Annales Geophysicae Discussions

Ann. Geophys. Discuss., author comment AC2
https://doi.org/10.5194/angeo-2021-35-AC2, 2021

Reply on RC2

Christopher M. Bard and John C. Dorelli

Author comment on "Magnetotail reconnection asymmetries in an ion-scale, Earth-like magnetosphere" by Christopher M. Bard and John C. Dorelli, Ann. Geophys. Discuss., https://doi.org/10.5194/angeo-2021-35-AC2, 2021

This paper presents results from a numerical experiment using Hall MHD model with scaled ion inertial length. The authors argue that Hall MHD is the cause of tail current sheet asymmetry in the scaled magnetosphere.

Major issues:

>The "small, Earth-like magnetosphere" in the title is an ambiguous term. Despite the fact that the input parameters, if converted to physical units, represent most likely a Earth-like system, the scaling factor applied together with some other treatments make the outcome more or less similar to Mercury in terms of normalized units especially in the tail. The model-data comparison is also targeted at Mercury but not Earth in later sections.

RESPONSE A: Following this comment and referee 1's comments, we have added in the physical value of the normalizations in order to facilitate the discussion. Additionally, we have changed our use of the term "small" to "ion-scale" in order to clarify that we are simulating a magnetosphere whose system size is closer to di than Earth's would be.

When we say our magnetosphere is “Earth-like”, we mean that:

1) The subsolar magnetopause stand-off distance is ~10 R_p;

2) The subsolar bow shock standoff distance is about 3 R_p further out than the magnetopause stand-off distance.

These relative distances can be controlled, independently of the physical size of the magnetosphere, by setting three dimensionless parameters:

1) M_A, the solar wind Alfvenic Mach number

2) beta_sw, the solar wind plasma beta

3) b = B_dip/B_sw, the ratio of dipole field strength at 1 R to the solar wind magnetic field.

When these three dimensionless parameters are set, the subsolar magnetopause standoff distance, in units of R_p, is given by: R_mp ~ (beta_sw/M_A)1/3 . Setting b then controls the bow shock standoff distance.

The “ion-scale” classification of the experimental magnetosphere is controlled by setting di, the ion inertial length, relative to the planetary radius R_p. Setting di does not affect the standoff distances described above; it only controls the global effects of Hall physics. Thus, it is possible to simultaneously have an ion-scale and Earth-like magnetosphere. “Ion-scale” relative to Hall physics, and “Earth-like" according to the magnetosphere aspect ratio.

Note that there is no ambiguity here with respect to Mercury. Mercury lives in a completely different magnetosphere parameter space than Earth, having a much smaller ratio of dipole B strength to solar wind B strength. However, relative to Hall physics, Mercury is much closer to the ion-scale Earth presented in this paper.

The fact that there are similarities between “small Earth” and Mercury does not point to any inconsistency or ambiguity in our approach. It simply means that there are some important similarities between “ion-scale Earth” and Mercury that may shed light on MESSENGER observations. That said, we will modify our discussion to make clear that there may be important differences in “small Earth” vs Mercury dynamics due to the different bow shock and magnetopause stand-off distances. Indeed, the interaction between system size and di will be an important future topic for comparing magnetospheres.

>From the MESSENGER observational references mentioned in this manuscript, the local PIC simulation [Liu+2019], and the global Hall/MHD-EPIC simulation [Chen+2019], the readers can know that

- Mercury's tail flux transport events, or dipolarization fronts, favors the dawnside.
- Mercury's tail current sheet in z is thicker on the dawnside.

>From the local PIC and global Hall/MHD-EPIC simulation results, the readers are aware that

- The Mercury-like current sheet is thinner on the dawnside near the reconnection region.
- Mercury’s tail current sheet is thicker in the outflow region on the dawnside.
- Mercury’s tail current sheet asymmetry is less obvious in strong IMF driving cases.

>The asymmetry demonstrated in this manuscript shows a thinner current sheet on the dawnside on average, which is consistent with the 31 di length current sheet local PIC run in [Liu+2019] but opposite to the MESSENGER observation at Mercury. In Section 4.3, the authors argue with Figure 7 & 8 that this could be due to temporal sampling effect at different stages of the substorm. The explanation is reasonable within a shell of radius r between 14 to 15 planet radii between certain distances away from the center, but not so obvious in outer regions which are probably closer to the center of X-lines. This may indicate that the thickness of the current sheet is far from uniform, and has a dependence on the relative distance from the reconnection region as well as the driving conditions. The normalized units make it relatively hard to interpret the driving conditions in the simulation, especially when comparing against Mercury or Earth observations.

RESPONSE B: We realize that there are several differences between the literature and our results. We will be more explicit in describing how our simulation differs from others, especially in terms of magnetospheric parameters and driving conditions. We note that the effective dissipation scale plays a role in determining the overall shape and thickness of the tail current sheet; this is much more difficult to compare directly between our simulation and MHD-EPIC.

As far as the reason for the discrepancy between the local PIC and global Hall/EPIC simulations (and MESSENGER data), we agree with the referee that there may be spatial as well as temporal structure that is not captured in the MESSENGER analysis. Our suggestion about temporal averaging is just speculation, and we will clarify this in the manuscript.

However, the main points from our analysis remain: 1) Plasmoid formation favors the dawn side, 2) the current sheet is on average thinner on the dawnside but there are periods where it is thicker (depending on the phase of the substorm), 3) all of these effects can be explained by Hall electric fields in a small Earth-like magnetosphere, as argued by Liu et al. [2019].

An important additional fact revealed by our study is that this effect is not specific to Mercury (with its particular magnetopause and bow shock standoff distances) but appears to be a universal consequence of the Hall effect in very different regions of magnetospheric parameter space.

Minor issues:

Introduction & Model Description

>6. It would be better to be consistent in the manuscript when using the text "ion inertial length" or the math symbol di. Define it once in the beginning and use the math symbol thereafter would be nicer.

RESPONSE: We have made this change.

>7. Regarding GPU: it is unclear what advantages GPUs offer in accelerating the Hall MHD model. It would be more intriguing to briefly mention the strengths compared to CPU computing or shorten the description since this manuscript is aimed at science.

RESPONSE: We have added a brief description about why GPUs work well for Hall MHD. Essentially, GPUs take advantage of parallelism in order to have a higher throughput for floating point operations. Finite-volume schemes are massively parallel: the calculation of how a computational cell evolves from t to t+\Delta t is independent of similar calculations for other cells. This makes explicit Hall MHD schemes (such as presented in this paper) quite amenable to GPU acceleration.

>8.Line 91: GLM is typically used on a regular grid. If the underlying grid for the field components is staggered then by definition the monopole of B is maintained as long as it is initially zero. If it is the case then it may be worthwhile mentioning that briefly.

RESPONSE: We used the same grid for the field components as the other MHD variables. We did not use a staggered grid.

>9. Paragraph around Line 125: since the constrained transport scheme is not actually implemented and used in the model, the authors may consider removing this part of the context.

RESPONSE: We had intended to mention that CT is another way to handle the divergence constraint, but we will remove this paragraph for clarity.

>10. Section 3, problem initialization: as mentioned before, it may be worthwhile to state the key normalized quantities (e.g. Mach number, wave speeds) as well which is better to argue and reproduce the experiments. Alternatively, we can also list physical units, if possible, for better comparison with observations.

RESPONSE: We have reframed the simulation setup in order to clarify the key normalization quantities, adding physical units where relevant and appropriate.

>11. Line 140: Since this is 3D, the center shall be (0,0,0).

RESPONSE: Yes, this is correct. We have fixed this typo.

>12. Line 145: inner BC float Bperp, 0 Bpar ☐ what is the physical interpretation/numerical consideration for this magnetic field boundary condition?

RESPONSE: This is a numerical consideration. We had difficulties with density depletion near the inner boundary and experimented with several different combinations of floating/fixing variables at the boundary. The one that worked best to produce a stable evolution without density depletion is presented in the paper.

We have made it more clear that this boundary prescription was arrived at via experimentation.

>13. Line 150, outer BC: the authors do not mention the size of the simulation domain in terms of normalized distance, which may let readers think that the cuts shown below are from the whole domain slices.

RESPONSE: We have added the domain size, which (in normalized lengths) is –35.6 < X < 122 , -86.4 < Y,Z < 86.4.

>14. Line 153: due to the fact that this numerical experiment is conducted on an Earth-like magnetosphere with no rotation involved, the meaning of dawn and dusk may be ambiguous to readers unfamiliar with the norms. It would be better to mention that even though there are no dipole tilt or rotation, dawn and dusk are used assuming the sun is rising from the east, etc.

RESPONSE: This is a good point. We have modified this discussion accordingly to better define the convention.

>15. Paragraph around Line 160: this part argues the usage of 5 against 10 cells per di for sake of computational efficiency. However, the bottleneck is ambiguous. On a rough estimation, the presented simulation size with 18e6 cells in 3D of the Hall MHD model in double precision requires 18e6*8*(12+3) ~ 2GB of memory to store the data, and the runtime memory usage can easily be doubled or tripled. This means that using 10 cells per di requires about an order of magnitude more memory, and 20 cells per di requires about 128GB, which may be the real bottleneck but not speed. If this is true, it would be good to mention it in the text.

RESPONSE: This is a good point; however, the Hall MHD explicit time step inversely depends on the square of the grid resolution. Doubling the resolution not only doubles the number of computational cells, but it also (in theory) quadruples the number of timesteps required for the same time period.

We have added discussion about the explicit time step in Hall MHD (also addressing a comment from Referee 1).

>16. Line 165: it is unclear why the authors choose to run the simulation first with northward IMF, then southward IMF before turning on the Hall term, while later in around Line 196 stating that shifting in solar wind IMF is not required to sustain generation of substorms. Also, why does the solar wind magnetic field have a small Bx component?

RESPONSE: When starting up the simulation from an initial non-magnetosphere condition, the magnetosphere needs time to settle into a quasi-steady state. We found it more stable to start with a northward IMF and then let the magnetosphere evolve into a southward IMF. Similarly, since it would take too long to run the entire simulation under Hall MHD, we evolve the magnetosphere under ideal MHD before turning the Hall term on. Since our goal is to see how the magnetosphere behaves under a southward IMF with the Hall term, we run the magnetosphere until southward IMF in ideal MHD, and then turn the Hall term on. This is a common procedure for magnetospheric simulations: see, e.g. [Chen+2019; DOI:10.1029/2019JA026840; end of first paragraph in Section 4].

The small Bx component mimics the dipole tilt of the Earth (about 10 degrees).

Section 4.1

>17. Figure 1: would be better to denote the finest cell region with a box to show the “effective” Hall region, even if the Hall term is presumably added to the whole domain. The colorbar range is saturated on the minimum edge, so it would be better to extend the ranges.

RESPONSE: We have adjusted the plot with an extended colorbar range, and added markings to the diagram showing the extent of the high-resolution region. We have also added (per Ref 1’s comments) a figure showing the value of di through the tail, demonstrating that we are properly resolving the Hall scale.

>18. Figure 2: even though it is mentioned on Line 168 that all the results below come from the simulation after flipping and the Hall term turned on, the left subfigure still shows a snapshot from ideal MHD, which probably comes from a time before the Hall term is turned on. The colorbar is missing, so readers are not sure whether the magnitude of current densities are on the same scale. Since the width of the tail current sheet is mentioned in the caption, it would be better to add notations in the figures to point out the estimated widths.

RESPONSE: We have added a colorbar and clarified that Figure 2 is intended in a similar manner as Figure 1: comparison and contrast between ideal and Hall MHD.

Additionally, we meant that the "width” in the x-direction varies across the y-direction of the current sheet (not referring to the thickness variation in the z-direction). We apologize for the typo in the caption to Figure 2; we meant to refer the reader to Figures 6 and 8, which show the current density (and its variation) in the xy-plane. We have clarified both these points in the paper.

Section 4.2

>19. Figure 3: in the electron subfigure, using yellow streamlines makes it harder to identify the lines from the background colored contour of current densities. I suggest changing the choice of streamline color. Since the finest resolution region only goes up to 15 R in the tail, it is unclear what kind of effect Hall term will have in the further downstream tail region.

RESPONSE: The finest resolution actually goes down to 20 R_p in the tail, which covers the current sheet presented in these snapshots. We agree that it is unclear what are the downstream effects, and this will have to be a topic for future studies.

We have changed the streamline color to blue.

>20. Line 185: the authors mention "small magnetospheres' in the context'. In principle, Hall effect and reconnection exist in magnetospheres of any size, which lead to depolarization. It would be interesting to point out to what extent drifting electrons contribute significantly to the dipolarization processes with respect to the size?

RESPONSE: Yes, the Hall effect and reconnection do exist in all magnetospheres. Reconnection is what generates dipolarizations, but that the Hall effect influences where reconnection/dipolarizations occur.

We have added some discussion to this section about how the size of the magnetosphere relative to the Hall scale (di) may affect the relationship between drifting electrons and dipolarization processes. Specifically, we speculate that making the magnetospheres larger relative to di will cause the drifting electrons to penetrate less deeply dawnward, and move observed dipolarizations closer to the tail center. In other words, this type of asymmetry we observe here may be more pronounced in ion-scale magnetospheres and weaker for system size >>> di.

>21. Paragraph around Line 190: from observations and currently available simulations, we know that the frequency of substorm occurrence, or broadly speaking, the process of magnetic flux buildup --- release, varies a lot in magnitudes across Mercury, Ganymede and Earth, etc. In the simulations from this paper, the authors state 7 out of dawnside, 0 out of dockside during the 45 t0 interval. There are several questions regarding this statement:

>22. How are the events recorded from the simulation?

RESPONSE: The events are recorded via visual observation of the output snapshots (similar to what is presented in Figure 4).

>23. Which is a closer analogy for this experiment magnetosphere in terms of substorm frequency in nature? Since it is called Earth-like, one would assume that the substorm frequency would be closer to Earth. Is that the case in the experiment?

RESPONSE: We clarify that although the magnetosphere is “Earth-like” in physical size, it is ion-scale relative to di (see response to Major issue above for discussion). The key point we are making is that the interaction between system size and di controls the nature and location of substorms, and not necessarily the physical size.

At Earth, the substorm cycle is roughly one hour and the Alfven time (t_A) is about R_E/(100km/s) ~ 63 seconds. So, a substorm cycle is about 60 t_A.

In our simulation, we set the normalized t_0 to the Alfven time. Since we observed seven events in a 45 t_0 duration, this implies that the experiment magnetosphere substorm cycle is on the order of 5-10 t_A. This is a closer analogy to Mercury with respect to substorm cycles.

>24. If it is indeed Earth-like in terms of substorm frequency, then the dawn-dusk asymmetry (which is opposite in Earth and Mercury observations) raises another question: how does the Hall effect influence both the magnetic energy pile-up --- release frequency as well as locations? Does the experiment indicate that asymmetry always comes with higher frequency substorms, or vice versa?

RESPONSE: It is not Earth-like in terms of substorm frequency (see response to previous question). We don't believe that this experiment on its own can clarify the relationship between substorm asymmetry and frequency, but additional experiments with system size >>> di and/or different magnetosphere standoff distances should clarify this point.

>25. Paragraphs around Line 60, Line 160 and Line 205: these contexts contain discussions about grid resolutions. The authors claim that 20-25 cells/di resolution is required to recover the fast Hall reconnection, while only 5 cells/di is applied in the simulation considering the limitations of resources and model. It may not be necessary to argue about the choice of 5 or 10 cells per di since neither is capable of recovering the fast reconnection.

RESPONSE: This is a fair point. We will remove that paragraph since it seems unnecessary.

>26. Additionally, the authors acknowledge (around Line 205) that the localized instabilities are missing from the simulation due to the under-resolved resolution. The authors may consider emphasizing if neglecting local tail instabilities has an effect in interpreting simulation results.

RESPONSE: Local tail instabilities would produce localized dipolarization fronts, and add more observed events on both dawn and dusk sides of the tail.

However, this would not affect the main result of our analysis: the Hall effect induces dawnward Bz flux transport via electron convection which leads to a dawnward asymmetry in plasmoid/dipolarization formation.

>27. Figure 4: colorbar required, maybe with a better choice of color range scale and norm?

RESPONSE: We have added the colorbar and slightly widened the color range. However, we did intentionally chose a color range scale to highlight the evolution of the dipolarization event. A more dynamic color range/norm would make it more difficult to see the ejection.

>28. Figure 5: Since the middle and right columns show cuts in the xz plane which are different from the left column, it would be very useful to add y axis labels (and ticks). Alternatively, reorganizing the figures such that the xy cuts lie in the first row, while the xz cuts lie in the second and third rows may also work.

RESPONSE: We have added y-axis labels to make the shift from xy to xz planes more clear.

Section 4.3

>29. Line 214: it is mentioned that the sampling is done randomly across the box plane and all times. It is relatively vague about the sampling period (which the reader may assume 45 t0 mentioned earlier) as well as the sampling frequency. Does "random" here indicate uniform sampling?

RESPONSE: Thank you for pointing this out, we did mean the 45 t_0 period. "Random" does indicate uniform sampling within this space and across the time period.

>30. Figure 7: this plot contains information both in time and space to illustrate the tail current sheet thickness asymmetry. However, temporal effects cannot be directly visualized due to the fact that all sample points are plotted using black dots of the same pattern. One would tend to think that samples from a given snapshot form a continued curved line in the plot. For instance, if one connects the points of the upper and lower envelopes, those shall come from the extreme states in the substorm cycle. The authors may consider adding that kind of information into the figure, using either lines, colors, marker shapes, or sizes.

RESPONSE: The current sheet samples are from a 2D area per time dimension, but the plot only shows sampled thickness vs. Y-coordinate. Thus, there may be multiple thicknesses plotted per Y-coordinate (each corresponding to separate X-locations). So, there cannot be a “continued curved line” in the plot; instead, the picture at a given time snapshot looks like what is shown in Figure 8 (the two right-hand plots). There is no “line”, but there is a varying spread of thicknesses across the Y-coordinate from dusk to dawn.

We did try a version of this plot with time information denoted by marker color and shape; however, there is significant overlap between times which heavily obscures any relevant information. Thus, we thought it best to separate the overall sampling (Figure 7) from detailed time information (selected sample shown in Figure 8).

The purpose of showing the overall sample (Figure 7) is to demonstrate that random sampling of the current sheet over many positions and times, akin to spacecraft measurements, can lead to a wide range of sampled thicknesses. It is meant to convey two things: 1) the average thickness on the dawnside is less than the average thickness on the duskside; 2) there is a wider variation of thicknesses on the dawnside.

>31. Figure 8: between the flux pile-up and flux unloading stages, the dawnside current sheet thicknesses change significantly while the duskside thicknesses are almost constant. Is this the case among the t = 0 ~ 45 t0 simulation time? Does it indicate that there is a strong preference of substorm energy release direction on the dawnside dictated by Hall effect? If so, this could be highlighted in the abstract.

RESPONSE: We find that the duskside thicknesses do fluctuate over the 45 t_0 period, but not as dramatically or quickly as the dawnside. The thicknesses generally remain within the range 1.5 R_E – 2.5 R_E, sometimes reaching 3 R_E.

Additionally, the duskside thicknesses have a tighter spread within the sample wedge compared to the dawnside (as seen in Figure 8); this holds over the 45 t_0 period.

We do highlight, in the abstract, the greater frequency of dipolarization events and energy release on the dawnside.

>32. Figure 9: a colored contour plot from one snapshot may not be enough to demonstrate the relation between current density and Bz within the current sheet as a function of time. This point may be better explained, e.g., with a 1D line plots of J and B at fixed locations across substorm cycles.

RESPONSE: Thank you for the suggestion. We have switched out this contour plot for the 1D line plots of J and Bz at a fixed location in the tail across the time period, with arrows indicating where pileup of B_z thickens the current sheet.