A kinetic perspective on azimuthal variation of magnetopause reconnection at scales below an Earth radius

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Abstract. Magnetic reconnection efficiency at the Earth’s magnetopause has recently been shown to exhibit variations in reconnection jet amplitudes at azimuthal scales below an Earth radius [1]. This finding, however, is obtained based on the bulk velocity moment measurements. If there exists a significant cold magnetospheric ion population in addition to the accelerated magnetosheath population, the combination of the two would yield a low bulk velocity moment that does not necessarily correspond to a weak reconnection activity. Here we analyse ion distribution functions of the three reconnection events in [1] to examine whether the varying jet amplitudes are due to the presence of cold magnetospheric ions or variations of reconnection acceleration. Our results show that, although the cold magnetospheric ions have lowered the absolute bulk velocity, the relative variation trend of the bulk velocity is consistent with that of the acceleration gained by magnetosheath ions. The result supports the interpretation that reconnection activity can vary azimuthally on scales below an Earth radius.

1. Introduction
The structure of magnetic reconnection in the direction of the X-line has yet been well understood. At Earth’s magnetopause and under a southward IMF, the direction typically corresponds to the azimuthal direction, and the structure of reconnection in this direction is critical to understand how much energy from the solar wind enters Earth’s magnetosphere. Progress has been made by surveying reconnection at spacecraft separated by various distances and examining whether and how much the process differs. At kinetic scales, signatures of reconnection are often simultaneously observed by spacecraft separated by tens of km [2-8]. On large scales of a few to >10 Earth radii (R\textsubscript{E}), the signatures are sometimes simultaneously observed [9-12], sometimes by one spacecraft only [13-15]. The latter suggests that reconnection transitions from active to inactive at a few- R\textsubscript{E} scale, although it is uncertain whether this
scale reflects the true scale of variation, or merely gives an upper bound because of the spatial resolution of the observations offered by the spacecraft separation.

The transition from active to inactive reconnection between the kinetic and a-few-\(R_E\) scale has been less investigated due to the lack of spacecraft observations from constellations or serendipitous conjunctions at sub-\(R_E\) scales. The sub-\(R_E\) scale generally corresponds to a few to tens of ion inertial lengths under typical magnetosheath conditions. Among the few reports, measurements during the first few years of the CLUSTER mission reveal that magnetic flux structures produced by transient magnetopause reconnection, i.e., flux transfer events, commonly (70%) do not extend across the whole constellation with spacing < 1 \(R_E\) [16]. A recent study [1] utilizes the constellation formed by three THEMIS spacecraft and finds that reconnection exhibits variations in the reconnection jet amplitudes within several tenths of \(R_E\). The major conclusions from this study are as follows.

a. Reconnection jets transition from being present to absent within tenths of \(R_E\), corresponding to tens of ion inertial lengths. The absence of jets is not due to spacecraft encountering an ion or electron diffusion region, or a magnetic flux rope flanked by two reconnection sites.

b. Strong (weak) reconnection jets are associated with strong (weak) broadband low-frequency electromagnetic waves.

c. Causes of the variation of the reconnection jets are not directly identified from local magnetopause or upstream magnetosheath conditions.

The amplitude of the reconnection jets in [1] is determined based on the bulk velocity moment, following the conventional Walén test procedure. The Walén relation predicts how the tangential velocity component changes as plasmas, such as those from the magnetosheath, flow across a rotational discontinuity. If the bulk velocity moment is >50% consistent with the Walén prediction, it is labeled as an active reconnection jet. The approach can be limited, however, when the penetrated magnetosheath population collocates with a significant population that pre-exists (and has not been accelerated by reconnection) in the magnetosphere because the combination of the two would yield a low bulk velocity moment that does not necessarily correspond to an inactive reconnection activity. And a cold magnetospheric ion population is visible in all the three events analyzed in [1]. It is hence important to examine particle distribution functions to understand the contribution of each population. In this paper we analyze ion distribution functions provided by THEMIS for the same three events in [1] to understand what gives rise to the reconnection jets of varying amplitudes, variations of the acceleration of reconnection or the presence of cold magnetospheric ions.

2. Observation

2.1 Event on September 27, 2010

To illustrate how reconnection jets transitioned from presence to absence according to the fluid signature of reconnection, Panels a1-a4, b1-b4, and c1-c4 in Figure 1 present measurements of magnetic field, plasma density, ion energy spectra, and ion bulk velocity, as modified from [1]. THD observed an ion bulk flow with a peak speed of 357 km/s (Panel c4). A Walén test reveals that the observed reconnection jet speed was 86% of the predicted speed, and that the direction differed from the predicted jet velocity by 15°. Therefore, when projecting the observed velocity onto the predicted jet direction, the observation was 83% of the prediction. THE also detected a reconnection jet, whose projection was 71% of the Walén prediction. On the other hand, the ion bulk flow at THA was only 39% of the Walén prediction.

The presence of cold ions in the magnetosphere can be seen from the plasma density derived from the spacecraft potential (blue lines in Panels a2, b2, and c2), which was higher than that measured by the electrostatic analyzers (black lines). The difference is due to the presence of particles with energy of \(\sim\) a few eV that are below the energy range of the electrostatic analyzers. The plasma density in the magnetosphere was similar among the three spacecraft, all being 2-3 cm\(^{-3}\).

To discern whether the slow flow at THA was due to the inclusion of the cold magnetospheric ions in the plasma moment computation, Panels a5, b5, and c5 present snapshots of ion distribution functions made by the three spacecraft at the inner/earthward edge of the magnetopause boundary layer. The low-latitude boundary layer is populated by plasma from both the magnetosphere and the magnetosheath.
The magnetosheath plasma enters the magnetosphere through magnetic reconnection or diffusion, and the former process involves an acceleration of plasma to Alfvénic speed and produces a D-shape distribution [17]. As for the magnetospheric plasma, the density of plasma originated from the plasma sheet is usually two orders of magnitude lower than the magnetosheath, although there often exists a colder component that is assumed to be originated from the ionosphere. In the following events, we refer to this colder component as cold magnetospheric ions although it at times was somewhat warm.

Considering that the penetrated magnetosheath particles are subject to the time-of-flight effect, where particles with higher parallel speeds can penetrate deeper into the magnetosphere given the same transverse drift, we focus on the inner edge of the boundary layer so as to capture the comparatively fast component of the accelerated magnetosheath ions. Operationally, the inner edge is determined as the first appearance of magnetosheath ions in the distribution functions as one approaches the boundary layer from the magnetospheric side. The location of such inner edge is marked as the black vertical lines in Panels a1-a4, b1-b4, and c1-c4. The inner edge also serves as a reference location to ensure that the reconnection signatures under comparison are taken from similar radial distance from the X-line so that the difference in signatures can mostly be attributed to variations in the X-line direction.

![Figure 1](https://example.com/image1)

**Figure 1.** Panels a1-a4, b1-b4, and c1-c4: magnetic field, plasma density, ion energy spectra, and ion bulk velocity at THA, THE, and THD, respectively. The magnetic field data were taken from high-resolution FGM data for THA and THD, and from low-resolution FGM data for THE. The plasma measurements were taken from burst mode ESA data for THA, and THD, and reduced mode for THE. The magnetic field and velocity are presented in LMN coordinates, which are determined by minimum variance analysis of each spacecraft data. Panels a5, b5, and c5: ion distributions at THA, THE, and THD, respectively, as taken from ESA data. These distributions are taken at the inner edge of the low latitude boundary layer, which is marked by the black vertical lines in Panels a1-a4, b1-b4, and c1-c4.

The ion distribution functions are presented in bulk velocity-magnetic field plane, and the small red line extended from the origin indicates the direction and speed of the bulk velocity moment of the distribution. A dashed black circle marking a speed of 400 m/s is overlain for the ease of comparison. This speed was selected arbitrarily, but as seen below it is on the order of the Walén-predicted reconnection jet speed at the inner edge of the boundary layer (the specific prediction varied from case to case and from spacecraft to spacecraft).
All three snapshots show the existence of two distinct populations, the dense and cold magnetospheric ions with a low speed, and the more tenuous and hotter magnetosheath ions. The speed of the magnetosheath ions decreases from THD, to THE, and to THA, similarly to the bulk flow speeds seen in Panels a4, b4, and c4. The speed at THA was significantly lower than the Walén prediction, which was 417 km/s at the given spacecraft location in the spacecraft reference frame. Although these distribution functions are expected to have captured the comparatively fast component of the accelerated magnetosheath ions, the ion speed was still far off the prediction. Therefore, although the magnitude of the bulk velocity was lowered by the cold magnetospheric ions, the azimuthal variation trend is consistent with the amount of acceleration gained by the magnetosheath ions. This suggests that the amount of acceleration of magnetosheath ions associated with reconnection decreased from THD to THA. The cold magnetospheric ions at THA had a substantial velocity perpendicular to the magnetic field (Panel a5), possibly resulting from the motion of the magnetopause.

2.2 Event on October 16, 2010
Similar features are also observed for the event occurring on October 16, 2010 in Figure 2. In Panels a3, b3, and c3, while the accelerated magnetosheath ions at the inner edge of the boundary layer had a velocity peaked at ~400 km/s at THA and THE, the velocity peaked at ~220 km/s at THD. The Walén relation predicts that a reconnection jet should have a speed of 380 km/s at THD in the spacecraft reference frame. This variation trend is consistent with that based on the bulk velocity moment shown in Panels a2, b2, and c2, and hence supports the interpretation that reconnection activity subsided from THE to THD, which were separated by 0.5 RE in the azimuthal direction.

Figure 2. Similar to Panels a3-a5, b3-b5, and c3-c5 in Figure 1 but show the magnetopause crossings on October 16, 2010.

2.3 Event on October 21, 2010
Although the event on October 21, 2020 is more complex than the above two events, we present its measurements in Figure 3 and discuss the implications. The spacecraft’s encounters with the boundary layer were brief in this event, because throughout the magnetopause crossings, only one data sample captured the simultaneous presence of magnetospheric and magnetosheath ions for THA and THE. THD did not capture such simultaneous presence, and we present the distribution function before the cold magnetospheric ion population was seen.

For THA and THE, the accelerated magnetosheath ions had a lower velocity at THA than at THE, and this relative strength is consistent with the bulk velocity moment, as the other two events. However, the presence of the cold magnetospheric ions has affected the determination of reconnection occurrence
at THE. For instance, while the bulk plasma velocity in Panel b2 was 36% of the Walén prediction, the accelerated magnetosheath ions in Panel b3 had a velocity consistent with a reconnection jet with a predicted speed of 335 km/s. (The accelerated magnetosheath ions at THA were still slower than the predicted reconnection jet speed of 364 km/s.) Indeed, when one is to make a binary classification of reconnection occurrence, the decision can be affected by the inclusion/exclusion of the cold magnetospheric ions as well as the specific choice of the threshold or criterial used for classification.

For THD, since the data were dominated by one ion population rather than the mixture of the magnetospheric and magnetosheath ions, the bulk velocity moment serves as an accurate characterization of the ion velocity. The same is true for THA and THE measurements taken outside the boundary layer. Hence, the Walén test conducted in [1] is still valid for these regions, and a comparison of Panels a2, b2, and c2 suggests that the acceleration of reconnection was largest at THD.

![Figure 3](image-url)  
**Figure 3.** Similar to Panels a5, b5, and c5 but show the ion distributions of magnetopause crossings on October 21, 2010.

Note that while in this paper consistent variation trends have been found between the bulk velocity moment and ion distribution functions, the consistency may not be generalized to all situations. It is still important to examine particle distributions in addition to performing the Walén test to ensure that a limited agreement with the Walén relation is not due to the inclusion of the cold magnetospheric ions.

3. Conclusion
We examined from a kinetic perspective whether reconnection at the Earth magnetopause varies at sub-$R_E$ in the azimuthal direction by inspecting the ion distribution functions. The results show that for the three studied events, there exist two ion populations at the plasma boundary layer, the cold magnetospheric ions and the accelerated magnetosheath ions. Based on these accelerated magnetosheath ions, we find that the amount of acceleration, compared with the Walén prediction, can decrease substantially over sub-$R_E$. This result supports the conclusion of [1], indicating that the sub-$R_E$ scale is indeed a critical azimuthal scale for magnetopause reconnection, at least during certain stages of its development.

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