nature portfolio

Peer Review File

Magnetic Reconnection in the Plasma Disk at 23 Jupiter Radii

Corresponding Author: Dr Jian-zhao Wang

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
The present study by Wang et al. describes two correlated observations of intermingling flux tubes in the plasma disk of Jupiter, claiming the first detection of localized flux tube interchange via magnetic reconnection, a previously-hypothesized process proposed to explain radial plasma transport in the inner Jovian and Kronian, corotation-driven magnetospheres. The manuscript is well-written, concise and illustrative. Most of my initial questions were addressed by the methods section. To argue the point, the manuscript presents in-situ detections of, firstly, a pair of entwined flux tubes with distinct features, and secondly, another crossing of the likely same flux tubes compressed further together. Data from this second crossing describes key features of magnetic reconnection (and especially of the ion diffusion region via a bipolar Hall magnetic field signature), with auxiliary lines of evidence that support the conclusion of encountering a magnetic reconnection site. This represents a direct observation of magnetic reconnection in a novel environment, with special significance in allowing the localized flux tube interchange process. Data and methodology is described well, and the deposited code reproduces most* required plots, using a standard Python environment, and is, if not extensively documented, parseable and looks to do what it is supposed to. However, there are some minor issues (especially with some references), listed below, that should be addressed before acceptance of the manuscript. Recommend minor revision.

Specific issues:

Line 55: Zhang+2012 discusses an observation of a plasmoid, not a diffusion region. This is indicative of RX at Venus, but not a direct observation. It is not relevant for this point. The following reference, however, demonstrates that at Venus: Gao+2021, https://doi.org/10.1029/2020JA028547.

Line 117: The description of ion-electron decoupling via high-energy ion PAD being asymmetric vs. electrons raises a question on a much stronger measure for detection of an ion diffusion region: agyrotropy, which should be significant at the diffusion region. I do not know if this is within the capacity of the instrumentation, at a sufficient cadence, but if yes, display of agyrotropic ions would serve to strengthen the argument further; see, e.g. Dai+2015, https://doi.org/10.5194/angeo-33-1147-2015.

Line 159: Øieroset+2016 describes a symmetric reconnection event (where strong guide field generates the resulting asymmetry), so this reference seems out of place here.

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*The CodeOcean reproducible run does not reproduce all components of Figure 3a (3/6 subpanels). This seems easily remedied.

Other stylistic suggestions:

Lines 44-47: Consider introducing the Ma+2016 reference earlier ("it is proposed (Ma+2016)"), and the Ma+2019 reference would be relevant for the process description already here.

Line 68: Please refer the reader to the Methods section for JSS definition.

Line 80: "typical plasma disk features" should be accompanied by a reference (e.g. Bagenal & Delamere, 2011)

Line 163: Please refer the reader also to the methods section for details on the LMN system here.

Figure 2: Panel a) Suggest adding annotation for the decomposition of inflowing magnetic field to reconnecting and guide fields: latter is noted, but for the former e.g. B_{in,RX}; B_{out,RX} for the reconnecting components, to not suggest rotation of the reconnecting fields
Panel b) Specifically "Hall current" instead of "Current" in legend

Extended data: The wave analysis, while interesting to see, is left on its own in relation to the reconnection study, with most signals seen outside of the reconnecting flux tube. A briefly expanded description on the extended data, describing its relevance, would not be out of place, and/or a mention in the manuscript on the availability and relevance of such data for further studies.

Data: Zenodo-based data is readily available. PDS-based links offer dataset descriptions, but the data access is behind the rather hard-to-use PDS/PPI interface – a direct link to the data referenced would be greatly appreciated.

(Remarks on code availability)
The code provided is written in Python, with a standard, readily-available environment, causing no barrier of entry. The plots of the manuscript (barring three panels from Figure 3a, which I would have expected to be reproduced) are reproduced well. The code does not include a separate README, but operation is straightforward and runs fast on CodeOcean. Some more details on the usage, inputs and purpose in the code would have been welcome ("This script reproduces the figure X of Wang+2025, using JADE dataset [link, instruction for possible pre-processing], edit these lines to adapt for other events [if applicable]"), but not strictly necessary in my opinion.

Reviewer #2

(Remarks to the Author)
Very nice article, aiming to provide in-situ signatures of the complex interplay between convective instabilities (here interchange instability in the Jovian magnetosphere) and magnetic reconnection. Suitable for a high impact, broad public journal as Nature Communications. That said, if and only if the Authors can clearly support their statements on the dynamics of flux tubes, on the detection of a reconnection outflow, or on the detection of other clear reconnection evidences (see my

main points, here below).

Main criticisms:

1) The Authors describe the dynamics of the flux tubes, observed in the northern side, as that of "colliding tubes", leading to the compression of the current sheet in between them, and thus to the on-set of magnetic reconnection. Even if plausible, this dynamics must be supported by observations.
Looking at the ion flows in Fig. 1, it is not clear to me if the average velocities inside the two flux tubes are, partially, directed one against the other (for sure, excluding from this picture the "localized" outflow jets). It would be clearer in the LNM base. Indeed, in Fig.2 V_N passes from ~0 Km/s just on the left of the current sheet, to ~60 Km/s on the right, suggesting compression. However, this velocity strongly varies as soon as Juno moves away, as shown by the measurement points at t~02:03:30 and t~02:04:00. Showing the ion velocity, in the LMN frame, on a longer time period of that of Fig. 2 (e.g. from t~02:00 to t~02:06:30) would corroborate, or invalidate, the idea of "colliding flux tubes".

2) The detection of the outflow in the low density tube is the main signature of magnetic reconnection in Juno data, but I'm not sure that the ion flow that is observed there can be identified as a reconnection outflow. Indeed, in Fig. 1, where the outflow is mainly along the \theta-direction (identified by the Authors as "Plasma jets") the V_\theta structure, with V_\theta around 150 Km/s (from t~02:03 to t~02:07), is too "wide" for being an outflow, that is expected to have a width of few d_i. Following Authors's estimation for the normal width of the current sheet (a transit time of ~15 seconds, corresponding to a width of ~ 2 d_i), I can deduce that the width of the structures at V_\theta around 150 Km/s (for which the crossing time is around ~4 minutes) is of the order of tenths of d_i, that is not compatible with a reconnection outflow width. Eventually, V_\theta is ~150 Km/s inside the whole low density flux tube. Something hardly compatible with a reconnection outflow. For sure, using the LMN base, as in Fig.2, would be far better for the outflow identification, but only two measurement points are shown at V_L around - 150 Km/s. For a correct identification of the outflow, the Authors must show the ion flow in the LMN base but for a longer time interval (e.g. from t~02:00 to t~02:07), and check the existence of a clear, thin (~ few d_i) jet.

3) If reconnection has occurred and finally has created field lines connecting the cold-dense flux tube to the hot-tenuous one, I would expect a parallel streaming of electrons going from one region to the other. In the Earth context, M. B. Bavassano Cattaneo et al., Ann. Geophys. 28, 893 (2010); M. Faganello et al. Europhys. Lett. 107, 19001 (2014); Y. Vernisse et al., J. Geophys. Res. Space Physics 121, 9926 (2016), showed that analyzing either the pitch angle distribution of electrons, as a function of time, for different energy range, or the distribution functions at given times, as function of v_\parallel and v_\perp, it is possible to infer i) the topology of magnetic field lines and ii) the location where, and the time at which, these lines have undergone reconnection. In the Earth context, reconnection was related to Kelvin-Hemlholtz vortices growing at the equators, distorting the field lines and finally inducing reconnection away from the equators, a mechanism not so different from the one that is discussed in the present article. I strongly advise the Authors to carefully analyze the pitch angle distribution, for different energies and times, for checking if it is possible to recognize parallel electron streams in one tube, arriving from the other one. Their presence would strongly support the idea that reconnection is/was going on. If the "local" outflow is confirmed, parallel streams could help in estimating the length of the X-line. If the local outflow is not, they could suggest that reconnection is/has going on at a different latitude with respect to the observed current sheet.

Minor points:

line 71: Here "rotational direction" means that of plasma flow, while a reader could think about that of the angular velocity vector (roughly parallel to the north-south direction). Stating that the \phi-component is approximate the velocity direction of the plasma/magnetospheric motion associate to Jupiter's rotation, would be better.

line 250: I do not agree with the explanation given here, for the stronger stretching of the inner (denser) flux tube. Actually, I agree that a denser tube is expected to stretch more, but I don not with the explanation. Indeed, in the rotating frame the centrifugal force can be seen as an effective gravity force, whose intensity is proportional to the density \rho. Neglecting field line curvature, the equilibrium is guaranteed by the gradient of the total (thermal plus magnetic) pressure. The contribution of the total pressure can be seen as a buoyancy. As a tube moves away from its equilibrium radial position, the radial component of the momentum equation can be approximated as follows (still neglecting the magnetic field curvature):

\rho_tube \partial_t u_r = (\rho_tube - \rho_background)*g_effective

For a nit too large radial displacement \xi_r, with respect to the tube equilibrium position, it reads

\rho_equilibrium \partial_tt \xi_r = (\partial_r \rho_equilibrium)*\xi_r*g_effective

For the sake of simplicity, I've neglected the plasma compressibility. Taking it into account does not change too much the physical explanation (e.g. the Brunt-Vasaila frequency would be given by the logarithmic radial derivative of the potential temperature profile, instead of the logarithmic radial derivative of the simple density).

Looking at that equation, the higher inertia of a denser tube does not play in favour of an higher acceleration/displacement, as suggested by the Authors.
e.g. for an exponentially decreasing equilibrium density, the (imaginary) frequency of unstable oscillation does not depend on the tube density (equilibrium density at the unperturbed tube position).

For a linear equilibrium gradient, the higher the equilibrium/tube density, the smaller the growth rate, thus the dispalcement value after a given time interval (neglecting nonlinear saturation).

For explaining why a denser tube is distorted more than a tenuous one (and I agree with that), the magnetic tension must be included.
Even if I neglected the magnetic tension for the equilibrium, the original flux tubes are distorted by the fact that the interchange instability mainly occurs at the equators, while it is stable far away.
The relative weight of inertia and magnetic tension is measured by the Alfven velocity V_A = B/\sqrt{\mu_0 \rho}. The denser the plasma, the lower the Alfven velocity, the easier for a plasma motion to distort field lines.
Thus, for a tenuous tube, the Alfven velocity is higher, it is harder for it to bent field lines.
For a denser tube, the Alfven velocity is lower, it is easier to bent field lines.
In my opinion, this is a more convincing explanation for why the denser tube could be more perturbed than the tenuous one.

(Remarks on code availability)

Reviewer #3

(Remarks to the Author)
Magnetic Reconnection i 1 n the Plasma Disk at 23 Jupiter Radii
by
Jian-zhao Wang, Fran Bagenal, Stefan Eriksson, Robert E. Ergun, Peter A. Delamere, 3 Robert J. Wilson, Robert W. Ebert, Philip W. Valek, Frederic Allegrini, Licia C. Ray

The authors note that the topic of their study is an analysis of Juno data, which allowed to find for the first time an ion diffusion region in Jupiter's inner magnetosphere. They claim to have found evidence of local interchange motion under the action of centrifugal force. This work sheds light on the understanding of how Io-genic plasma is transported in Jupiter's magnetosphere. The topic of the work is actual and important.

The article is well written. The experimental material is presented in detail. Theoretical interpretations are given. However, there are several questions that would be desirable to answer.

1) Page 2, lines 47-48. The authors wrote: “the localized flux tube interchange driven magnetic reconnection (X. Ma et al., 2016) although there is no observational evidence to date to support this mechanism”. It is advisable to briefly describe "this mechanism" so that readers understand what it is. Moreover, Ma et al. (1916) wrote about “a pair of the high-latitude reconnection sites”, while in the considered work both reconnection sites are near the plasma sheet, as it follows from their figures 1a,b. On page 2, line 72 it is written: “this event occurred at a radial distance of 23.3 RJ and a local time of 22.6 hr, near the midnight magnetic equator”. Moreover, on pages 4-5, lines 131-132 it is stated: “reconnection events are located 0.39 RJ south and 0.33 RJ north of the plasma disk center, respectively”.

2) Page 2, line 70. “the north-to-south direction”. Is this related to rotation or magnetic axis?

3) Fig. 2a. The arrows illustrating inflow are drawn a little bit unclear.

4) Page 4, lines 119-120. It is written: “In summary, the observations of magnetic fields, plasma bulk flow parameters, and PADs are consistent with the detection of a reconnection event.” Can the process described be considered as reconnection? It is usually believed that during reconnection the topology of magnetic field lines changes. Does this happen in the presented observations? If so, it would be desirable to describe it in detail. If this is not the case, this needs to be explained.

5) Fig. 4c. What kind of magnetic field lines are in the rightmost equatorial part of the scheme inside the region bounded by the blue line on the left and the green line on the right? How is the magnetic field directed there? It seems that magnetic field there is directed from top to bottom at the left side, as well as at the right side also, which is impossible (div B =0).

6) Page 10. It is written that 23.3 Jupiter radii “is also far from any Galilean moons, eliminating the influence of moon plasma interactions.” However, Callisto is not too far (at ~ 26.3 Jupiter radii).

(Remarks on code availability)

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

My comments have been adequately addressed, but I would still like to ask for the following clarification on the data. Given the discussion on the point on electron PADs raised by Reviewer #2 is concluded satisfactorily* with R.#2 I recommend acceptance.

> Data: Zenodo-based data is readily available. PDS-based links offer dataset descriptions, but the data access is behind the rather hard-to-use PDS/PPI interface – a direct link to the data referenced would be greatly appreciated.
> Response:
> For the Juno data available on PDS, we have replaced the DOI links with direct links to the data sources in the revised manuscript.

I do believe the DOI links should still be the primary reference. As it is currently, I am able to access FGM and JED data via the DOI links, but not the JAD-5-MOMENTS or JAD-3-CALIBRATED via their DOI landing pages - those data access links look to be unfortunately dead, leading to this confusion. This may not be directly in the hands of the authors, but this issue should be resolved outside of this peer review process.

JAD_L50_QLK_ELECTRONS_2020206.csv seems like it should be available via the JAD-5-MOMENTS dataset, but the JAD-5-MOMENTS only provides the following data for the time period:
JAD_L50_ELC_MOM_ISO_2D_ELECTRONS_2020206, which deviates from the QLK dataset. The provenance of the QLK file should be clarified (compatible data is available via e.g. AMDA).

*Further, with respect to the Author's response to Reviewer#2:

> The x-axis is the pitch angle and the y-axis is energy. No asymmetric PADs were observed before or after the X-line, which is expected and can be explained by the magnetic topology. In Kelvin-Helmholtz (KH) studies at Earth, reconnection occurs on open flux tubes, with one end connected to the solar wind. As a result, PADs are asymmetric, often field-aligned or anti-field-aligned, revealing electron streams entering and exiting flux tubes. In contrast, the reconnection in this study is from flux tube interchange, occurring on closed field lines. Electrons are trapped and bounce between both ends, producing symmetric PADs with bidirectional flows.

I feel I need to point out that this reasoning is jumping a bit ahead of the point: reconnected flux tubes should still show a mixture of streaming electron populations between the flux tubes, and the asymmetry of the PADs, after reconnection, should be retained on time scales less than electron bounce time. For the local process here it would indeed be a relevant and strong indicator of reconnection, but I do not see whether or not the presented PADs disprove the claim either.

(Remarks on code availability)
The code now reproduces the remaining figures.

Reviewer #2

(Remarks to the Author)
The Authors' answer to my point 2) is not convincing.

Their comparison with the Saturn event is not appropriate for two reasons:

- Ion flow data from Cassini are low quality, as Arridge et al. fairly admit.
Thus, ion outflows are badly identified.

- Cassini is moving roughly along the tail so, for a magnetotail reconnection event, as that discussed by Arridge et al., Cassini could see the ("long-lasting") reconnection ion outflow for a long time, since it is moving mainly along the jet direction.
On the contrary, Juno is supposed to moves perpendicularly to the ion outflow (along the N direction, in the present paper). It is thus supposed to cross the ion outflow, and not to move "along it". The time duration of high ion flow should thus be related to the ion outflow width (as the Authors did for estimating the current sheet width), and that duration should be independent of the fact that reconnection is lasting for a long or for short time.

Thus, invoking "long-lasting reconnection", for explaining a claimed reconnection outflow that lasts five time longer than the current sheet, is not correct here. It is OK for a satellite moving along ~L, not along ~N.

A more pertinent comparison is the one with the event analysed by Kacem et al. (even if the quality of MMS/temporal resolution of MMS data is uncomparable with that of Juno). Indeed,

1) MMS is crossing two interlaced flux tubes, with reconnection going on in between the tubes, as in the present event (even if the mechanism that created the two interacting flux tubes at the Earth is different from that at Jupiter).

2) MMS is crossing the current sheet in between the two flux tubes along its normal direction, as it is the case for Juno here, so that detection duration can be translated in spatial width.

Note that Kacem et al. adopt two different local frames, LMN as the local frame of the "whole event" (crossing of both flux tubes), and a more local/refined U_V, U_J, U_P frame for the current sheet crossing (with U_P normal to the sheet, and U_V along the outflow)

Looking at MMS data, in particular at the component of the ion fluid velocity along L (Fig. 6, panel (f)), it is true that high velocity flows are observed for "long time" (from ~14:16:40, identified as T_2, to 14:16:58, identified as T_4), in comparison to the current sheet crossing time (from T_2=14:16:40 to T_3=14:16:43) BUT MMS clearly show the presence of a thin (duration/width comparable with that of the current sheet), localized ion jet, that is identified as the reconnection ion outflow at t~14:16:41. The rest of period with high ion velocity (T_3 to T_4), looking as a broader flow structure, is identified as the ion velocity inside one of the two flux tube, i.e. the velocity at which the tube is moving, if we suppose that the frozen-in condition holds there.
This double structure (thin reconnection ion outflow, around t=14:16:41, plus a broader ion flow associated to the flux tube motion, from 14:16:45 to 14:16:58) is even more clear using the more local/refined U_V, U_J, U_P frame, as shown by the ion fluid velocity along U_V in Fig. 9, panel (g).

Coming back to the present article, where Juno is supposed to cross the current sheet along N, a single, broad structure of the L component of the ion fluid velocity can not, in my opinion, be identified as a reconnection ion outflow.

It is possible that a localized, thin outflow is hidden on the left part of the broad flow structure, due to the 30s temporal resolution of ion fluxes, adopted in the article.
I imagine that raw fluxes have been integrated over 30s time windows in order to have a better noise-to-signal ratio.

In my opinion, there are three possible issues:

a) Fluxes averaged over a shorter time window (duration smaller or comparable with that of the current sheet) are OK from the noise point of view, and clearly show the presence of a double structure in V_L, as in Kacem et al., with a thin ion outflow close to the current sheet, and a broad peak related to the flux tube motion. In that case, the Authors could clearly affirm that a direct proof of a magnetic reconnection outflow is present in Juno data. Including the necessary modifications, the article would be OK for me.

b) These fluxes are OK from the noise point of view, but still exhibit a single, broad peak for V_L (without a localized, thin outflow on the left). As discussed above, this single broad peak can not be identified as the reconnection outflow. In this case, several evidences point toward magnetic reconnection (magnetic configuration, including what has been identified as a Hall field, PA distributions with enhanced perpendicular energy in the low density tube,...), but the final proof (the outflow) is lacking. In my opinion, without a clear detection of an outflow, reconnection is the main suspect, but the Authors can not speak about a direct observation of it.
Without a direct observation, the main reason for a Nature publication would fail. The Authors' work remains very interesting, but it would be more appropriate for a more specialized journal.

c) The noise-to-signal is too high for shorter time windows. The Authors could speculate about the possible presence of a thin, localized outflow, hidden in the broad velocity peak by the poor temporal resolution. I would let the Editor judge if such "possible hidden proof" would be sufficient for accepting the article.

(Remarks on code availability)

Reviewer #3

(Remarks to the Author)
Since the authors responded to my remarks, they put attention to these issues, so I have no further comments.

(Remarks on code availability)

Version 2:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
I thank the authors for addressing my comments. I have no further issues.

(Remarks on code availability)

Reviewer #2

(Remarks to the Author)

I strongly appreciate the effort Authors did in searching for clear signatures of the reconnection outflow in the high resolution Juno data.
I agree with them that the data quality of Juno is not comparable with what we are used to having in recent Earth's missions. Not being able to detect the reconnection outflow is a venial sin, that does not degrade the remarkability of the event Juno observes, and the quality of this work.
The article thus deserves publication on Nature Communications.

On the other hand, some of the statements in the Discussion/Conclusion are not so clear, and could let the reader think that the large flow structure observed by Juno is the reconnection outflow, while it is not (and the Authors agree with me on that point, as clearly stated in their answer).
For avoiding that, it is mandatory to :

1) At line 319 of the "tracked manuscript", after "We also examined the highest resolution plasma data available, as shown in Fig. S4 of the Supplementary Information"
add
", in order to search for a clear signature of a reconnection outflow, with a typical width ~ d_i, and thus a duration of few tenths of seconds, possible hidden in the large-scale flow structure."

2) At line 375 of the "tracked manuscript", replace "vertically directed reconnection outflows" with "clear signatures of magnetic reconnection, in particular in the local magnetic field configuration and in particle fluxes".

(Remarks on code availability)

Response to the comments of Reviewer #1:

The present study by Wang et al. describes two correlated observations of intermingling flux tubes in the plasma disk of Jupiter, claiming the first detection of localized flux tube interchange via magnetic reconnection, a previously-hypothesized process proposed to explain radial plasma transport in the inner Jovian and Kronian, corotation-driven magnetospheres. The manuscript is well-written, concise and illustrative. Most of my initial questions were addressed by the methods section. To argue the point, the manuscript presents in-situ detections of, firstly, a pair of entwined flux tubes with distinct features, and secondly, another crossing of the likely same flux tubes compressed further together. Data from this second crossing describes key features of magnetic reconnection (and especially of the ion diffusion region via a bipolar Hall magnetic field signature), with auxiliary lines of evidence that support the conclusion of encountering a magnetic reconnection site. This represents a direct observation of magnetic reconnection in a novel environment, with special significance in allowing the localized flux tube interchange process. Data and methodology is described well, and the deposited code reproduces most* required plots, using a standard Python environment, and is, if not extensively documented, parseable and looks to do what it is supposed to. However, there are some minor issues (especially with some references), listed below, that should be addressed before acceptance of the manuscript. Recommend minor revision.

Response:

Thank you for your comments. They are very helpful and relevant for improving the manuscript. We have provided point-by-point responses and incorporated your suggestions into the revised manuscript. Additionally, we have improved the uploaded code to ensure it runs more smoothly. Please see the responses below for details.

Specific issues:

Line 55: Zhang+2012 discusses an observation of a plasmoid, not a diffusion region. This is indicative of RX at Venus, but not a direct observation. It is not relevant for this point. The following reference, however, demonstrates that at Venus:
Gao+2021, https://doi.org/10.1029/2020JA028547.

Response:

In the revised manuscript, this sentence has been expanded into two parts. The first part cites diffusion region observations and simulations in Earth's magnetosphere. The second part references observations at other planets, such as Saturn, Venus, and Mars.

Line 117: The description of ion-electron decoupling via high-energy ion PAD being asymmetric vs. electrons raises a question on a much stronger measure for detection of an ion diffusion region: agyrotropy, which should be significant at the diffusion region. I do not know if this is within the capacity of the instrumentation, at a sufficient cadence, but if yes, display of agyrotropic ions would serve to strengthen the argument further; see, e.g. Dai+2015, https://doi.org/10.5194/angeo-33-1147-2015.

Response:

Agyrotropy occurs when the gyromotion of particles is disrupted in a magnetized plasma. It is a signature of kinetic-scale processes, especially within the diffusion region of magnetic reconnection. Juno's JADE-I instrument measures the full sky once per spacecraft spin (~30 s), allowing us to examine agyrotropy using data accumulated over this interval. To assess agyrotropy, we plot the ion velocity distributions in the $v_{\perp 1}/v_{\perp 2}$ plane outside and inside the diffusion region. Here, $v_{\parallel}$ is aligned with the magnetic field, and $v_{\perp 2}$ is directed along $\vec{B} \times \vec{v}$, where $\vec{v}$ is the ion bulk velocity obtained from forward modeling. The three directions $v_{\parallel}$, $v_{\perp 1}$, and $v_{\perp 2}$ form a right-handed coordinate system. Due to high uncertainty in low-energy data, we only include measurements above 0.5 keV/q. Outside the diffusion region, the velocity distribution is circular and symmetric, consistent with gyrotropy. Unfortunately, inside the diffusion region, the ion counts are too low to confidently determine the presence of agyrotropy. The cadence of the instrument is insufficient for a definitive analysis.

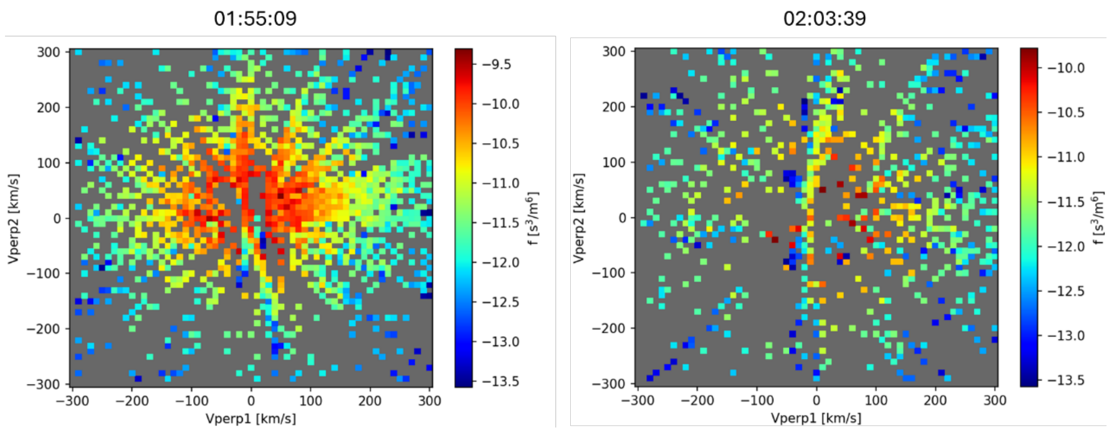

Fig. 1. The ion velocity distributions (left) outside and (right) inside the diffusion region of magnetic reconnection.

Line 159: Øieroset+2016 describes a symmetric reconnection event (where strong guide field generates the resulting asymmetry), so this reference seems out of place here.

Response:

This paper and others are cited to support the idea that reconnection can occur in current sheets similar to the one in this study, not to illustrate symmetry or asymmetry. Therefore, we have retained this citation in the revised manuscript.

Line 184: Especially as the high-density flux tube does not display velocity reversal, it would be very good to add a reference for the preferred jetting on the low-density side.

Response:

Several studies on magnetic reconnection with density asymmetry have shown that the outflow can be biased toward the low-density side. For example, using simulations, Cassak & Shay (2008) and Birn et al. (2008) found that the bulk outflow is directed toward the lower-density region when a density difference exists across the dissipation region. Kacem et al. (2018) demonstrated that this outflow bias on the low-density side can extend over a spatial scale larger than the current sheet thickness, which is very similar to the situation in our study. We have cited these papers in the revised manuscript to support our observations.

References:

Cassak, P. A., & Shay, M. A. (2007). Scaling of asymmetric magnetic reconnection: General theory and collisional simulations. Physics of Plasmas, 14(10)

Birn, J., Borovsky, J. E. and Hesse, M. (2008). Properties of asymmetric magnetic reconnection. Physics of Plasmas, 15(3)

Kacem, I., Jacquey, C., Génot, V., et al. (2018). Magnetic reconnection at a thin current sheet separating two interlaced flux tubes at the Earth's magnetopause. Journal of Geophysical Research: Space Physics, 123(3), 1779-1793

Line 187: The Pucci+2018 reference considers effects from two reconnection jets colliding in a strong guide field, and especially for the resulting secondary current sheets to be aligned along the guide field. It is not obvious to me that this line of reasoning supports the claim of outflow jets themselves aligning along the guide field. The Pritchett+2015 reference does not concern guide field reconnection, even if it shows localized reconnection jet being (nontrivially) displaced in the guide field direction. The outflow modulation claim therefore requires other references, or another explanation.

Response:

Two possibilities could explain the outflow in the M-direction. First, the $\vec{M}$=(0.22, 0.48, 0.85) vector points roughly along the co-rotation phi-direction around Jupiter (see the Methods section of the manuscript for details). v_M may be associated with the planet exerting a force that more easily pulls on the recently reconnected, low-density field lines. Second, the significant density asymmetry, the highly twisted magnetic topology, relatively strong magnetization, and the distance from the X-line may also contribute to outflow deflection. In such cases, magnetic tension and reconnection electric fields may favor jet formation in the out-of-plane direction.

*The CodeOcean reproducible run does not reproduce all components of Figure 3a (3/6 subpanels). This seems easily remedied.

Response:

Sorry for the confusion. All plots can, in fact, be reproduced using the code uploaded during the first-round peer review. The confusion likely arose because one script generates multiple panels of Fig. 3(a), depending on the selected UTC range. For example, the high-density tube (upper left panel) and low-density tube (middle left panel) plots in Fig. 3(a), both based on JADE data, are produced using the same file with different UTC inputs. To clarify this, we have updated the code by adding separate scripts, each corresponding to a specific panel in Fig. 3(a). Please refer to the updated code for details.

Other stylistic suggestions:

Lines 44-47: Consider introducing the Ma+2016 reference earlier ("it is proposed (Ma+2016)"), and the Ma+2019 reference would be relevant for the process description already here.

Response:

Ma et al. (2016) simulated the local twisting of flux tubes due to interchange. Ma et al. (2019) illustrated the full process in a three-stage diagram. Accordingly, we cited Ma et al. (2016) first, followed by Ma et al. (2019), in the revised manuscript.

References:

Ma, X., Delamere, P. A., Otto, A. (2016). Plasma transport driven by the Rayleigh-Taylor instability. Journal of Geophysical Research: Space Physics, 121(6), 5260-5271.

Ma, X., Delamere, P. A., Thomsen, M. F., et al. (2019). Flux tube entropy and specific entropy in Saturn's magnetosphere. Journal of Geophysical Research: Space Physics, 124(3), 1593-1611.

Line 68: Please refer the reader to the Methods section for JSS definition.

Response:

We have revised the manuscript accordingly.

Line 80: "typical plasma disk features" should be accompanied by a reference (e.g. Bagenal & Delamere, 2011)

Response:

Here, typical features refer to a large B_θ and a near-corotating flow at the event location (23 R_J) under average conditions. Two relevant studies are Connerney et al. (2018) and Wang et al. (2024). We have revised the manuscript accordingly.

References:

Connerney, J. E. P., Kotsiaros, S., Oliversen, R. J., et. (2018). A new model of Jupiter's magnetic field from Juno's first nine orbits. Geophysical Research Letters, 45(6), 2590-2596.

Wang, J. Z., Bagenal, F., Wilson, R. J., et al. (2024). Radial and vertical structures of plasma disk in Jupiter's middle magnetosphere. Journal of Geophysical Research: Space Physics, 129(7), e2024JA032715.

Line 163: Please refer the reader also to the methods section for details on the LMN system here.

Response:

We have revised the manuscript accordingly.

Figure 2: Panel a) Suggest adding annotation for the decomposition of inflowing magnetic field to reconnecting and guide fields: latter is noted, but for the former e.g. B_{in,RX}; B_{out,RX} for the reconnecting components, to not suggest rotation of the reconnecting fields. Panel b) Specifically "Hall current" instead of "Current" in legend

Response:

We have revised Fig. 2 accordingly and added notations of B_{RX} to the plot. Please see the revised manuscript for details.

Extended data: The wave analysis, while interesting to see, is left on its own in relation to the reconnection study, with most signals seen outside of the reconnecting flux tube. A briefly expanded description on the extended data, describing its relevance, would not be out of place, and/or a mention in the manuscript on the availability and relevance of such data for further studies.

Response:

Thank you for this suggestion. After reconnection, harmonic plasma waves near the local electron plasma frequency (f_{pe}) and its second harmonic ($2f_{pe}$) are observed by Juno's WAVES instrument on the low-density side. These waves may be generated by nonlinear interactions between the reconnection jets and the ambient plasma (Dokgo et al., 2019). Plasma waves associated with reconnection are beyond the scope of this study and are left for future investigation. We have added the plot in the Supplementary Information and the briefly description in the manuscript.

References:

Dokgo, K., Hwang, K., Burch, J, et al. (2019). High‐frequency wave generation in magnetotail reconnection: Nonlinear harmonics of upper hybrid waves. Geophysical Research Letters, 46(14), 7873-7882. DOI: 10.1029/2019GL083361

Data: Zenodo-based data is readily available. PDS-based links offer dataset descriptions, but the data access is behind the rather hard-to-use PDS/PPI interface – a direct link to the data referenced would be greatly appreciated.

Response:

For the Juno data available on PDS, we have replaced the DOI links with direct links to the data sources in the revised manuscript.

Remarks on code availability:

The code provided is written in Python, with a standard, readily-available environment, causing no barrier of entry. The plots of the manuscript (barring three panels from Figure 3a, which I would have expected to be reproduced) are reproduced well. The code does not include a separate README, but operation is straightforward and runs fast on CodeOcean. Some more details on the usage, inputs and purpose in the code would have been welcome ("This script reproduces the figure X of Wang+2025, using JADE dataset [link, instruction for possible pre-processing], edit these lines to adapt for other events [if applicable]"), but not strictly necessary in my opinion.

Response:

Thank you for the suggestion. We have added instructions and comments at the beginning of each code file. Please refer to the newly uploaded code for details.

Response to the comments of Reviewer #2:

Very nice article, aiming to provide in-situ signatures of the complex interplay between convective instabilities (here interchange instability in the Jovian magnetosphere) and magnetic reconnection. Suitable for a high impact, broad public journal as Nature Communications. That said, if and only if the Authors can clearly support their statements on the dynamics of flux tubes, on the detection of a reconnection outflow, or on the detection of other clear reconnection evidences (see my main points, here below).

Response:

Thank you for your comments. They have been very helpful in improving the manuscript. We have provided point-by-point responses and made the corresponding revisions. Please see the content below.

Main criticisms:

1) The Authors describe the dynamics of the flux tubes, observed in the northern side, as that of "colliding tubes", leading to the compression of the current sheet in between them, and thus to the on-set of magnetic reconnection. Even if plausible, this dynamics must be supported by observations. Looking at the ion flows in Fig. 1, it is not clear to me if the average velocities inside the two flux tubes are, partially, directed one against the other (for sure, excluding from this picture the "localized" outflow jets). It would be clearer in the LNM base. Indeed, in Fig.2 V_N passes from ~0 Km/s just on the left of the current sheet, to ~60 Km/s on the right, suggesting compression. However, this velocity strongly varies as soon as Juno moves away, as shown by the measurement points at t~02:03:30 and t~02:04:00. Showing the ion velocity, in the LMN frame, on a longer time period of that of Fig. 2 (e.g. from t~02:00 to t~02:06:30) would corroborate, or invalidate, the idea of "colliding flux tubes".

Response:

Thank you for pointing out this issue. The idea that the current sheet is introduced by collision or compression between two flux tubes is inferred to be the most likely mechanism. We examined the flow velocity in the N-direction (v_N) over a broader time range, as shown below. Except for the two measurements near the X-line, no converging flows are observed before or after the X-line on this larger timescale. This could be explained by several factors. First, the X-line is a highly localized structure and may rotate rapidly compared to the 6-minute interval examined here. Given the complex magnetic topology caused by stretching and twisting, the observations outside the diffusion region are not necessarily well organized in the local LMN coordinate system. Second, in Fig. 1, panel (m), the dense flux tube located before the current sheet shows a negative v_r, while the tenuous tube located after the sheet exhibits a positive v_r. This suggests that, on a larger scale, the two tubes are moving toward each other. Third, the cadence of JADE is limited to a resolution of ~30 seconds. Compared to v_M and v_L, the N-component (v_N) is much smaller and may not be accurately resolved through forward modeling. In the revised manuscript, we have added this response in the Discussion section of the manuscript and the plot in the Supplementary Information.

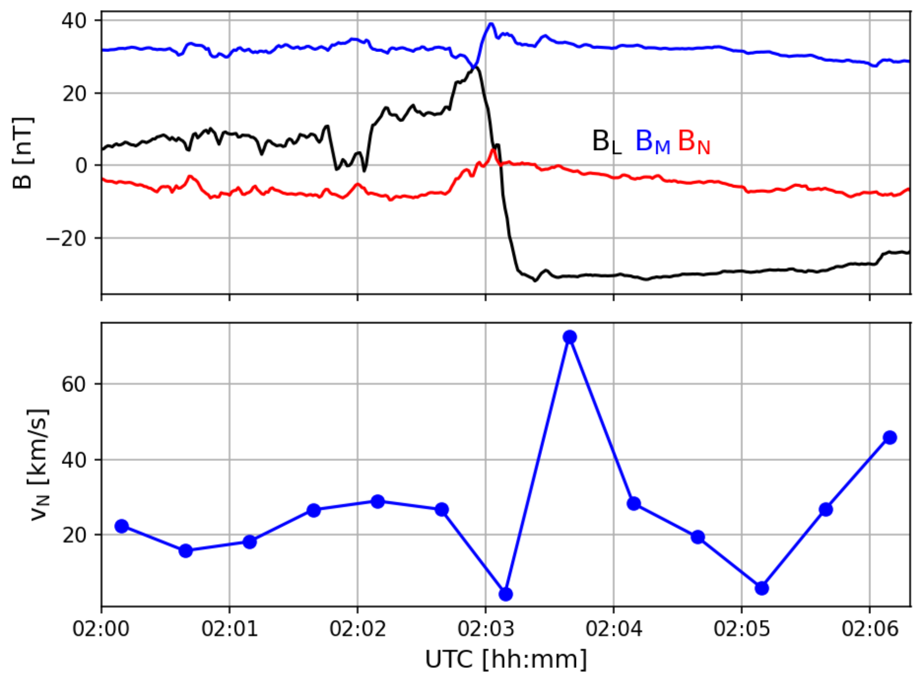

Fig. 1. (upper) The magnetic field in the LMN coordinate system and (lower) the plasma flow velocity in the normal direction of the current sheet.

2) The detection of the outflow in the low density tube is the main signature of magnetic reconnection in Juno data, but I'm not sure that the ion flow that is observed there can be identified as a reconnection outflow. Indeed, in Fig. 1, where the outflow is mainly along the \theta-direction (identified by the Authors as "Plasma jets") the V_\theta structure, with V_\theta around 150 Km/s (from t~02:03 to t~02:07), is too "wide" for being an outflow, that is expected to have a width of few d_i. Following Authors's estimation for the normal width of the current sheet (a transit time of ~15 seconds, corresponding to a width of ~ 2 d_i), I can deduce that the width of the structures at V_\theta around 150 Km/s (for which the crossing time is around ~4 minutes) is of the order of tenths of d_i, that is not compatible with a reconnection outflow width. Eventually, V_\theta is ~150 Km/s inside the whole low density flux tube. Something hardly compatible with a reconnection outflow.

For sure, using the LMN base, as in Fig.2, would be far better for the outflow identification, but only two measurement points are shown at V_L around - 150 Km/s. For a correct identification of the outflow, the Authors must show the ion flow in the LMN base but for a longer time interval (e.g. from t~02:00 to t~02:07), and check the existence of a clear, thin (~ few d_i) jet.

Response:

We examined the outflow over a broader time interval, from 02:00:00 UT to 02:09 UT, as shown below. Following magnetic reconnection, the outflow remains stable and persists for approximately 5 minutes, which is about 10 times longer than the current sheet crossing. This unusually large-scale outflow, along with its bias toward the low-density side, can be explained by several possible mechanisms. First, the strong density gradient across the current sheet may cause the outflow to extend more into the low-density region. The lower inertia in this region allows the reconnected field lines to evacuate plasma more efficiently and propagate farther. Kacem et al. (2018) reported a case with similar features at Earth's magnetosphere, in which the outflow was biased toward the low-density side and extended over spatial scales much larger than the current sheet thickness. Quantitatively, in their case, the outflow duration is at least five times longer than the current sheet observation. Second, the centrifugal force resulting from rapid planetary rotation may sustain a steady inflow in reconnection. The reconnection does not easily shut down, allowing outflow jets to persist and extend far. For example, Arridge et al. (2016) reported a reconnection event in Saturn's magnetosphere that lasted over 19 hours. Third, a moderate guide field can suppress turbulent mixing and promote well-directed, collimated jets that remain coherent over long distances. In the revised manuscript, we have added this response in the Discussion section of the manuscript and the plot in the Supplementary Information.

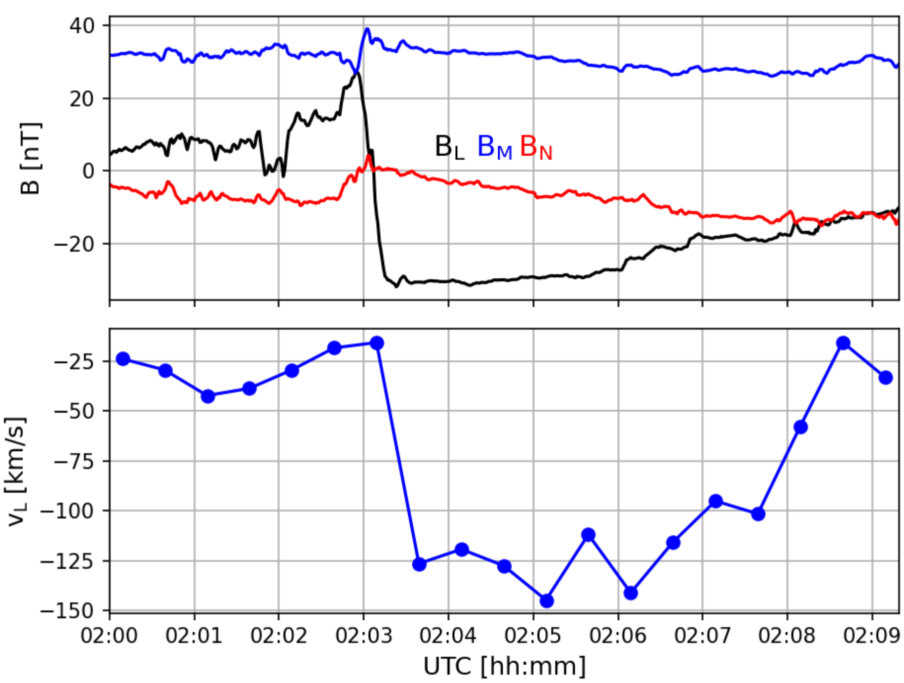

Fig. 2. (upper) The magnetic field in the LMN coordinate system and (lower) the outflow velocity after magnetic reconnection.

References:

Kacem, I., Jacquey, C., Génot, V., et al. (2018). Magnetic reconnection at a thin current sheet separating two interlaced flux tubes at the Earth's magnetopause. Journal of

Geophysical Research: Space Physics, 123(3), 1779-1793
Arridge, C. S., Eastwood, J. P., Jackman, C. M., et al. (2016). Cassini in situ observations of long-duration magnetic reconnection in Saturn's magnetotail. Nature Physics, 12(3), 268-271

3) If reconnection has occurred and finally has created field lines connecting the cold-dense flux tube to the hot-tenuous one, I would expect a parallel streaming of electrons going from one region to the other. In the Earth context, M. B. Bavassano Cattaneo et al., Ann. Geophys. 28, 893 (2010); M. Faganello et al. Europhys. Lett. 107, 19001 (2014); Y. Vernisse et al., J. Geophys. Res. Space Physics 121, 9926 (2016), showed that analyzing either the pitch angle distribution of electrons, as a function of time, for different energy range, or the distribution functions at given times, as function of v_\parallel and v_\perp, it is possible to infer i) the topology of magnetic field lines and ii) the location where, and the time at which, these lines have undergone reconnection. In the Earth context, reconnection was related to Kelvin-Hemlholtz vortices growing at the equators, distorting the field lines and finally inducing reconnection away from the equators, a mechanism not so different from the one that is discussed in the present article. I strongly advise the Authors to carefully analyze the pitch angle distribution, for different energies and times, for checking if it is possible to recognize parallel electron streams in one tube, arriving from the other one. Their presence would strongly support the idea that reconnection is/was going on. If the "local" outflow is confirmed, parallel streams could help in estimating the length of the X-line. If the local outflow is not, they could suggest that reconnection is/has going on at a different latitude with respect to the observed current sheet.

Response:

We examined the electron pitch angle distribution (PAD) over a broader interval, from 02:02:30 UT to 02:04:00 UT, covering the ion diffusion region. Each panel shows a 1-second observation, and it is the highest resolution available from Juno. The x-axis is the pitch angle and the y-axis is energy. No asymmetric PADs were observed before or after the X-line, which is expected and can be explained by the magnetic topology. In Kelvin-Helmholtz (KH) studies at Earth, reconnection occurs on open flux tubes, with one end connected to the solar wind. As a result, PADs are asymmetric, often field-aligned or anti-field-aligned, revealing electron streams entering and exiting flux tubes. In contrast, the reconnection in this study is from flux tube interchange, occurring on closed field lines. Electrons are trapped and bounce between both ends, producing symmetric PADs with bidirectional flows.

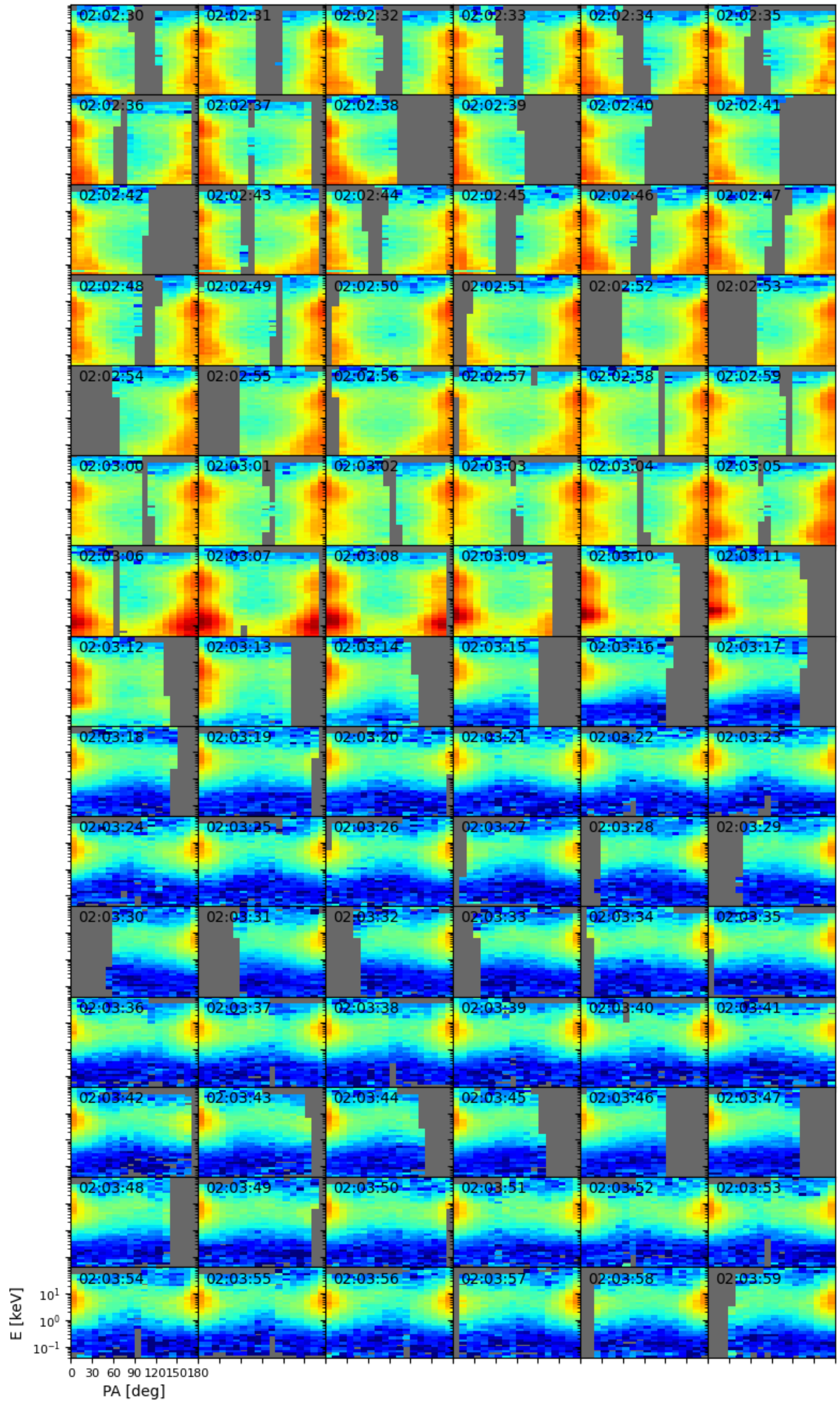

Fig. 3. Pitch angle distribution of electrons with 1-second resolution.

Minor points:

line 71: Here "rotational direction" means that of plasma flow, while a reader could think about that of the angular velocity vector (roughly parallel to the north-south direction). Stating that the \phi-component is approximate the velocity direction of the plasma/magnetospheric motion associate to Jupiter's rotation, would be better.

Response:

We have revised the manuscript accordingly.

line 250: I do not agree with the explanation given here, for the stronger stretching of the inner (denser) flux tube. Actually, I agree that a denser tube is expected to stretch more, but I don not with the explanation. Indeed, in the rotating frame the centrifugal force can be seen as an effective gravity force, whose intensity is proportional to the density \rho. Neglecting field line curvature, the equilibrium is guaranteed by the gradient of the total (thermal plus magnetic) pressure. The contribution of the total pressure can be seen as a buoyancy. As a tube moves away from its equilibrium radial position, the radial component of the momentum equation can be approximated as follows (still neglecting the magnetic field curvature):
\rho_tube \partial_t u_r = (\rho_tube - \rho_background)*g_effective
For a nit too large radial displacement \xi_r, with respect to the tube equilibrium position, it reads
\rho_equilibrium \partial_tt \xi_r = (\partial_r \rho_equilibrium)*\xi_r*g_effective
For the sake of simplicity, I've neglected the plasma compressibility. Taking it into account does not change too much the physical explanation (e.g. the Brunt-Vasaila frequency would be given by the logarithmic radial derivative of the potential temperature profile, instead of the logarithmic radial derivative of the simple density).

Looking at that equation, the higher inertia of a denser tube does not play in favour of an higher acceleration/displacement, as suggested by the Authors. e.g. for an exponentially decreasing equilibrium density, the (imaginary) frequency of unstable oscillation does not depend on the tube density (equilibrium density at the unperturbed tube position). For a linear equilibrium gradient, the higher the equilibrium/tube density, the smaller the growth rate, thus the dispalcement value after a given time interval (neglecting nonlinear saturation).

For explaining why a denser tube is distorted more than a tenuous one (and I agree with that), the magnetic tension must be included. Even if I neglected the magnetic tension for the equilibrium, the original flux tubes are distorted by the fact that the interchange instability mainly occurs at the equators, while it is stable far away. The relative weight of inertia and magnetic tension is measured by the Alfven velocity V_A = B/\sqrt{\mu_0 \rho}.

The denser the plasma, the lower the Alfven velocity, the easier for a plasma motion to distort field lines. Thus, for a tenuous tube, the Alfven velocity is higher, it is harder for it to bent field lines. For a denser tube, the Alfven velocity is lower, it is easier to bent field lines. In my opinion, this is a more convincing explanation for why the denser tube could be more perturbed than the tenuous one.

Response:

Thank you for the detailed explanation. The dependence of the interchange motion growth rate on plasma density can be understood through the dispersion relation. As described in Ferrière (2006) and illustrated in Achilleos et al. (2015), when considering only the centrifugal force, the dispersion relation of the interchange mode is given by:

$$\omega_0^2 = \vec{g} \cdot \left(\frac{\nabla \rho_0}{\rho_0} - \frac{\vec{g}}{V_A^2 + 2C_\perp^2} \right)$$

In the first term, as the reviewer correctly noted, the frequency ω_0 depends on the equilibrium density and its gradient at the unperturbed flux tube location, rather than the density of the perturbed tube. In the second term, the frequency also depends on the Alfvén speed. Since a denser flux tube has a lower Alfvén speed, this leads to a larger growth rate. From this perspective, the denser tube undergoes greater distortion due to the interchange process. We have clarified this explanation in the revised manuscript.

References:

Ferrière, K. (2006). Low-frequency waves and instabilities in collisionless plasmas. Space Science Reviews, 122(1), 247-253.

Achilleos, N., André, N., Blanco-Cano, X., et al. (2015). 1. Transport of mass, momentum and energy in planetary magnetodisc regions. Space Science Reviews, 187, 229-299.

Response to the comments of Reviewer #3:

The authors note that the topic of their study is an analysis of Juno data, which allowed to find for the first time an ion diffusion region in Jupiter's inner magnetosphere. They claim to have found evidence of local interchange motion under the action of centrifugal force. This work sheds light on the understanding of how Io-genic plasma is transported in Jupiter's magnetosphere. The topic of the work is actual and important.

The article is well written. The experimental material is presented in detail. Theoretical interpretations are given. However, there are several questions that would be desirable to answer.

Response:

Thank you for your comments. We have provided point-by-point responses below and revised the manuscript accordingly. Please see the responses for details.

1) Page 2, lines 47-48. The authors wrote: "the localized flux tube interchange driven magnetic reconnection (X. Ma et al., 2016) although there is no observational evidence to date to support this mechanism". It is advisable to briefly describe "this mechanism" so that readers understand what it is. Moreover, Ma et al. (1916) wrote about "a pair of the high-latitude reconnection sites", while in the considered work both reconnection sites are near the plasma sheet, as it follows from their figures 1a,b. On page 2, line 72 it is written: "this event occurred at a radial distance of 23.3 RJ and a local time of 22.6 hr, near the midnight magnetic equator". Moreover, on pages 4-5, lines 131-132 it is stated: "reconnection events are located 0.39 RJ south and 0.33 RJ north of the plasma disk center, respectively".

Response:

First, 'this mechanism' refers to the localized interchange driven magnetic reconnection. We have rewritten this paragraph in the revised manuscript; please refer to the revised version for details. Second, we compared this event with the simulation by Ma et al. (2016). On the one hand, the term 'high-latitude' in their study is vague and lacks quantitative definition. They set a uniform density profile along the z direction, which may result in larger separation between two reconnection sites. In contrast, the plasma disk features an exponential decrease in density with distance from the equator. The simulation in Ma et al. (2016) is based on artificial onset conditions rather than realistic ones, which likely accounts for the differences. On the other hand, Ma et al. (2016) also wrote: "For the Jovian inner magnetosphere, it is expected that the RT instability is localized inside of the Io plasma torus (i.e., scale height of the torus ~1R_J), because both the large density gradient and the centrifugal force are localized at low latitudes, and the magnetic field line motion at high latitudes is limited by the Pedersen conductivity." Our event occurred within the plasma disk, which contains most of the mass, and is consistent with this description. We have clarified this point in the Discussion section of the revised manuscript.

2) Page 2, line 70. “the north-to-south direction”. Is this related to rotation or magnetic axis?

Response:

The north-to-south direction follows Jupiter’s spin axis. We have clarified this in the revised manuscript.

3) Fig. 2a. The arrows illustrating inflow are drawn a little bit unclear.

Response:

We have edited the plot accordingly. Please see the revised manuscript for details.

4) Page 4, lines 119-120. It is written: “In summary, the observations of magnetic fields, plasma bulk flow parameters, and PADs are consistent with the detection of a reconnection event.” Can the process described be considered as reconnection? It is usually believed that during reconnection the topology of magnetic field lines changes. Does this happen in the presented observations? If so, it would be desirable to describe it in detail. If this is not the case, this needs to be explained.

Response:

In the event we present, multiple lines of evidence indicate that the topology of the magnetic field lines changes due to magnetic reconnection. First, the rapid rotation and variation in B_θ and B_ϕ suggest a twisted flux tube structure. A sharp boundary at the center of this structure supports the presence of a thin current sheet. Second, in the LMN coordinate analysis, a clear reversal in B_L indicates that the spacecraft crossed the current sheet from one side to the other. The bipolar signature in B_M provides direct evidence of the Hall magnetic field within the diffusion region, characteristic of local magnetic reconnection. We have emphasized these observational signatures in the revised manuscript. Please see the Discussion section for details.

5) Fig. 4c. What kind of magnetic field lines are in the rightmost equatorial part of the scheme inside the region bounded by the blue line on the left and the green line on the right? How is the magnetic field directed there? It seems that magnetic field there is directed from top to bottom at the left side, as well as at the right side also, which is impossible (div B =0).

Response:

As noted in the Fig. 4 caption, this diagram is a simplified 2-D projection of a 3-D structure of twisted flux tubes. Although two magnetic field lines appear to overlap in the diagram, the divergence-free condition ($\nabla \cdot B = 0$) remains satisfied in the 3D geometry.

6) Page 10. It is written that 23.3 Jupiter radii “is also far from any Galilean moons, eliminating the influence of moon plasma interactions.” However, Callisto is not too far (at ~ 26.3 Jupiter radii).

Response:

We argue that this event is far from any moon when considering the moons' radii. For example, the distance between this event and Callisto is 3 R_J, or approximately 89 R_C (where R_C=2,403 km is Callisto's radius). This location is well beyond the region of possible interaction with Callisto.

Response to the comments of Reviewer #1:

My comments have been adequately addressed, but I would still like to ask for the following clarification on the data. Given the discussion on the point on electron PADs raised by Reviewer #2 is concluded satisfactorily* with R.#2 I recommend acceptance.

> Data: Zenodo-based data is readily available. PDS-based links offer dataset descriptions, but the data access is behind the rather hard-to-use PDS/PPI interface – a direct link to the data referenced would be greatly appreciated.
> Response:
> For the Juno data available on PDS, we have replaced the DOI links with direct links to the data sources in the revised manuscript.

I do believe the DOI links should still be the primary reference. As it is currently, I am able to access FGM and JED data via the DOI links, but not the JAD-5-MOMENTS or JAD-3-CALIBRATED via their DOI landing pages - those data access links look to be unfortunately dead, leading to this confusion. This may not be directly in the hands of the authors, but this issue should be resolved outside of this peer review process.

JAD_L50_QLK_ELECTRONS_2020206.csv seems like it should be available via the JAD-5-MOMENTS dataset, but the JAD-5-MOMENTS only provides the following data for the time period: JAD_L50_ELC_MOM_ISO_2D_ELECTRONS_2020206, which deviates from the QLK dataset. The provenance of the QLK file should be clarified (compatible data is available via e.g. AMDA).

Response:

Thank you for your comments. We agree that PDS is hard to use, especially given the confusion between the old and new versions. As you suggested, we have included both the link and DOI of the related data in the revised manuscript, so the reader can use either one. As you mentioned, the links for the JADE moments and JADE Level 3 Version 04 data are dead on the DOI landing pages. We will report this issue to have it fixed.

Lastly, both JAD_L50_QLK_ELECTRONS_2020206.csv and JAD_L50_HLS_ELC_MOM_ISO_2D_ELECTRONS_2020206_V01.csv contain the derived electron moments. The former is the internal version we use at LASP, CU Boulder, before uploading to PDS. The latter is the PDS-uploaded version, which are 2-D moments based on the electron pitch angle distribution. To avoid the confusion, we updated the plot using the latter version. Thank you for the careful check, and we apologize for the confusion.

*Further, with respect to the Author's response to Reviewer#2:

> The x-axis is the pitch angle and the y-axis is energy. No asymmetric PADs were observed before or after the X-line, which is expected and can be explained by the magnetic topology. In Kelvin-Helmholtz (KH) studies at Earth, reconnection occurs on open flux tubes, with one end connected to the solar wind. As a result, PADs are asymmetric, often field-aligned or anti-field-aligned, revealing electron streams entering and exiting flux tubes. In contrast, the reconnection in this study is from flux tube interchange, occurring on closed field lines. Electrons are trapped and bounce between both ends, producing symmetric PADs with bidirectional flows.

I feel I need to point out that this reasoning is jumping a bit ahead of the point: reconnected flux tubes should still show a mixture of streaming electron populations between the flux tubes, and the asymmetry of the PADs, after reconnection, should be retained on time scales less than electron bounce time. For the local process here it would indeed be a relevant and strong indicator of reconnection, but I do not see whether or not the presented PADs disprove the claim either.

Response:

Thank you for your comments. In the first-round revision, the statement comparing reconnection at the magnetopause and on closed field lines was somewhat overstated. As you suggested, in high-resolution data, asymmetric electron PADs are always expected on timescales shorter than the electron bounce time. As shown in the first-round revision, the JADE instrument does not observe large asymmetries in the PADs. To understand this, we first calculate the electron bounce time. Following Norgren et al., (2025), the electron bounce frequency is

$$\omega_b \sim \sqrt{eB_L v_e / m_e N}$$

where e is the elementary charge, B_L~30 nT is the L-direction component of the magnetic field in the diffusion region, v_e is the electron velocity, m_e is the electron mass, and N~725 km is the current sheet thickness (see the section entitled 'Diffusion Region Observations' in the manuscript for details). Assuming an electron energy of 1 keV, the frequency is ω_b~369 s^{-1}, corresponding to a bounce time of $t_b = 2\pi/\omega_b$~0.017 s. The highest resolution of JADE-E is 1 s. Therefore, the electron bounce time is much shorter than the instrument's cadence, which may explain why asymmetries are not observed in the electron PADs between the low- and high-density flux tubes. Second, an asymmetric electron PAD is expected in the electron diffusion region, which is tiny compared with the spacecraft's relatively fast motion. Consequently, the instrument's dwell time in the region is insufficient to resolve electron PAD asymmetries.

References:

Norgren, C., Chen, L. J., Graham, D. B., et al. (2025). Electron and ion dynamics in reconnection diffusion regions. Space Science Reviews, 221(5), 1-73. DOI: 10.1007/s11214-025-01197-z

Response to the comments of Reviewer #2:

The Authors' answer to my point 2) is not convincing.

Their comparison with the Saturn event is not appropriate for two reasons:

- Ion flow data from Cassini are low quality, as Arridge et al. fairly admit.
Thus, ion outflows are badly identified.

- Cassini is moving roughly along the tail so, for a magnetotail reconnection event, as that discussed by Arridge et al., Cassini could see the ("long-lasting") reconnection ion outflow for a long time, since it is moving mainly along the jet direction.
On the contrary, Juno is supposed to moves perpendicularly to the ion outflow (along the N direction, in the present paper). It is thus supposed to cross the ion outflow, and not to move "along it". The time duration of high ion flow should thus be related to the ion outflow width (as the Authors did for estimating the current sheet width), and that duration should be independent of the fact that reconnection is lasting for a long or for short time.

Thus, invoking "long-lasting reconnection", for explaining a claimed reconnection outflow that lasts five time longer than the current sheet, is not correct here. It is OK for a satellite moving along ~L, not along ~N.

A more pertinent comparison is the one with the event analysed by Kacem et al. (even if the quality of MMS/temporal resolution of MMS data is uncomparable with that of Juno). Indeed,

1) MMS is crossing two interlaced flux tubes, with reconnection going on in between the tubes, as in the present event (even if the mechanism that created the two interacting flux tubes at the Earth is different from that at Jupiter).

2) MMS is crossing the current sheet in between the two flux tubes along its normal direction, as it is the case for Juno here, so that detection duration can be translated in spatial width.

Note that Kacem et al. adopt two different local frames, LMN as the local frame of the "whole event" (crossing of both flux tubes), and a more local/refined U_V, U_J, U_P frame for the current sheet crossing (with U_P normal to the sheet, and U_V along the outflow)

Looking at MMS data, in particular at the component of the ion fluid velocity along L (Fig. 6, panel (f)), it is true that high velocity flows are observed for "long time" (from ~14:16:40, identified as T_2, to 14:16:58, identified as T_4), in comparison to the current sheet

crossing time (from T_2=14:16:40 to T_3=14:16:43) BUT MMS clearly show the presence of a thin (duration/width comparable with that of the current sheet), localized ion jet, that is identified as the reconnection ion outflow at t~14:16:41. The rest of period with high ion velocity (T_3 to T_4), looking as a broader flow structure, is identified as the ion velocity inside one of the two flux tube, i.e. the velocity at which the tube is moving, if we suppose that the frozen-in condition holds there.
This double structure (thin reconnection ion outflow, around t=14:16:41, plus a broader ion flow associated to the flux tube motion, from 14:16:45 to 14:16:58) is even more clear using the more local/refined U_V, U_J, U_P frame, as shown by the ion fluid velocity along U_V in Fig. 9, panel (g).

Coming back to the present article, where Juno is supposed to cross the current sheet along N, a single, broad structure of the L component of the ion fluid velocity can not, in my opinion, be identified as a reconnection ion outflow.

It is possible that a localized, thin outflow is hidden on the left part of the broad flow structure, due to the 30s temporal resolution of ion fluxes, adopted in the article.
I imagine that raw fluxes have been integrated over 30s time windows in order to have a better noise-to-signal ratio.

In my opinion, there are three possible issues:

a) Fluxes averaged over a shorter time window (duration smaller or comparable with that of the current sheet) are OK from the noise point of view, and clearly show the presence of a double structure in V_L, as in Kacem et al., with a thin ion outflow close to the current sheet, and a broad peak related to the flux tube motion. In that case, the Authors could clearly affirm that a direct proof of a magnetic reconnection outflow is present in Juno data. Including the necessary modifications, the article would be OK for me.

b) These fluxes are OK from the noise point of view, but still exhibit a single, broad peak for V_L (without a localized, thin outflow on the left). As discussed above, this single broad peak can not be identified as the reconnection outflow. In this case, several evidences point toward magnetic reconnection (magnetic configuration, including what has been identified as a Hall field, PA distributions with enhanced perpendicular energy in the low density tube,...), but the final proof (the outflow) is lacking. In my opinion, without a clear detection of an outflow, reconnection is the main suspect, but the Authors can not speak about a direct observation of it.
Without a direct observation, the main reason for a Nature publication would fail. The Authors' work remains very interesting, but it would be more appropriate for a more specialized journal.

c) The noise-to-signal is too high for shorter time windows. The Authors could speculate about the possible presence of a thin, localized outflow, hidden in the broad velocity peak by the poor temporal resolution. I would let the Editor judge if such "possible hidden proof" would be sufficient for accepting the article.

Response:

We appreciate your detailed feedback. We interpret your comments as being primarily concerned with the lack of direct observation of jets in the diffusion region. Following your suggestions, we examined the plasma data at the highest available resolution, as shown below. The time resolutions for electrons and ions are 1 second and 2 seconds, respectively. Within the identified diffusion region, an enhancement in electron density is observed, which is a signature of electron trapping by parallel electric field near the X-line (Egedal et al., 2008). As expected, the heavy ion signals peak every 30 seconds (lower left panel), reflecting JADE-I's once-per-spin sampling cadence for ion flows. In comparison, after the diffusion region, the proton signals peak every 15 seconds (lower right panel), indicating bi-directional proton flows and the decoupling from heavy ions after reconnection. Unfortunately, Juno did not observe a narrow ion jet within the diffusion region. JADE has twelve 22.5 deg wide anodes, and at each time step, it samples only a small portion of the 4π steradian sky. Given the narrow spatial extent of the diffusion region, the JADE anodes are unlikely to observe the jet at the current sheet due to limitations in angular and temporal resolution. Since JADE-I was not able to resolve narrow ion jets, we have modified the text and figures to use ‘accelerated flow’ instead of ‘jet’.

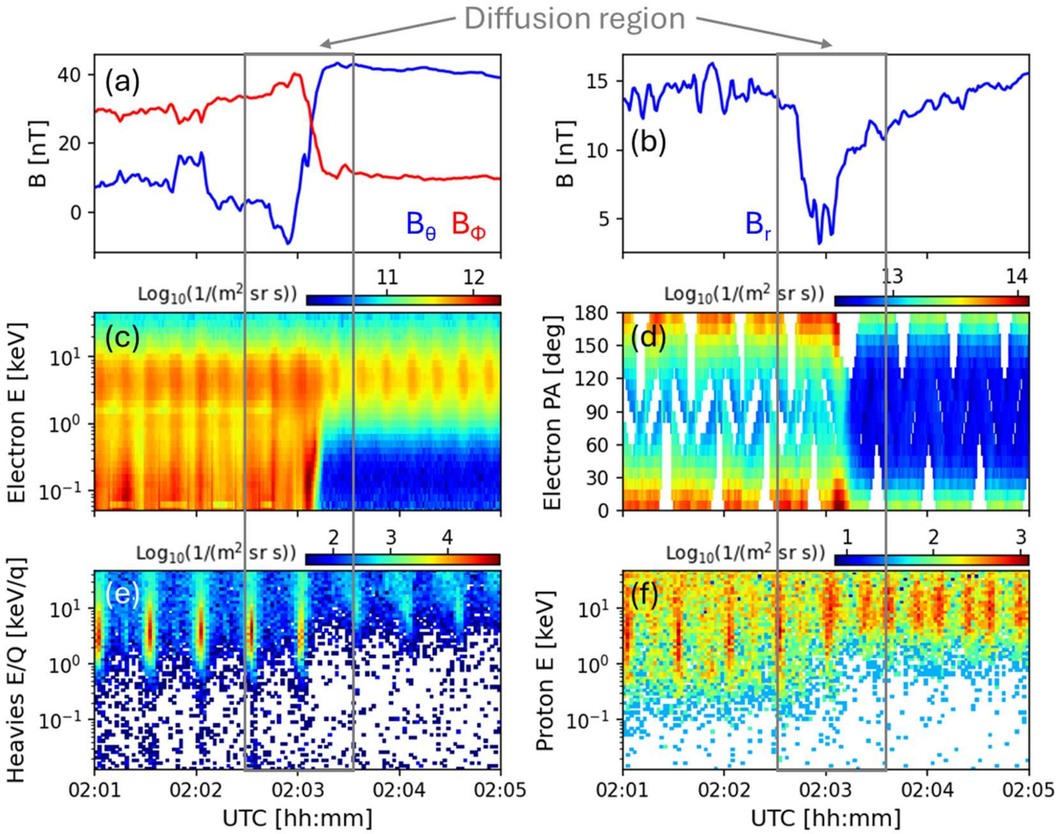

Fig. 1. The magnetic field and plasma observations near the diffusion region of the magnetic reconnection event, including (a,b) the magnetic field, (c) electron flux spectra, (d) electron pitch angle distribution, (e) heavy ion flux spectra, and (f) proton flux spectra.

Another possible explanation is the possible complex trajectory within the diffusion region. For example, if Juno followed the trajectory illustrated below, it may not have traversed the outflow region but instead skimmed over it in an arch-shaped path, thereby missing the narrow jets in the diffusion region. A further advantage of this trajectory is that it could explain the small-scale positive B_N bump in the B_N panel, assuming Juno entered the opposite half of the diffusion region during the interval. However, we do not wish to overstate this event; therefore, this complex trajectory is not adopted in the manuscript.

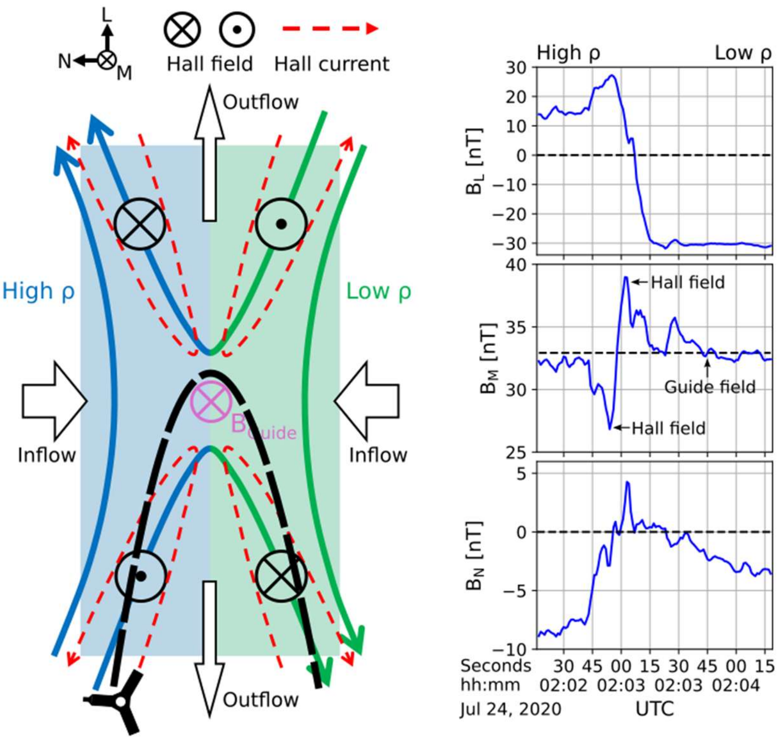

Fig. 2. The ion diffusion region observation with an arch-shaped path of Juno. (left) Illustration of the diffusion region. (right) Magnetic fields in the LMN coordinate system.

Our conclusion is that the primary evidence of reconnection is the perturbed magnetic field (i.e., the Hall field) along with the Alfvénic ion flow on the low-density side of this narrow layer. Moreover, we examined all 51 plasma disk crossings by Juno between 20 and 25 R_J. Overview plots for each crossing are available at https://zenodo.org/records/17094279. Many of these events exhibit small-scale, intermittent signatures accompanied by fluctuating magnetic fields. The alternating presence of hot, tenuous plasma and cold, dense plasma observed in these cases is a typical signature of flux tube interchange, the dominant plasma transport mechanism in this region. Among all the cases, only the event analyzed in this study shows a strong magnetic field signature characterized by entangled flux tubes, twisted magnetic field topology, and a thin current sheet—highlighting the uniqueness of this event. Given the prevalence of flux tube interchange in this region and the signatures in this particular case, we propose that it most likely represents a magnetic reconnection event driven by localized flux tube interchange.

For deep space missions (especially those to the outer planets), instrument resolution is always limited by constraints on mass, power, and telemetry. It is not feasible to perform high-resolution analyses comparable to those based on MMS data. For example, two Nature papers, Arridge et al. (2016) and Guo et al. (2018), reported magnetic reconnection events at Saturn without plasma flow values. In both studies, the Hall magnetic field served as the primary evidence for identifying reconnection. In this study, despite the expectation of a narrow ion jet within the diffusion region, we report multiple pieces of evidence consistent with magnetic reconnection, including the unambiguous Hall magnetic field signature. The event analyzed in this study is the most conspicuous reconnection event observed in Jupiter's magnetosphere to date. Beyond the reconnection event itself, the most striking aspect of this study is the first observational evidence for a new Io plasma transport scenario: localized flux tube interchange. The mechanism of Io plasma transport has long been a top-tier open question in Jupiter science.

Finally, as demonstrated in the manuscript, we exclude other possible mechanisms, leaving magnetic reconnection as the only one that could produce the strong perturbed signatures in this case. For these reasons, we believe this work deserves publication in Nature Communications.

References:

Egedal, J., Fox, W., Katz, N., et al. (2008). Evidence and theory for trapped electrons in guide field magnetotail reconnection. Journal of geophysical research: Space physics, 113(A12), 12207. DOI: 10.1029/2008JA013520

Response to the comments of Reviewer #2:

I strongly appreciate the effort Authors did in searching for clear signatures of the reconnection outflow in the high resolution Juno data. I agree with them that the data quality of Juno is not comparable with what we are used to having in recent Earth's missions. Not being able to detect the reconnection outflow is a venial sin, that does not degrade the remarkability of the event Juno observes, and the quality of this work. The article thus deserves publication on Nature Communications.

On the other hand, some of the statements in the Discussion/Conclusion are not so clear, and could let the reader think that the large flow structure observed by Juno is the reconnection outflow, while it is not (and the Authors agree with me on that point, as clearly stated in their answer).

Response:

Thank you for your comments. We also appreciate your evaluation of our efforts in revising the paper. Following your additional comments, we have revised the Discussion and Conclusion sections to make sure there are no misunderstandings.

For avoiding that, it is mandatory to :

1) At line 319 of the "tracked manuscript", after "We also examined the highest resolution plasma data available, as shown in Fig. S4 of the Supplementary Information" add ", in order to search for a clear signature of a reconnection outflow, with a typical width ~ d_i, and thus a duration of few tenths of seconds, possible hidden in the large-scale flow structure."

Response:

We have revised the manuscript accordingly.

2) At line 375 of the "tracked manuscript", replace "vertically directed reconnection outflows" with "clear signatures of magnetic reconnection, in particular in the local magnetic field configuration and in particle fluxes".

Response:

We have revised the manuscript accordingly.