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Interactive comment on "Local time extent of magnetopause reconnection X-lines using space–ground coordination" *by* Ying Zou et al.

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This paper is concerned with estimating the extent of reconnection X-lines on the Earth's magnetopause, with an overall aim of measuring, and understanding spatial and temporal variability in magnetic reconnection. For studies of this type, conjugate observations combining spacecraft and ground-based measurements can be very important. There are some aspects of reconnection (such as the localised plasma physics) that can only be measured by in-situ spacecraft. There are also some aspects (such as the macrophysics of the process) that can only be measured by instruments that provide a wider view, such as auroral imagers or ground-based radars. However, the local time extent of reconnection regions can only be determined unambiguously using ionospheric measurements (in the absence of a massive armada of spacecraft).

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Similarly, the amount of flux transfer occurring during reconnection can only be determined unambiguously using ionospheric measurements. And consequently, the patchy (spatial variation) and bursty (temporal variation) of reconnection can only be unambiguously studied using ionospheric measurements. To measure the extent of reconnection from ionospheric measurements (which can then be mapped back to the magnetopause) first requires the identification of the ionospheric footprint of the open-closed magnetic field line boundary (OCB). The regions where the ionospheric plasma flow crosses this boundary (in the frame of the boundary – which is typically in motion itself) map to the regions on the magnetopause where reconnection is occurring. Although the text shows that the authors appear to appreciate this, they do not analyse their ionospheric data in this way. Consequently, I have some major issues with the introductory text and the radar data analysis and presentation. The authors need to address these major points before the paper can be reviewed properly. (1) Some of the background referencing is misdirected and inadequate: The referencing of spacecraft observations associated with reconnection (extending from lines 95 to 117) starts with the phrase – 'The extent of reconnection X-lines has been observationally determined based on fortuitous satellite conjunctions. . .'. This is not true. Even if the word 'determined' was changed to 'estimated' it would still be a stretch of the truth. The 'extent of reconnection X-lines' cannot be unambiguously determined (or even estimated) from spacecraft observations. Interpretations of multiple spacecraft observations still have to make the assumption that the X-line is continuous between spacecraft, or that it is not continuous between spacecraft. X-lines may also continue longitudinally outside of the view of the spacecraft. All that multiple spacecraft measurements can do (given that the assumptions made are correct) is provide upper or lower limits on the X-line extent.

Response: We completely agree with the reviewer's opinion on the limitations of spacecraft observations. Those limitations are the exact motivation of adopting the space-ground approach in this paper as mentioned in the introduction section. We change the statement to "studies have attempted to constrain the extent of reconnection X-lines based on fortuitous satellite conjunctions”. The word “constrain” has been used by the paper “Spacecraft measurements constraining the spatial extent of a magnetopause reconnection X line” by Walsh et al. 2017.

The referencing of ionospheric observations associated with reconnection (extending from lines 118 to 141) concentrates on those related mainly to local (often single radar) measurements of fast anti-sunward flows observed by radar (such as pulsed ionospheric flows [PIFs]) and their auroral counterpart (poleward-moving auroral forms [PMAFs]). These typically occur within the polar cap, and not necessarily at the ionospheric footprint of the OCB. Although all these observations are of phenomena that are consequences of reconnection, and which provide important information about the patchy and bursty nature of reconnection (and links to FTEs, etc.), they don’t allow the unambiguous estimation of the extent of the X-line. Hence, many of these references are actually superfluous to the paper. As mentioned above, to measure the extent of the reconnection X-line in the ionosphere requires the identification of the footprint of the OCB and the region for which there is plasma flow across it. (Although, similar caveats to the spacecraft observations also exist if there is not complete longitudinal coverage covering the whole ionospheric projection of the X-line.) There are a large number of papers that have studied and measured reconnection in this way that are not mentioned in the introduction of the present paper. A significant reference that reviews most of the work in this area, as well as outlining the techniques required to make these measurements, is Chisham et al. (2008) – Remote sensing of the spatial and temporal structure of magnetopause and magnetotail reconnection from the ionosphere – Rev. Geophys., 46, RG1004. Other papers that have measured the extent of the reconnection X-line using these methods include; (i) Pinnock et al. (2003) – The location and rate of dayside reconnection during an interval of southward interplanetary magnetic field – Ann. Geophys., 21, 1467-1482, which studied the same event that was observed in Equator-S data by Phan et al. (2000). They estimated the length of the reconnection X-line on the dayside magnetopause at this time to be âĹij38 Re based on the 10 hours of local time that flow was observed crossing the OCB in the ionosphere. (ii) Chisham et al. (2004) – Measuring the dayside reconnection rate during an interval of due northward interplanetary magnetic field – Ann. Geophys., 22, 4243-4258, which measured the X-line extent of lobe reconnection during northward IMF to be âĹij6-11 Re.

Response: We thank the reviewer for the important references. We realize that the term “X-line extent” in our manuscript has caused confusion. In our original terminology we used “magnetic separator” to refer to the global configuration along which reconnection occurs at various rates, and used “X-lines” to refer to regions of strong reconnection, i.e., reconnection bursts. Such usage has been common in the literature (especially in FTE studies [e.g., Fear et al., 2008, 2010] and local numerical simulations [e.g., Shay et al., 2003; Sheperd and Cassak, 2012]). But to avoid confusion we replace “extent of X-lines” with “extent of reconnection bursts” throughout the text. Therefore the title of the paper is “local time extent of magnetopause reconnection bursts using space-ground coordination”. Similar changes are made throughout the text.

The references suggested by the reviewer provide valuable groundwork of clarifying the scope of this study. We rewrite the first paragraph as “. . .Reconnection tends to occur at sites of strictly anti-parallel magnetic fields as anti-parallel reconnection [e.g. Crooker, 1979; Luhmann et al., 1984], or occur along a line passing through the subsolar region as component reconnection [e.g. Sonnerup, 1974; Gonzalez and Mozer, 1974]. Evidence shows either or both can occur at the magnetopause and the overall reconnection extent can span from a few up to 40 Re [Paschmann et al., 1986; Gosling et al., 1990; Phan and Paschmann, 1996; Coleman et al., 2001; Phan et al., 2001, 2003; Chisham et al., 2002, 2004, 2008; Petrinec and Fuselier, 2003; Fuselier et al., 2002, 2003, 2005, 2010; Petrinec and Fuselier, 2003; Pinnock et al., 2003; Bobra et al., 2004; Trattner et al., 2004, 2007, 2008, 2017; Trenchi et al., 2008]. However, reconnection does not necessarily occur uniformly across this configuration but has spatial variations [Pinnock et al., 2003; Chisham et al., 2008]. The local time extent of reconnection bursts is the focus of this study.”

(2) Identification of the extent of the reconnection region from fast ionospheric flows is flawed: Lines 52-54 state – ‘The extent has also been inferred by radars as fast ionospheric flows moving anti-sunward across the open-closed field line boundary, but whether a particular ionospheric flow results from reconnection needs to be confirmed.’ Firstly, the measured flows do not need to be fast. The fast flows highlighted in the paper are obviously driven by reconnection but these are predominantly polar cap flows (relating to the newly-opened flux tubes moving over the polar regions towards the nightside), not flows at and across the OCB. Any flow across the OCB, whether fast or slow, implies that reconnection has occurred, as closed flux has been converted to open flux. By the same argument, if flow across the OCB is measured, spacecraft measurements are not required to prove that this flow is a result of reconnection (hence I disagree with the statement on lines 132-135). Lines 198-206 detail the SuperDARN radars used in the study. What I do not understand is why the authors restricted their study to only a few of the northern hemisphere radars when there is a much wider network of northern hemisphere SuperDARN radars that would provide a much greater longitudinal coverage? Larger coverage provides a much better global picture of the ionospheric convection and hence the reconnection driven flows across the OCB.

Response: We agree that conceptually ionospheric flows moving across the OCB, even slow, should be related to reconnection. However, to the best of our knowledge, there has been no confirmation of whether weak ionosphere flows meet the quantitative in-situ magnetopause reconnection criteria and our event #1 (updated as seen in the attachment) suggests that they actually correspond to plasma jets at the magnetopause much slower than the Alfven speed. Thus the slow ionospheric flows do not meet the in-situ definition of reconnection but should be treated separately. The focus of this paper is on strong bursts of reconnection. But our study, as well as Chisham et al. [2008], may have suggested that there are two components of reconnection at different scales: weak background reconnection signified by the slow flows, and embedded strong reconnection bursts signified by the fast flows.

To avoid confusion, we replace the sentence as “The validity of the assumption can be tested by radars via examining ionospheric flows moving anti-sunward across the open-closed field line boundary”.

The PolarDARN radars utilized in the paper have provided sufficient coverage for studying reconnection bursts in the area of satellite-ground conjunction. Reconnection bursts may also activate outside the radar FOV, but those are not the focus of the satellite-ground conjunction study and the terminology change mentioned above clarifies that this paper is not meant to determine the global X-line extent but individual reconnection burst extent. Backscatters from radars at lower latitudes were limited (see Figure S2) because the cusp, and the associated ionospheric irregularities, occurred at relatively high latitude (>77-78° MLAT). It is noteworthy to point out the studied events occurred under non-storm time, while previous studies using a wide network of SuperDARN radars focus on storm time period where the OCB has expanded to low latitude.

Lines 297-298 state – ‘The extent is determined at half of the maximum flow speed, which was âĹij400 m/s’. Why? There is still flow across the boundary outside this region that results from reconnection. Consequently, the dashed magenta lines in figures 2, 4, and 6 mean nothing, except to nicely frame the fast poleward flows into the polar cap. In a similar vein, lines 366-367 state ‘We quantify the flow azimuthal extent as the full-width-at-half-maximum (FWHM) of the velocity profile’. Why? Any poleward flow (across the OCB) represents the creation of newly reconnected flux. In all 3 examples there are significant poleward flows east of the dashed magenta lines. In figures 2e and 2f the flow extent is ‘quantitatively determined’ using measurements at 80 degrees latitude. Why use the flows at this latitude to determine the longitudinal extent when they are well within the polar cap? These are not the same as the flows at the OCB latitude, and hence they do not show the longitudinal extent of reconnection. Hence, they cannot be reliably used to estimate the length of the X-line.

Response: We appreciate the reviewer's comment. As clarified above, we focus on reconnection bursts, which appear as fast anti-sunward flows in the ionosphere. It has been a common approach to measure the reconnection burst extent as the flow extent at a latitude poleward of the OCB [Goertz et al., 1985; Pinnock et al., 1993, 1995; Provan and Yeoman, 1999; Thorolfsson et al., 2000; McWilliams et al., 2001a, 2001b; Elphic et al., 1990; Denig et al., 1993; Neudegg et al., 1999, 2000; Lockwood et al.. 2001; Wild et al., 2001, 2003, 2007; McWilliams et al., 2004; Zhang et al., 2008]. Slow flows have been allowed to extend beyond the boundaries of the fast flows [Mcwilliams et al., 2004], and we have clarified how fast and slow ionosphere flows are contrasted in terms of in-situ flows above. Since the longitudinal profile of the flow velocity has a skewed Gaussian shape, we have used FWHM. The use of FWHM is analogous to the methodology of Shay et al. [2003], who define reconnection as regions where the current density is larger than half of what is carried by the electron Alfven speed. This is clarified in the text.

We have compared our flow velocity profile with the reconnection electric field at the OCB in Figure S3. Figures S3a-c present the OCB (dashed black line) of the first case study around the space-ground conjunction time and longitude following Chisham and Freeman [2003, 2004] and Chisham et al. [2004, 2005a, 2005b, 2005c]. The OCB was nearly along a constant latitude. Figures S3d-f present time series of the spectral width measurements along beams 4, 7, and 10, as a function of latitude. The time series plot allows us to determine the speed of the OCB motion and we determined the speed at each individual beam. Figure S3g presents the electric field along the OCB in the frame of the ionosphere (dotted), and in the frame of the OCB (solid). The latter is the reconnection electric field. The reconnection electric field had essentially the same FWHM as the flow slightly poleward of the OCB (difference being less than the radar spatial resolution).

We note that the process of tracking OCB motion can introduce large uncertainties, especially for our events where the OCB moved very slowly (Figure S1). Given the radar spatial (∼0.3°) and temporal (2 min) resolution, the speed of OCB has an uncertainty of ∼300 m/s. This results in a signal to noise ratio generally around or even below one, even though we have not yet considered the measurement error associated with spectral widths or the error of using 150 m/s as the OCB threshold in any given event. A similarly poor signal to noise ratio has been found in Chisham et al. [2008]. This would affect the estimate of the electric field and would reduce the confidence of the results. The flow velocity poleward of the OCB is less affected by the OCB uncertainties.

Given that the electric field profiles at the OCB latitude and the flow velocity profile slightly poleward are about the same, that the echoes are more continuous at higher latitudes, and that our approach is consistent with a number of past works cited above, we think that our approach is sufficient to lead to the conclusion.

(3) The open-closed field line boundary (OCB) in the ionosphere is insufficiently determined: Lines 390-391 state 'The flow crossed the open-closed field line boundary at 77 degrees MLT. . .'. The determination of the OCB location is not clearly outlined anywhere or displayed clearly on the figures. Indeed, the OCB location in figures 2, 4, and 6 is never sufficiently determined (or visually presented) so it is impossible to know what the longitudinal extent of flows across the boundary is. The boundary is vaguely discussed as being the equatorward edge of the cusp, which is identified in these figures as being co-located with regions of high Doppler spectral width. (In actuality, comparing figures 2c and 2d, the poleward flow at the equatorward edge of the cusp is slower than that within the polar cap, and most likely extends over a wider longitudinal region.) Although the high spectral width regions circled in these figures may very likely be a result of cusp precipitation, they do not necessarily highlight the full extent of the cusp. High spectral width values are observed within the polar cap at all magnetic local times (see the discussions and references in Chisham et al. (2008) [details above], and Chisham et al. (2007) – A decade of the Super Dual Auroral Radar Network (SuperDARN): scientific achievements, new techniques and future directions – Surv. Geophys., 28, 33-109 [specifically sect. 4, pages 60-67]). If Doppler spectral

width is being used to estimate the location of the OCB then it is important to determine the spectral width boundary (SWB) location (see references in the same 2 papers). It is also important that spectral width values are only considered from radar beams that are aligned close to the meridional direction (see Chisham et al. (2005) – The accuracy of using the spectral width boundary measured in off-meridional SuperDARN HF radar beams as a C5 ANGEOD Interactive comment Printer-friendly version Discussion paper proxy for the open-closed field line boundary – Ann. Geophys., 23, 2599-2604).

Response: The references provided by the reviewer are highly relevant and have been included in the text. The OCB is determined as the 150 m/s spectral width boundary [e.g., Baker et al., 1995, 1997; Chisham and Freeman, 2003] as indicated in the text although we did not present the details in our previous manuscript. The details are now displayed in Figures S1 and S3. We also mark this boundary in Figures 2, 4, and 6 as a black dashed line.

We agree with the reviewer that high spectral width can span across a wide range. But here we look for structures embedded in the spectral width because the existence of a localized enhancement indicates enhanced energy input from the magnetosphere over a finite area. This is consistent with our focus on reconnection bursts. The “cusp” feature we refer to follows the dynamic cusp model where the cusp precipitation is driven by reconnection bursts. To avoid confusion with the traditional cusp, we rename it as enhanced soft electron precipitation.

(4) Quality and clarity of the figures containing the radar data: The radar data plots in figures 2, 4, and 6 are incredibly messy, cluttered, and difficult to interpret, especially panels a and d, where line-of-sight (LOS) velocity and spectral width are displayed across the radar fields-of-view. These figures need to be simplified. Is all the LOS velocity data required in panel a? Are the merged vectors not information enough? Especially given that the LOS data on their own are open to severe misinterpretation. Can a boundary be determined from the spectral width data (see above) rather than highlighting a vague blob of high spectral width? If such a boundary was determined, then

over-plotting this boundary on the velocity vector panels would be highly informative.

Response: We thank the reviewer for the suggestion and have simplified panels a and d by deleting isolated LOS backscatters and minimizing the overlap of backscatters. The OCB has also been overlaid on panels a, b, and c. We mentioned about determination of spectral width boundary. The red blobs in Figures 2d, 4d, and 6d highlight structures of high spectral width which are not related to the OCB determination but enhanced soft electron precipitation.

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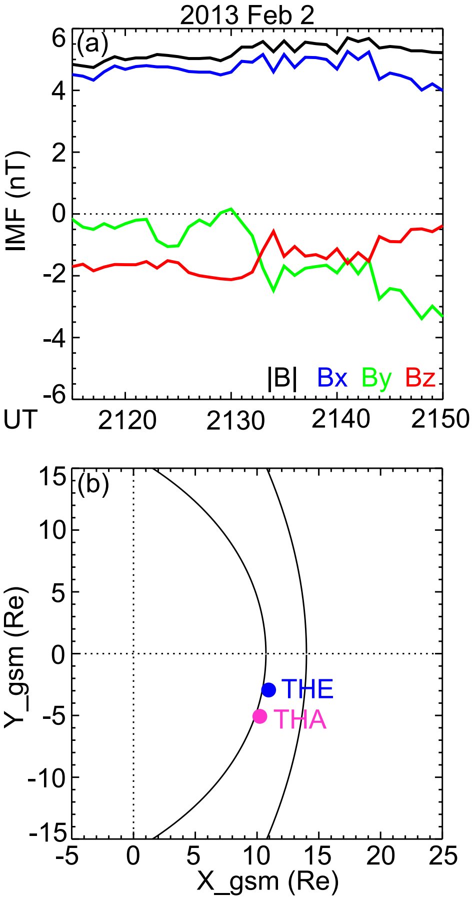

Fig. 1. Figure 1a: OMNI IMF condition on Feb 2, 2013. Figure 1b: THE and THA locations projected to the GSM X-Y plane. The inner curve marks the magnetopause and the outer curve marks the bow shock.

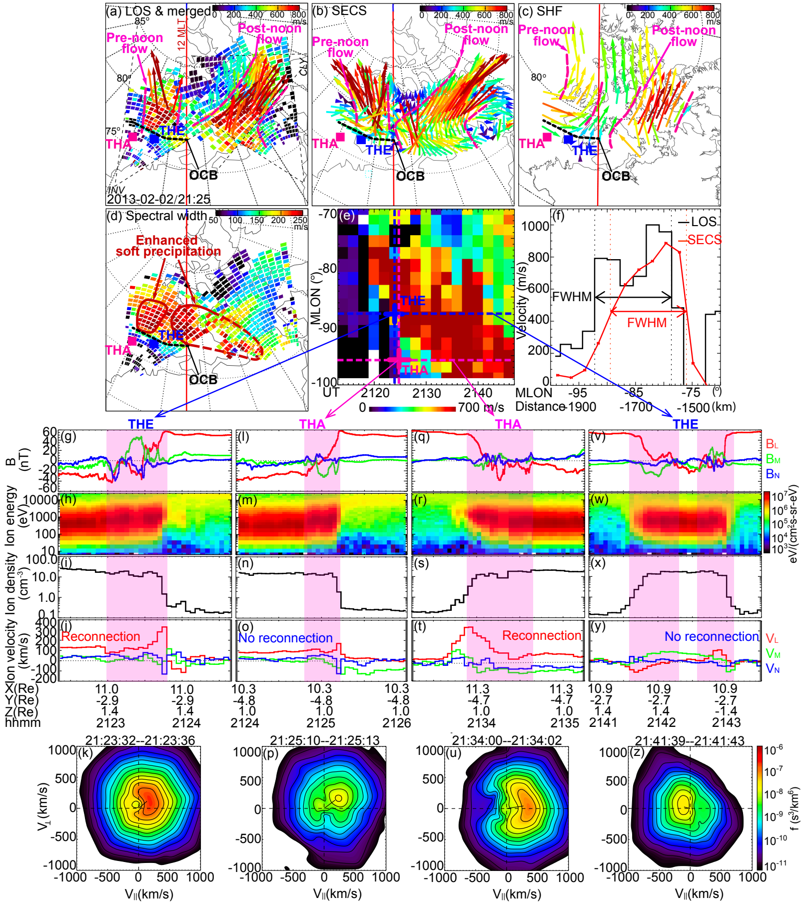

Fig. 2. Figure 2a: SuperDARN LOS speeds (color tiles) and merged velocity vectors (color arrows) in the Altitude adjusted corrected geomagnetic (AACGM) coordinates. The FOVs of the RKN, INV, and CLY radars ar

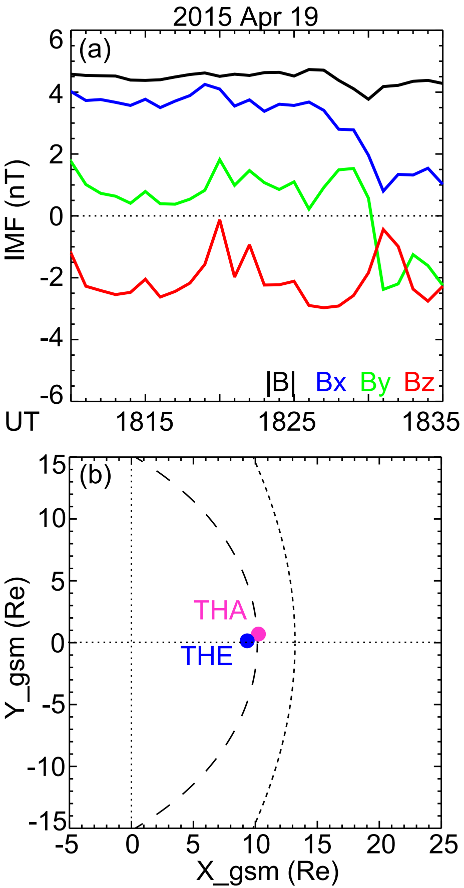

Fig. 3. Figure 3: OMNI IMF condition and THEMIS satellite locations on Apr 19, 2015 in a similar format to Figure 1.

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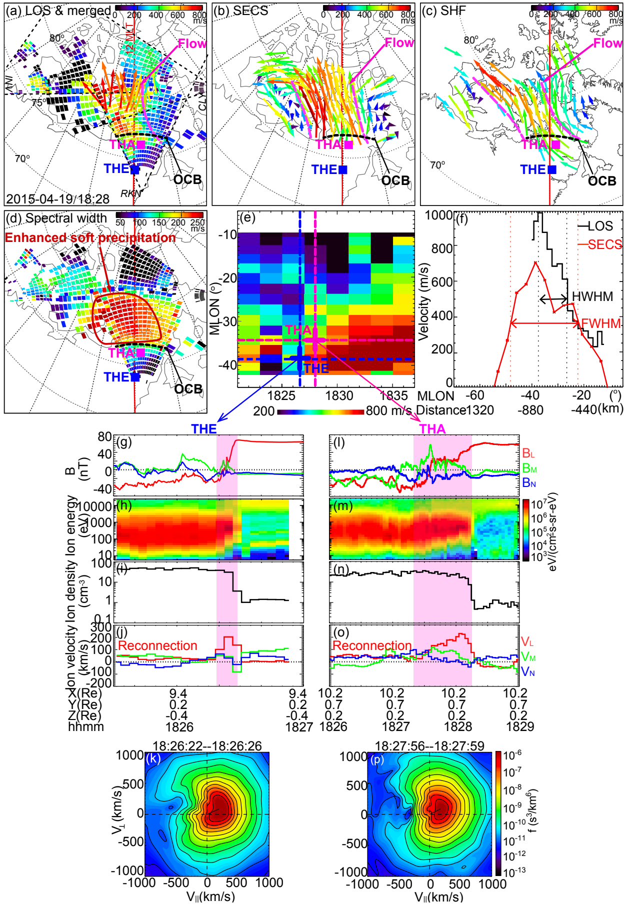

Fig. 4. Figure 4. THEMIS and SuperDARN measurements of reconnection bursts on Apr 19, 2015 in a similar format to Figure 2. The velocity time evolution in Figure 4e and the velocity profile in Figure 4f are t

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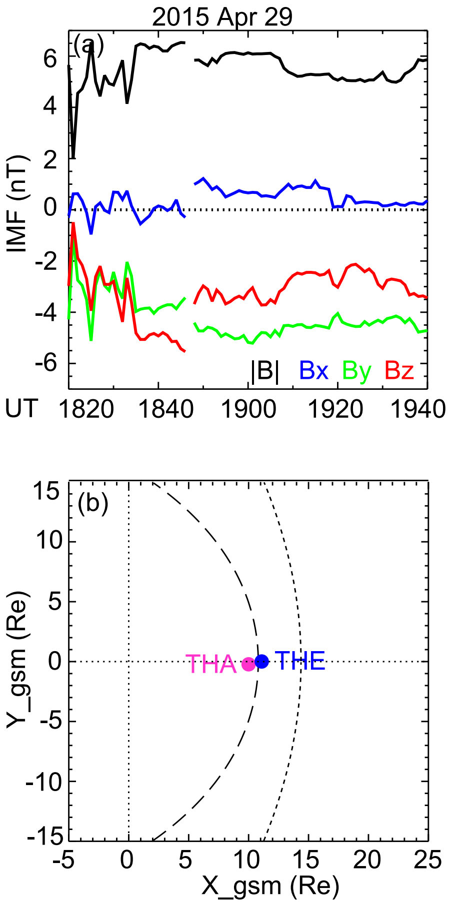

Fig. 5. Figure 5. OMNI IMF condition and THEMIS satellite locations on Apr 29, 2015 in a similar format to Figure 1.

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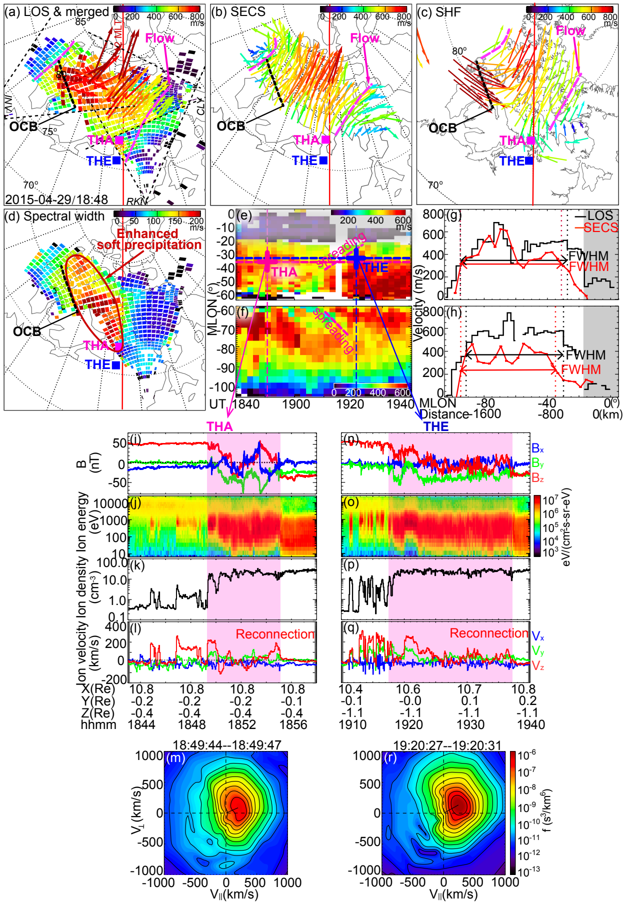

Fig. 6. Figures 6a-d: SuperDARN measurements of reconnection bursts on Apr 29, 2015 in a similar format to Figures 2a-d except that in Figure 6a the color of the CLY color tiles represent LOS speeds towards t

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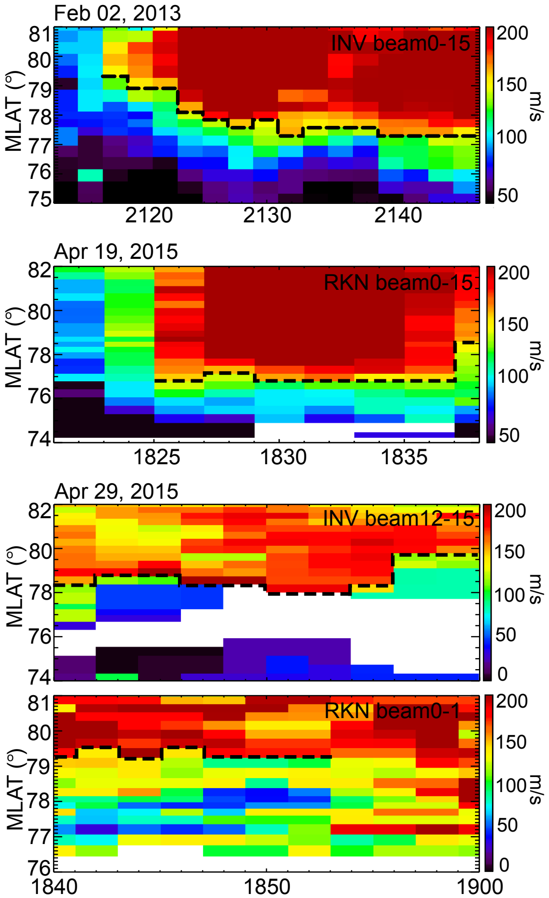

Fig. 7. Figure S1. Location of the open-closed field line boundary (marked by the black dashed line) in the three studied events. The open-closed field line boundary is determined based on the spectral width

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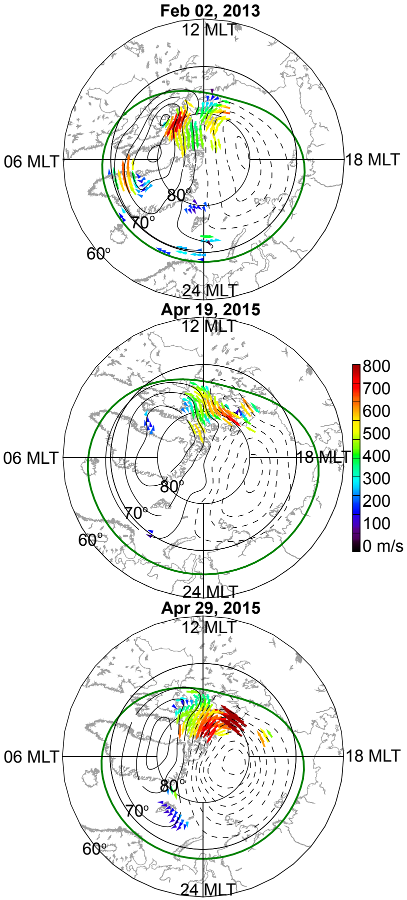

Fig. 8. Figure S2. Global convection maps of the three studied events. The SHF velocities are shown as color arrows, and the contours of the electric potential are shown as black solid (at the duskside) and d

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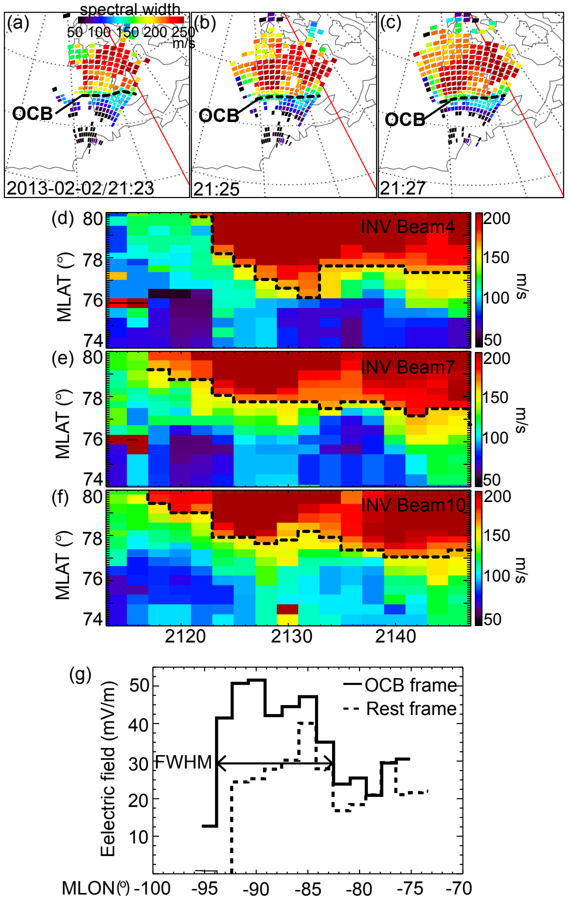

Fig. 9. Figure S3. Reconnection electric along the open-closed field line boundary for the Feb 02, 2013 event. Figures S3a-c: snapshots of spectral width measurements around the space-ground conjunction time