mechanism controlling whether reconnection occurs or not, in many space plasma environments, from planetary magnetospheres to the solar wind and heliopause. Here, we show that there exists a possible observational bias, operating at least in the context of the Earth's magnetopause, that can lead to a similar statistical correlation because outflow speeds expected from magnetic reconnection strongly depend on both the magnetic shear and plasma β . Low velocity jets become increasingly difficult to observe when they become comparable to the surrounding flow fluctuation level. We conclude that the role of diamagnetic suppression at the Earth's magnetopause remains unclear.

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Introduction—Magnetic reconnection is a universal process in which local microphysics can change the magnetic connectivity of plasma flows on a large scale. The occurrence of magnetic reconnection in magnetized systems often leads to sudden flow acceleration and plasma heating as well as to drastic modifications of the plasma transport throughout the system at both small and large scales [1–7]. These consequences of reconnection have been observed *in situ* in a large variety of environments, from the Earth's magnetotail [6] and magnetopause [7] to the solar wind [8–11], planetary magnetospheres [12], and laboratory devices [13]. Given its drastic impact on these systems, understanding the mechanisms and conditions that control the onset of reconnection, and how fast it reconfigures magnetic flux, is of primary importance. In the general case of noncoplanar reconnection, the answer to

these questions largely depends on which component of the total field undergoes merging, since it controls the tension force driving the process.

Two decades ago, Swisdak *et al.* [14] proposed a mechanism that could play an important role in controlling the local orientation of an X line. Assuming reconnection locally occurs in a 2D fashion, the authors suggested that, for noncoplanar upstream conditions, the reconnection plane would likely be the one where reconnection is less susceptible to be slowed down by the in-plane ion and electron diamagnetic drift. In cases where the diamagnetic drift is faster than the outflow speed expected from magnetic tension, reconnection would not even develop. In a later study, Swisdak *et al.* [15] proposed the following condition under which magnetic reconnection would be suppressed by diamagnetic drifts:

$$\Delta\beta > 2 \frac{L}{\delta_i} \tan\left(\frac{\theta}{2}\right), \quad (1)$$

where $\Delta\beta$ is the difference in plasma β between the two upstream conditions, θ is the shear angle between the asymptotic magnetic fields, δ_i the local ion inertial length, and L the thickness of the current sheet. The upstream β and the magnetic shear angle being rather easily accessible from *in situ* current sheet observations, the publication of relation (1) paved the way to confronting theoretical predictions to

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measurements to obtain the indirect evidence of the diamagnetic suppression effect, which several works tackled [9,16–18].

Despite minor methodological differences, these studies adopted the same overall procedure, which consisted of plotting the magnetic shear angle against the jump in plasma β across observed current sheets, discriminating between those considered as “reconnecting” and those not. The discrimination between these two classes being made on whether a plasma jet was observed or not (and more specifically whether these jets pass the so-called Walén test [19] at least qualitatively [9,16]).

Figure 1 shows published couples $(\theta, \Delta\beta)$ obtained from crossings of the Earth’s magnetopause made by the *Double Star* [17] and *THEMIS* [16,18] spacecraft, and colored depending on whether the current sheet was labeled as reconnecting or not. Overall, and considering a gradient length scale L spanning $0.5\delta_i$ to $2\delta_i$, reconnecting and nonreconnecting current sheets seem reasonably well separated by Eq. (1). This overall agreement was interpreted as a strong (indirect) evidence supporting the local suppression of magnetic reconnection by diamagnetic drifts.

During that period, given these consistent observational confirmations, diamagnetic suppression became a well established paradigm and is now widespread in the literature for the studies focusing on magnetic reconnection in various environments such as the solar wind [11,20–27], Mercury [28], Earth [29–35], Jupiter [36–39], Ganymede [40], Saturn [38,41–46], Uranus [38,47], Neptune [38,48], and the heliopause [49]. In such studies, Eq. (1) is typically used either to corroborate the detection or absence of reconnection signatures in events under consideration, or to assess the possible occurrence of magnetic reconnection in systems

where measurements are rare or do not exist yet but where θ and $\Delta\beta$ could be estimated.

However, in spite of appearing successful, the statistical confirmation of the theory was also seen as surprising since one could have expected other suppression mechanisms to blur the pattern unless they have the same dependence on both $\Delta\beta$ and θ . It was then rightfully concluded [16] that “*if that is true, diamagnetic drift of the X line may be the main effect that controls the occurrence of reconnection at the subsolar magnetopause.*”

In this Letter, we show that the statistical correlation observed in the $(\theta, \Delta\beta)$ plane for current sheets interpreted as reconnecting or not, can also be obtained if considering the effect of an observational bias. We show that plasma jet speeds are theoretically expected to have a strong correlation with both the magnetic shear and plasma β and slow jets are harder to contrast against surrounding variations in the flow time series. In the End Matter, we also derive the scaling relation for conditional suppression of magnetic reconnection by diamagnetic drifts in asymmetric conditions and show it does not depend on $\Delta\beta$, contrary to Eq. (1).

The Letter is organized as follows. The following section demonstrates the existence of an observational bias that tends to limit the visual observability of reconnection jets from spacecraft time series to some region of the $(\theta, \Delta\beta)$ space. We then discuss the obtained results and our conclusions.

Expected statistical observational bias—Although magnetic reconnection may be evidenced through multiple signatures in spacecraft *in situ* data, the most consistent one has been the observation of accelerated plasma flows. In the context of studies assessing the importance of diamagnetic suppression of magnetic reconnection [9,17,18], the observation of a reconnection jet has been

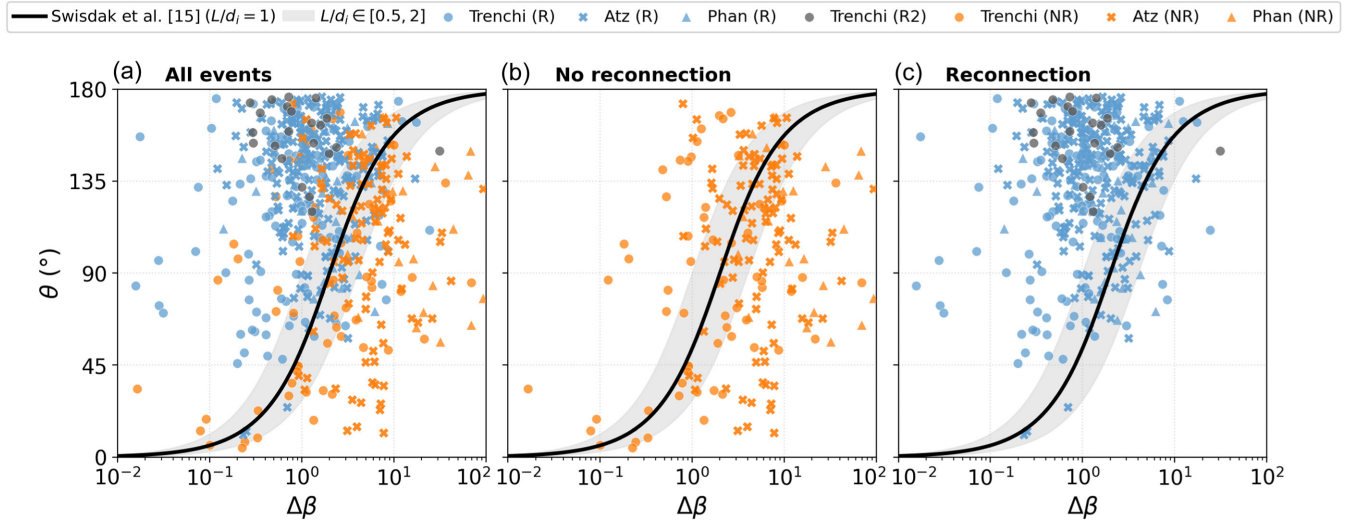


FIG. 1. Distribution of $(\theta, \Delta\beta)$ published from *Double Star* [17] and *THEMIS* [16,18] magnetopause crossings. Blue and orange markers are current sheets marked as reconnecting (R) or nonreconnecting (NR), respectively. Gray circle markers denote crossings with a jet reversal identified in [17]. The solid black line represents Eq. (1) with $L = 1\delta_i$, the gray area represent the region where $0.5 < L/\delta_i < 2$. Panels (b) and (c) plot nonreconnecting and reconnecting subsets already plotted on panel (a) in isolation for clarity.

the condition upon which a current sheet was classified as either reconnecting or not. However, the absence of evidence is not evidence of the absence. Observing a jet is evidence that reconnection is occurring somewhere. But the absence of a jet is not evidence that there is no reconnection occurring, and even less that a particular mechanism suppressed it.

At the Earth's magnetopause, the detection of a reconnection jet relies on the correlation between the variation of the velocity components with those of the magnetic field. However, selecting events with good certainty first requires the observations, “at the magnetopause proper or in the boundary layer ... [of] plasma flows with a different velocity, either in magnitude or direction, with respect to the adjacent magnetosheath” [50]. This flow comparison is generally difficult if the velocity during the crossing of the boundary does not detach clearly from the variations of the time series representing the bulk velocity in the magnetosheath. This leaves room for a possible observational bias if the jet velocity depends on θ and/or $\Delta\beta$. Although this reasoning applies to all environments where reconnection is observed, this Letter focuses on its observation at the Earth's magnetopause, which, frequently crossed by spacecraft, is the most suitable for a statistical study.

We propose to evaluate the likelihood of visually detecting reconnection jets in conditions statistically representative of the magnetopause seen by a spacecraft and study this likelihood in the $(\theta, \Delta\beta)$ plane. Our methodology is decomposed in three main steps. First, calculate the distribution of the expected reconnection outflow speeds given the natural distribution of upstream parameters met by spacecraft in a large statistical set of Earth's magnetopause crossings. Then, estimate how likely each expected flow speed is to be detected by comparing it to the fluctuation level in the adjacent magnetosheath time series. Finally, report the crossings in the $(\theta, \Delta\beta)$ plane, classified as observable or nonobservable, and discuss how their distribution relates to that of reconnecting and nonreconnecting current sheets reported in previous studies.

We use Magnetospheric MultiScale (MMS) data from 2015 to 2021 measured from the Fast Plasma Investigation [51] and Flux Gate Magnetometer instruments [52]. Magnetopause crossings are automatically selected as a transition between the magnetosphere and the magnetosheath, identified by a previously trained gradient boosting detection algorithm [53–56]. In this Letter, we retain only “clear” magnetopause encounters, defined by a single transition over a 10-min interval to select quiet conditions for which upstream conditions are meaningful, and as many points classified as magnetosheath as magnetosphere. We then associate with each crossing the conditions in the adjacent magnetosphere and magnetosheath. We finally obtain a dataset of 437 magnetopause crossings, sampling the typical intersections of MMS with the dayside magnetopause, with their associated upstream conditions.

From these intervals, we extract the median values of the magnetic field components, the particle density, the plasma temperature, and the standard deviation of the magnetosheath flow speed $\sigma_{v_{\text{msh}}}$.

We then estimate the amplitude of the jet velocity reconnection would produce in each of the conditions represented by the detected crossings, using the asymmetric Cassak-Shay scaling law [57] given by Eq. (2), assuming the X line locally bisects upstream field orientations to determine the merging components $B_{r,\text{msh}}$ and $B_{r,\text{msp}}$,

$$V_{\text{jet}}^2 = \frac{B_{r,\text{msh}}B_{r,\text{msp}}}{m_p\mu_0} \frac{B_{r,\text{msh}} + B_{r,\text{msp}}}{B_{r,\text{msh}}n_{\text{msp}} + B_{r,\text{msp}}n_{\text{msh}}}. \quad (2)$$

For each of the magnetopause crossings, the core of the present Letter is to determine whether the jet speed estimated from upstream conditions following Eq. (2) can be expected to detach from surrounding time series flow fluctuations. The expected jet is hereafter qualified as “observable” if

$$Q \equiv (V_{\text{jet}} > \alpha\sigma_{v_{\text{msh}}}), \quad (3)$$

where α controls how much a jet must detach from the surrounding time series fluctuations to be considered as observable. At the end of this process, we have a dataset of 437 couples $(|\Delta\beta|, \theta)$, each associated with its observability value Q_i .

Note that the observability of a jet depends on the observer, and Q_i only is a statistical proxy of it. Although skilled observers may detect some events deemed nonobservable, we assume Q_i represents well the degree of certainty one subjectively assesses when considering retaining an interval for a statistical study. Figure 2 shows an MMS inbound magnetopause crossing along with the predicted regions. For this particular crossing, we see the magnetic field reversal is mainly supported by the B_z geocentric solar magnetospheric component and well correlated with a strong signature of flow acceleration in the V_z geocentric solar magnetospheric component. Furthermore, the expected jet speed in the Earth rest frame matches well the observed peak speed. In this event, the magnetosheath flow fluctuation is $\sigma_{v_{\text{msh}}} \approx 21$ km/s, the magnetic shear $\theta \approx 166^\circ$, and the expected jet speed $V_{\text{jet}} \approx 209$ km/s so that $V_{\text{jet}} \approx 10\sigma_{v_{\text{msh}}}$, which easily qualifies a potential jet produced under these upstream conditions as observable, which is consistent with the easy identification of a jet around 06:34.

We emphasize that the proxy of observability Q only concerns the contrast between the magnetosheath flow fluctuations and the jet speed expected from automatically measured upstream conditions. Therefore, while we expect not to observe, statistically, jets in conditions assessed as nonobservable, the opposite is not true and jets may be missing in conditions assessed as observable simply because reconnection is not occurring, either because of some physical reasons or because the crossing is not temporally resolved. To clarify these assertions, we have

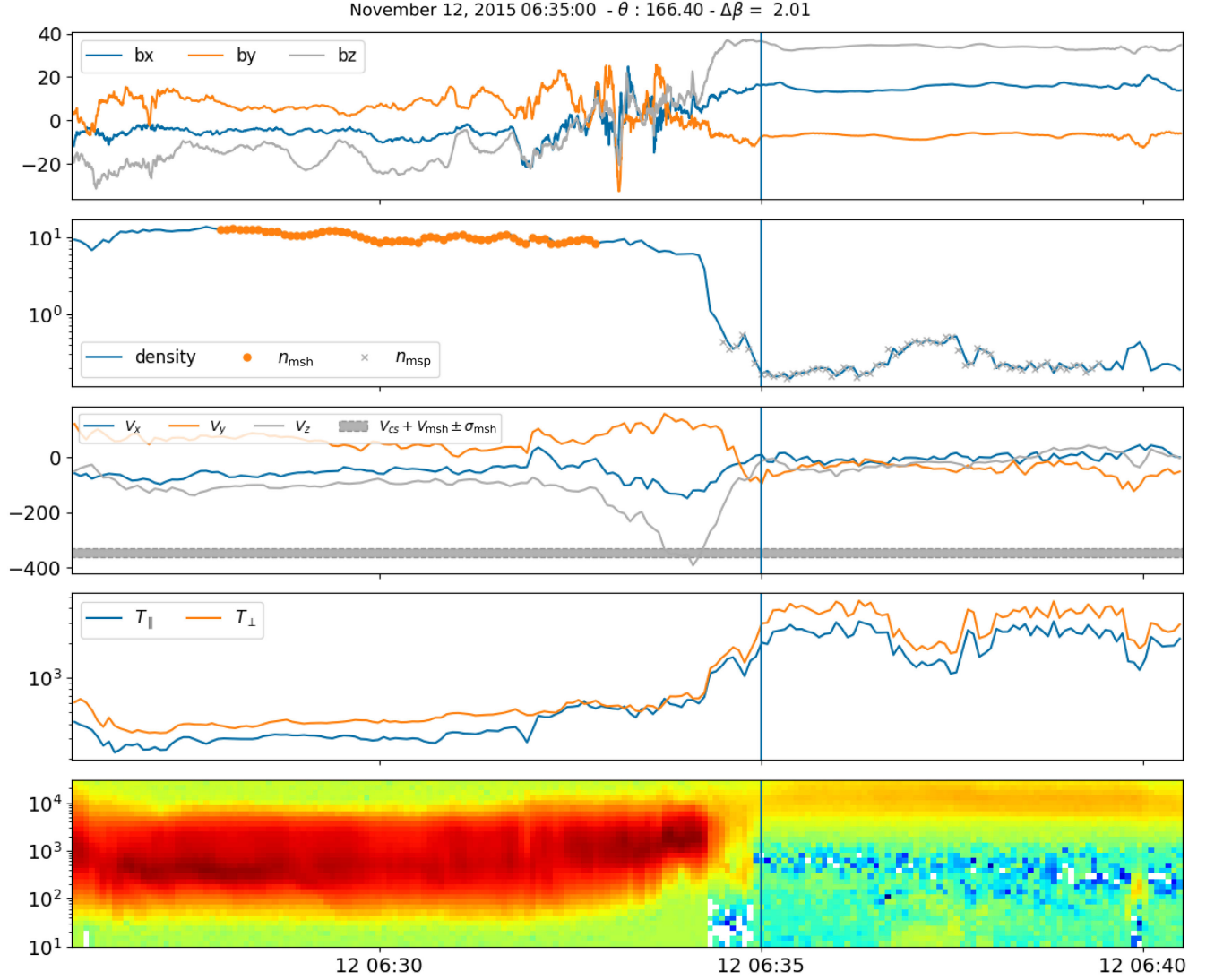


FIG. 2. From top to bottom: magnetic field components, particle density, ion bulk velocity components, temperature parallel and perpendicular to the magnetic field and ion omnidirectional energy flux measured by *MMSI*. The density panel also shows as circles and crosses the densities taken as magnetosheath (msh) and magnetosphere (msp) reference values, respectively. The bulk velocity panel also shows the predicted Cassak-Shay outflow speed in a gray band whose width is given by the standard deviation of the bulk velocity over the magnetosheath reference data. The vertical blue line indicates the position of the magnetopause crossing detected as the transition between regions automatically identified as the magnetosheath and magnetosphere.

looked at each of the 437 magnetopause crossings individually, and manually classified them further into those for which a reconnection jet is actually seen and those not (including by using burst data as necessary).

Table I shows the result of this cross-classification. As expected, jets are dominantly detected for crossings associated with observable conditions. Nonobservable conditions only correspond to a very small proportion of the observed reconnection jets. Their presence in this category may result from several reasons such as an observability Q being lower than the chosen arbitrary threshold, or the extracted upstream conditions not being exactly relevant to the ongoing reconnection event for reasons such as unsteadiness or the X line being at large distance from the crossing. Table I also reveals

that crossings where no jet is seen are nearly equally dispatched into observable and nonobservable conditions. This is expected, as previously said, since reconnection may not be happening whether conditions would qualify a jet as observable or not.

Figure 3 shows the position in the $(\theta, \Delta\beta)$ space, of the 437 expected flow jets velocities. Each sample is colored by its value of Q , and sized proportionally to the value of $\sigma_{v_{msh}}$. The observable and nonobservable expected outflow speeds do not distribute randomly in the $(\theta, \Delta\beta)$ space. In fact, Eq. (1) seems to separate our crossings arguably as well as in studies assessing the role of diamagnetic suppression. However, here, Eq. (1) is totally irrelevant to our classification, which is based on the expected

TABLE I. Confusion matrix of magnetopause crossings classified as observable or nonobservable and whether a reconnection jet is visible or not.

	Jet (%)	No jet (%)
Nonobservable	8.5	24
Observable	52.9	14.3

observability of jets with respect to background fluctuations, and not on their actual detection. Overall and unsurprisingly, observable expected outflows [Fig. 3(c)] are found at large shears while jets expected to be non-observable [Fig. 3(b)] are rather located at low shear. This can easily be explained by the dependence of V_{jet} on the merging component, which, for a given magnetic field amplitude, decreases with the magnetic shear, leading to slower jets, thus less detached from the magnetosheath flow fluctuations. Most observable jets are found for magnetic shears above $\theta \approx 90^\circ$. Interestingly, the expected outflows that continue to be classified as observable at lower magnetic shears are those associated with a lower fluctuation level for which weak jets can still detach. In contrast, all fluctuation levels are seen for expected outflows at large shear. Similarly, the few nonobservable outflows found at high shear all are associated with large magnetosheath flow fluctuations whereas those at low shear show all kinds of fluctuations. If the separation between observable and nonobservable outflows is mostly seen in the dependence with the magnetic shear, there is also a smaller but visible bias in $\Delta\beta$. The outflow speeds are

expected to be less observable as $\Delta\beta$ increases. This can be understood once noticing that, as shown in the bottom panel of Fig. 3, at the Earth's magnetopause, $\Delta\beta = |\beta_{\text{msp}} - \beta_{\text{msh}}| \approx \beta_{\text{msh}}$, and that larger β_{msh} means either lower magnetic field or larger density, or both, in all cases leading to slower expected outflows according to Eq. (2). Figures in the same format as Fig. 3 are provided as Supplemental Material [58] to show how the distribution of nonobservable and observable computed outflow speeds evolve as the observability threshold is changed from $\sigma_{v_{\text{msh}}}$ to $10\sigma_{v_{\text{msh}}}$. Raising the threshold means being more conservative regarding the observability of a jet and results in blue points being more restricted to higher shears.

Discussion and conclusion—In this Letter, we have shown that the reconnection outflow speed expected at the magnetopause and statistically estimated on a large set of magnetopause upstream conditions met by the MMS spacecraft may not always be observable simply because their detection requires that they may be well separated from flow variations of the surrounding time series. The scaling dependence of the outflow speed on the merging component and plasma density makes it strongly correlated with the magnetic shear angle and upstream plasma β . Jets are expected to be slower as the magnetic shear decreases and as β increases, down to the point where their speed becomes of the order of the adjacent magnetosheath flow fluctuation level. Jets in such circumstances should become increasingly harder to identify in time series. This bias suggests that low shear high β jets can become observationally “invisible” as if reconnection was not occurring.

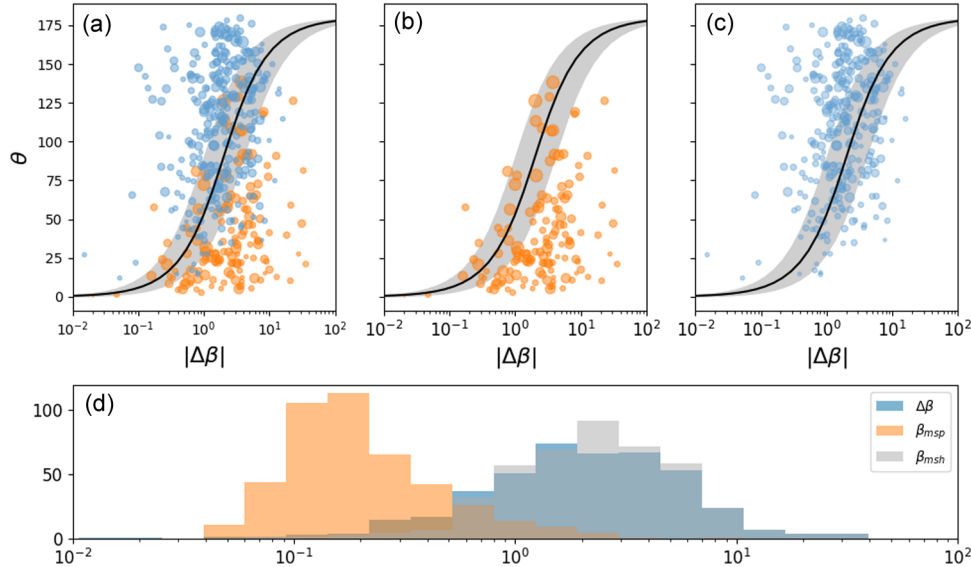


FIG. 3. Panel (a) shows the distribution of the 437 $(\theta, \Delta\beta)$ couples colored by their observability Q from Eq. (3), with $\alpha = 3$. The size of the circle marker represents the standard deviation of the flow speed in the reference magnetosheath. Blue and orange markers represent observable ($Q = \text{True}$) and nonobservable ($Q = \text{False}$) conditions. As in Fig. 1, the solid black line represents Eq. (1) with $L = 1$ and the gray area is where $0.5 < L/\delta_i < 2$. Panels (b) and (c) report observable and nonobservable points in isolation, respectively, for clarity. Panel (d) shows the distribution of the plasma β in the magnetosheath and magnetosphere reference measurements, as well as that of $\Delta\beta$.

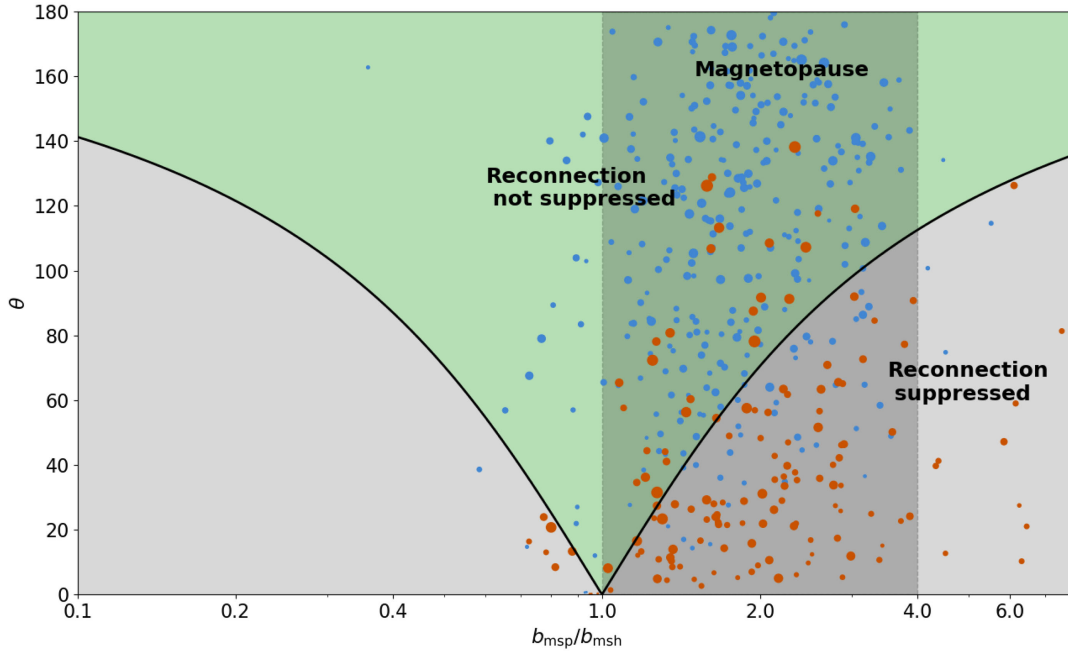


FIG. 4. The green area represents where Eq. (A8), with $L = \delta_i$, is satisfied and diamagnetic drifts do not suppress magnetic reconnection, in contrast to the gray region where it does. The dark gray vertical band is the typical area where magnetopause reconnection will take place. The blue and orange markers are the same as those on Fig. 3.

We think the bias discussed in this Letter is general enough so to exist in observations of all environments. However, its importance in each specific environment remains unclear as it mainly depends on the range of shear angles allowed in the system under consideration and the level of surrounding flow fluctuations in that system. In the solar wind, for instance, reconnection has been identified with extremely low magnetic shear angles down to few degrees [9]. This appears possible because, in spite of often being qualified as a turbulent environment, solar wind exhausts often show structures extremely consistent with laminar interpretations [11] and flow fluctuations are generally insignificant in comparison to any jet velocity. It is worth noting that, by flow fluctuations, we mean those existing in time series, which are not necessarily the same as those intrinsic to the flow itself. The magnetopause is always subject to varying upstream ram pressure and surface waves. As a result, spacecraft often cross the boundary multiple times, either partially or completely. Being by nature a boundary separating a large plasma flow and a relatively quasistagnant region, these multiple crossings create apparent large flow fluctuations. This temporal effect increases the impact of the discussed bias but is only relevant to magnetopauses and not solar wind exhausts. According to [22], solar wind exhausts seem to never fall in the suppressed part of the $(\theta, \Delta\beta)$ parameter space, as given by Eq. (1), no matter if reconnection signatures were identified or not, leading to the conclusion that diamagnetic suppression is not sufficient to explain the absence of reconnection.

In conclusion, while there is no reason to doubt that diamagnetic drift can suppress magnetic reconnection in

principle, the present Letter suggests that the observational evidence to support the impact of this mechanism at the magnetopause remains to be found. Relying solely on the nonobservation of an Alfvénic jet to conclude on the absence of reconnection not only is subject to the bias discussed in this Letter, but probably has other limitations. Excluding rare observations of jet reversals, it is unclear whether the local upstream conditions often used to evaluate diamagnetic suppression are relevant to the actual location of the X line producing the jet. Jet signatures are also expected to be obfuscated by the existence of multiple X lines and flux ropes or plasmoids. Such structures are known to be very common at the magnetopause, the heliospheric current sheet, and other media. It is obvious that there has to be a location somewhere in between two such X lines where there is no jet, while the conclusion of the current sheet being non-reconnected would be false. Considering the role of the current sheet thickness parameter also is a good example of the difficulty in interpreting the data [32], since thinner current sheets are generally known to be more conducive to the development of reconnection but at the same time more prone to suppressing it via faster diamagnetic drifts.

The analysis of *in situ* measurements has been done with the Python package SPEasy and the software SciQLOP developed at the French center for plasma physics data (CDPP) using data distributed from both CDPP/AMDA and CDAweb.

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Data availability—The data that support the findings of this article are openly available from CDAWeb [59] and can be retrieved from the Python package SPEasy [60].

- [1] R. Wang, S. Lu, S. Wang, X. Li, and Q. Lu, Recent progress on magnetic reconnection by *in situ* measurements, *Rev. Mod. Plasma Phys.* **7**, 27 (2023).
- [2] M. Hesse and P. A. Cassak, Magnetic reconnection in the space sciences: Past, present, and future, *J. Geophys. Res. Space Phys.* **125**, e25935 (2020).
- [3] K. J. Hwang, R. Nakamura, J. P. Eastwood, S. A. Fuselier, H. Hasegawa, T. Nakamura, B. Lavraud, K. Dokgo, D. L. Turner, R. E. Ergun, and P. H. Reiff, Cross-scale processes of magnetic reconnection, *Space Sci. Rev.* **219**, 71 (2023).
- [4] P. A. Cassak, Inside the black box: Magnetic reconnection and the magnetospheric multiscale mission, *Space Weather* **14**, 186 (2016).
- [5] P. A. Cassak, Y. H. Liu, and M. A. Shay, A review of the 0.1 reconnection rate problem, *J. Plasma Phys.* **83**, 715830501 (2017).
- [6] J. P. Eastwood, H. Hietala, G. Toth, T. D. Phan, and M. Fujimoto, What controls the structure and dynamics of Earth's magnetosphere?, *Space Sci. Rev.* **188**, 251 (2015).
- [7] K. J. Trattner, S. M. Petrinen, and S. A. Fuselier, The location of magnetic reconnection at Earth's magnetopause, *Space Sci. Rev.* **217**, 41 (2021).
- [8] J. T. Gosling, R. M. Skoug, D. J. McComas, and C. W. Smith, Direct evidence for magnetic reconnection in the solar wind near 1 AU, *J. Geophys. Res. Space Phys.* **110**, A01107 (2005).
- [9] T. D. Phan, J. T. Gosling, G. Paschmann, C. Pasma, J. F. Drake, M. Øieroset, D. Larson, R. P. Lin, and M. S. Davis, The dependence of magnetic reconnection on plasma β and magnetic shear: Evidence from solar wind observations, *Astrophys. J. Lett.* **719**, L199 (2010).
- [10] B. Lavraud, A. Ruffenach, A. P. Rouillard, P. Kajdic, W. B. Manchester, and N. Lugaz, Geo-effectiveness and radial dependence of magnetic cloud erosion by magnetic reconnection, *J. Geophys. Res. Space Phys.* **119**, 26 (2014).
- [11] N. Fargette, B. Lavraud, A. P. Rouillard, P. S. Houdayer, T. D. Phan, M. Øieroset, J. P. Eastwood, G. Nicolaou, A. Fedorov, P. Louarn, C. J. Owen, and T. S. Horbury, Clustering of magnetic reconnection exhausts in the solar wind: An automated detection study, *Astron. Astrophys.* **674**, A98 (2023).
- [12] D. J. Gershman, S. A. Fuselier, I. J. Cohen, D. L. Turner, Y.-H. Liu, L.-J. Chen, T. D. Phan, J. E. Stawarz, G. A. DiBraccio, A. Masters, R. W. Ebert, W. Sun, Y. Harada, and M. Swisdak, Magnetic reconnection at planetary bodies and astrospheres, *Space Sci. Rev.* **220**, 7 (2024).
- [13] H. Ji, J. Yoo, W. Fox, M. Yamada, M. Argall, J. Egedal, Y. H. Liu, R. Wilder, S. Eriksson, W. Daughton, K. Bergstedt, S. Bose, J. Burch, R. Torbert, J. Ng, and L. J. Chen, Laboratory study of collisionless magnetic reconnection, *Space Sci. Rev.* **219**, 76 (2023).
- [14] M. Swisdak, B. N. Rogers, J. F. Drake, and M. A. Shay, Diamagnetic suppression of component magnetic reconnection at the magnetopause, *J. Geophys. Res. Space Phys.* **108**, 1218 (2003).
- [15] M. Swisdak, M. Opher, J. F. Drake, and F. Alouani Bibi, The vector direction of the interstellar magnetic field outside the heliosphere, *Astrophys. J.* **710**, 1769 (2010).
- [16] T. D. Phan, G. Paschmann, J. T. Gosling, M. Øieroset, M. Fujimoto, J. F. Drake, and V. Angelopoulos, The dependence of magnetic reconnection on plasma β and magnetic shear: Evidence from magnetopause observations, *Geophys. Res. Lett.* **40**, 11 (2013).
- [17] L. Trenchi, M. F. Marcucci, and R. C. Fear, The effect of diamagnetic drift on motion of the dayside magnetopause reconnection line, *Geophys. Res. Lett.* **42**, 6129 (2015).
- [18] E. A. Atz, B. M. Walsh, J. M. Broll, and Y. Zou, The spatial extent of magnetopause magnetic reconnection from *in situ* THEMIS measurements, *J. Geophys. Res. Space Phys.* **127**, e2022JA030894 (2022).
- [19] B. U. O. Sonnerup, I. Papamastorakis, G. Paschmann, and H. Luehr, Magnetopause properties from AMPTE/IRM observations of the convection electric field: Method development, *J. Geophys. Res.* **92**, 12137 (1987).
- [20] J. T. Gosling and T. D. Phan, Magnetic reconnection in the solar wind at current sheets associated with extremely small field shear angles, *Astrophys. J. Lett.* **763**, L39 (2013).
- [21] T. D. Phan *et al.*, Parker solar probe *in situ* observations of magnetic reconnection exhausts during encounter 1, *Astrophys. J. Suppl. Ser.* **246**, 34 (2020).
- [22] T. D. Phan *et al.*, Parker solar probe *in situ* observations of magnetic reconnection exhausts during encounter 1, *Astrophys. J. Suppl. Ser.* **246**, 34 (2020).
- [23] M. Akhavan-Tafti, J. Kasper, J. Huang, and S. Bale, Discontinuity analysis of the leading switchback transition regions, *Astron. Astrophys.* **650**, A4 (2021).
- [24] B. Lavraud *et al.*, Magnetic reconnection as a mechanism to produce multiple thermal proton populations and beams locally in the solar wind, *Astron. Astrophys.* **656**, A37 (2021).
- [25] A. B. Lotekar, I. Y. Vasko, T. Phan, S. D. Bale, T. A. Bowen, J. Halekas, A. V. Artemyev, Y. V. Khotyaintsev, and F. S. Mozer, Kinetic-scale current sheets in near-sun solar wind: Properties, scale-dependent features and reconnection onset, *Astrophys. J.* **929**, 58 (2022).
- [26] S. Eriksson, M. Swisdak, J. M. Weygand, A. Mallet, D. L. Newman, G. Lapenta, I. Wilson, Lynn B., D. L. Turner, and B. Larsen, Characteristics of multi-scale current sheets in the solar wind at 1 au associated with magnetic reconnection and the case for a heliospheric current sheet avalanche, *Astrophys. J.* **933**, 181 (2022).
- [27] I. Y. Vasko, K. Alimov, T. D. Phan, F. S. Mozer, and A. V. Artemyev, Kinetic-scale current sheets in the solar wind at 5 AU, *J. Geophys. Res. Space Phys.* **129**, e2024JA032586 (2024).
- [28] G. A. DiBraccio, J. A. Slavin, S. A. Boardsen, B. J. Anderson, H. Korth, T. H. Zurbuchen, J. M. Raines, D. N. Baker, R. L. McNutt, and S. C. Solomon, MESSENGER observations of magnetopause structure and dynamics at Mercury, *J. Geophys. Res. Space Phys.* **118**, 997 (2013).
- [29] S. A. Fuselier *et al.*, Large-scale characteristics of reconnection diffusion regions and associated magnetopause crossings observed by MMS, *J. Geophys. Res. Space Phys.* **122**, 5466 (2017).

- [30] M. Øieroset *et al.*, Reconnection with magnetic flux pileup at the interface of converging jets at the magnetopause, *Geophys. Res. Lett.* **46**, 1937 (2019).
- [31] D. Koga, W. D. Gonzalez, V. M. Souza, F. R. Cardoso, C. Wang, and Z. K. Liu, Dayside magnetopause reconnection: Its dependence on solar wind and magnetosheath conditions, *J. Geophys. Res. Space Phys.* **124**, 8778 (2019).
- [32] Y. Vernisse *et al.*, Latitudinal dependence of the Kelvin-Helmholtz instability and beta dependence of vortex-induced high-guide field magnetic reconnection, *J. Geophys. Res. Space Phys.* **125**, e27333 (2020).
- [33] S. Toledo-Redondo, K. J. Hwang, C. P. Escoubet, B. Lavraud, J. Fornieles, N. Aunai, R. C. Fear, J. Dargent, H. S. Fu, S. A. Fuselier, K. J. Genestreti, Y. V. Khotyaintsev, W. Y. Li, C. Norgren, and T. D. Phan, Solar wind—magnetosphere coupling during radial interplanetary magnetic field conditions: Simultaneous multi-point observations, *J. Geophys. Res. Space Phys.* **126**, e29506 (2021).
- [34] K. Maheshwari, T. D. Phan, M. Øieroset, N. Fargette, B. Lavraud, J. L. Burch, R. J. Strangeway, D. J. Gershman, and B. L. Giles, Investigation of the diamagnetic drift condition for the suppression of magnetic reconnection in 3D interlinked reconnection events with magnetic flux pileup, *Astrophys. J.* **940**, 177 (2022).
- [35] K. J. Genestreti *et al.*, Multiscale observation of magnetotail reconnection onset: I. Macroscopic dynamics, *J. Geophys. Res. Space Phys.* **128**, e2023JA031758 (2023).
- [36] M. Desroche, F. Bagenal, P. A. Delamere, and N. Erkaev, Conditions at the expanded Jovian magnetopause and implications for the solar wind interaction, *J. Geophys. Res. Space Phys.* **117**, A07202 (2012).
- [37] D. A. Ranquist, F. Bagenal, R. J. Wilson, G. Hospodarsky, R. W. Ebert, F. Allegrini, P. Valek, D. J. McComas, J. E. P. Connerney, W. S. Kurth, and S. J. Bolton, Survey of Jupiter's dawn magnetosheath using Juno, *J. Geophys. Res. Space Phys.* **124**, 9106 (2019).
- [38] D. J. Gershman and G. A. DiBraccio, Solar cycle dependence of solar wind coupling with giant planet magnetospheres, *Geophys. Res. Lett.* **47**, e89315 (2020).
- [39] J. Montgomery, R. W. Ebert, G. Clark, S. A. Fuselier, F. Allegrini, F. Bagenal, S. J. Bolton, G. A. DiBraccio, and R. J. Wilson, Investigating the occurrence of magnetic reconnection at Jupiter's dawn magnetopause during the Juno era, *Geophys. Res. Lett.* **49**, e99141 (2022).
- [40] N. Kaweeyanun, A. Masters, and X. Jia, Favorable conditions for magnetic reconnection at Ganymede's upstream magnetopause, *Geophys. Res. Lett.* **47**, e86228 (2020).
- [41] A. Masters, J. P. Eastwood, M. Swisdak, M. F. Thomsen, C. T. Russell, N. Sergis, F. J. Crary, M. K. Dougherty, A. J. Coates, and S. M. Krimigis, The importance of plasma β conditions for magnetic reconnection at Saturn's magnetopause, *Geophys. Res. Lett.* **39**, L08103 (2012).
- [42] R. P. Sawyer, S. A. Fuselier, J. Mukherjee, and S. M. Petrinec, An investigation of flow shear and diamagnetic drift effects on magnetic reconnection at Saturn's dawnside magnetopause, *J. Geophys. Res. Space Phys.* **124**, 8457 (2019).
- [43] S. A. Fuselier, R. Frahm, W. S. Lewis, A. Masters, J. Mukherjee, S. M. Petrinec, and I. J. Sillanpää, The location of magnetic reconnection at Saturn's magnetopause: A comparison with Earth, *J. Geophys. Res. Space Phys.* **119**, 2563 (2014).
- [44] S. A. Fuselier, S. M. Petrinec, R. P. Sawyer, J. Mukherjee, and A. Masters, Suppression of magnetic reconnection at Saturn's low-latitude magnetopause, *J. Geophys. Res. Space Phys.* **125**, e27895 (2020).
- [45] I. Cheng, N. Achilleos, A. Masters, G. Lewis, M. Kane, and P. Guio, Electron bulk heating at Saturn's magnetopause, *J. Geophys. Res. Space Phys.* **126**, e28800 (2021).
- [46] W. Mo, S. K. Vines, R. C. Allen, C. M. Jackman, and C. Paranicas, Magnetopause dynamics at Saturn as observed by Cassini, *J. Geophys. Res. Space Phys.* **128**, e2022JA031258 (2023).
- [47] A. Masters, Magnetic reconnection at Uranus' magnetopause, *J. Geophys. Res. Space Phys.* **119**, 5520 (2014).
- [48] A. Masters, Magnetic reconnection at Neptune's magnetopause, *J. Geophys. Res. Space Phys.* **120**, 479 (2015).
- [49] S. A. Fuselier and I. H. Cairns, Reconnection at the heliopause: Predictions for Voyager 2, *J. Phys. Conf. Ser.* **900**, 012007 (2017).
- [50] L. Trenchi, M. F. Marcucci, G. Palloccchia, G. Consolini, M. B. Bavassano Cattaneo, A. M. di Lellis, H. Rème, L. Kistler, C. M. Carr, and J. B. Cao, Occurrence of reconnection jets at the dayside magnetopause: Double Star observations, *J. Geophys. Res. Space Phys.* **113**, A07S10 (2008).
- [51] C. Pollock *et al.*, Fast plasma investigation for magnetospheric multiscale, *Space Sci. Rev.* **199**, 331 (2016).
- [52] C. T. Russell *et al.*, The magnetospheric multiscale magnetometers, *Space Sci. Rev.* **199**, 189 (2016).
- [53] G. Nguyen, N. Aunai, B. M. d. Welle, A. Jeandet, B. Lavraud, and D. Fontaine, Massive multi-mission statistical study and analytical modeling of the Earth's magnetopause: 1. A gradient boosting based automatic detection of near-earth regions, *J. Geophys. Res. Space Phys.* **127**, e2021JA029773 (2022).
- [54] B. Michotte de Welle, N. Aunai, G. Nguyen, B. Lavraud, V. Génot, A. Jeandet, and R. Smets, Global three-dimensional draping of magnetic field lines in Earth's magnetosheath from in-situ spacecraft measurements, *J. Geophys. Res. Space Phys.* **127**, e2022JA030996 (2022).
- [55] B. Michotte de Welle, N. Aunai, B. Lavraud, V. Génot, A. Jeandet, G. Nguyen, A. Ghisalberti, and R. Smets, Spatial distribution of plasma density and magnetic field amplitude in the dayside magnetosheath as a function of the IMF orientation, *Front. Astron. Space Sci.* **11**, 1427791 (2024).
- [56] B. Michotte de Welle, N. Aunai, B. Lavraud, V. Génot, G. Nguyen, A. Ghisalberti, R. Smets, and A. Jeandet, Global environmental constraints on magnetic reconnection at the magnetopause from *in situ* measurements, *J. Geophys. Res. Space Phys.* **129**, e2023JA032098 (2024).
- [57] P. A. Cassak and M. A. Shay, Scaling of asymmetric magnetic reconnection: General theory and collisional simulations, *Phys. Plasmas* **14**, 2114 (2007).
- [58] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/rlxh-smd1> for figures in the same format as Fig. 3 are provided as Supplemental Material [58] to show how the distribution of nonobservable and observable computed outflow speeds evolve as the observability threshold is changed from $\sigma_{v_{\text{msh}}}$.
- [59] <https://cdaweb.gsfc.nasa.gov>.
- [60] <https://github.com/sciqlop/speasy>.

End Matter

The condition for diamagnetic suppression—This section aims at deriving the condition for the suppression of magnetic reconnection by diamagnetic drifts. The proposed derivation accounts for the asymmetry of the current sheet, which former derivations neglect [14,15]. In a given plane x - y , where x and y are the outflow and inflow directions, respectively, the condition for reconnection to occur translates into $V_{\text{out}} > V_{\star}$, where V_{out} is the reconnection outflow speed and $V_{\star} = |v_{i\star}| + |v_{e\star}|$ the sum of the ion and electron diamagnetic drift speeds. The outflow velocity V_{out} can be estimated using the Cassak-Shay scaling law to account for asymmetric magnetic fields and densities,

$$V_{\text{cs}} = \sqrt{\frac{B_1 B_2}{m_p n_0 \mu_0}} \quad (\text{A1})$$

with

$$n_0 = \frac{B_2 n_1 + B_1 n_2}{B_1 + B_2}. \quad (\text{A2})$$

Assuming the X line aligns with the bisection of the upstream fields, and given the magnetic shear angle θ , the reconnecting components are $B_{ix} = B_i \sin \theta/2$ and the outflow velocity becomes

$$V_{\text{out}} = V_{\text{cs}} \sin(\theta/2). \quad (\text{A3})$$

The diamagnetic drift velocity $V_{\star}$ is given by

$$V_{\star} = \left| \frac{\nabla P \times \mathbf{B}}{enB^2} \right|, \quad (\text{A4})$$

where P , e , and n are the total (electron and ions) thermal pressure, the elementary electrical charge, and the particle density (assuming quasineutrality $n \equiv n_e \approx n_i$), respectively, and $\mathbf{B}$ the magnetic field. Evaluated in the current sheet at the location of the field reversal where the magnetic field points along the X line and its only nonzero component is B_{0z} and the density is n_0 , the condition for suppressing reconnection becomes

$$V_{\text{cs}} \sin(\theta/2) < \frac{\nabla P}{en_0 B_{0z}}. \quad (\text{A5})$$

In this equation, as in Eq. (1), the suppression of reconnection depends on how the thermal pressure and

the magnetic field (in amplitude and direction) vary across the current layer. However, these two quantities are not independent from each other. Pressure balance links the variation of the pressure to that of the magnetic field amplitude so that, at the reversal exactly, $\mu_0 \partial_y P = B_{0z} \partial_y B_z \approx B_{0z} \Delta B_z / L$, with $\Delta B_z = |B_{z1} - B_{z2}|$ and L is the current sheet thickness. This relation between P and B through pressure balance must be accounted for as all combinations of the two quantities are not possible, as Eq. (1) seems to suggest. The condition for suppression becomes

$$V_{\text{cs}} \sin(\theta/2) < \frac{\Delta B_z}{en_0 \mu_0 L}. \quad (\text{A6})$$

Unlike under symmetric conditions, asymmetric upstream inflow regions have different out-of-plane components $B_{zi} = B_i \cos(\theta/2)$, such that $\Delta B_z = \Delta B \cos(\theta/2)$. We obtain

$$\tan(\theta/2) < \frac{\Delta B}{en_0 L \mu_0 V_{\text{cs}}}. \quad (\text{A7})$$

Injecting Eq. (A1) and introducing $r = B_1/B_2$ leads to

$$\tan(\theta/2) < \frac{\delta_i}{L} \sqrt{\frac{(1-r)^2}{r}}. \quad (\text{A8})$$

Note, as expected, that this formula is invariant when replacing r by $\tilde{r} = B_2/B_1$.

Inspecting Fig. 4 shows that symmetric reconnection is never suppressed, as expected since diamagnetic drift only exists for noncoplanar configurations. Suppression then becomes more important as the field amplitude asymmetry increases, starting with the suppression of the lower shears and progressively extending to larger magnetic shears. Consistently with Eq. (A8), reconnection of antiparallel ($\theta = \pi$) magnetic fields is never suppressed, since in such condition $\nabla P = 0$ and the diamagnetic drift vanishes. Given the typical ratio of the magnetic field amplitudes at the Earth's magnetopause, it is probable that reconnection is never suppressed for shear angles larger than $\theta \approx 100^\circ$. As can be seen on Fig. 4(c) the observational and statistical confirmation of this theoretical prediction is also subject to the same possible observational bias discussed in this Letter because of the dependence of the jet velocity on both the magnetic shear and the magnetic field amplitude asymmetry.