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Comment on angeo-2021-35

Anonymous Referee #2

Referee 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-RC2, 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. 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.

Minor issues:

Introduction & Model Description

- 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.
- 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.
- 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.
- 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.
- 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.
- Line 140: Since this is 3D, the center shall be (0,0,0).
- Line 145: inner BC float Bperp, 0 Bpar ☐ what is the physical interpretation/numerical consideration for this magnetic field boundary condition?
- 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.
- 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.

- 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.
- 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?

Section 4.1

- 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.
- 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.

Section 4.2

- 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.
- 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?
- 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:

- How are the events recorded from the simulation?
- 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?
- 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?
- 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. 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.
- Figure 4: colorbar required, maybe with a better choice of color range scale and norm?
- 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.

Section 4.3

- 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?
- 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.
- 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.
- 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.