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Interactive comment on "Asymmetries in the Earth's dayside magnetosheath: results from global hybrid-Vlasov simulations" *by* Lucile Turc et al.

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We thank the referee for their positive evaluation of our manuscript and for providing constructive remarks. Please find below our point-by-point response in bold font.

The paper studies asymmetry in the Earth's dayside magnetosheath using global hybrid-Vlasov simulations and compares numerical results with a statistical dataset of THEMIS observations. The paper is clearly written and the results are new and interesting. However, some details about modeling are missed. I partly agree with the comments of three other reviewers and mention several important points from their

reports below. I could recommend the paper for publication after major revision.

Major remarks 1. Although the Vlasiator model is well known and I believe it has been thoroughly described in the literature, the paper should provide more details on the runs under discussion. In particular, (as also mentioned by one of the reviewers) the paper says nothing about spatial resolution. It would be useful to compare the resolution with the ion inertial length and gyroradius. The authors have already answered this issue in their reply to Reviewer 1 and I suppose it will appear in the paper too. The paper does not describe the simulation domains in each case; it only mentions that their size is different between the runs. I would be also curious to know what happens if the simulated intervals in Runs 2A and 2B would be increased since now they are shorter than in Run 1.

In Run 1, the simulation box extends from -48.6 to $64.3\,\mathrm{R_E}$ in the x direction and from -59.6 to $39.2\,\mathrm{R_E}$ in the z direction. In Runs 2A and 2B, it extends from -7.9 to $46.8\,\mathrm{R_E}$ in the x direction and between $\pm 31.3\,\mathrm{R_E}$ in the y direction. We will add the simulation domain extents, as well as more information regarding the spatial resolution, in the revised manuscript . Our Vlasiator runs comprise two phases. First, in the initialisation phase, the near-Earth magnetic environment forms self-consistently due to the interaction of the dipole field with the incoming solar wind. Then, the run continues in an almost steady state. Due to the 2D set-up of our runs, we never reach a completely steady state because the IMF piles up in front of the magnetopause, causing a slow expansion of the bow shock. In simulations including the foreshock on the dayside, as is the case for the three runs presented here, the main parameter which determines when a run is stopped is when foreshock waves reach the +x boundary, as extending the simulation would likely cause unphysical wave reflection. As concerns the magnetosheath properties, we do not expect significant changes if Runs 2A and 2B were to be extended, except for a larger magnetosheath thickness, due to the field line pile-up.

2. Both the Reviewers 1 and 3 noted that comparison with MHD runs for exactly the same solar wind conditions will be useful because this would emphasize which variations in the magnetosheath downstream of the quasi-parallel bow shock are essentially kinetic structures and cannot be predicted by MHD models. However, I do not think that it is necessary to run all MHD models available from CCMC, but it would be enough to make three runs with at least one model (e.g. SWMF/BATSRUS).

While we agree with the reviewer that an in-depth comparison of magnetosheath asymmetries in MHD and kinetic simulations would be an interesting topic of research, we feel that such a study lies beyond the scope of the present paper, as was also noted by Reviewer 3. Identifying the source of discrepancies between different numerical models is not trivial, as many factors can come into play, such as the spatial and temporal resolution, the numerical solvers being used, and so on. Even among MHD models, significant differences are observed, as shown for example by Gordeev et al. [2015], who compared the outputs of the different MHD models available at CCMC.

Our paper presents a comprehensive and self-contained analysis of a set of three hybrid-Vlasov simulations complemented with spacecraft observations, which allow us to draw firm conclusions regarding the effects of several solar wind parameters. Whenever possible, we compared our results with MHD theory and with the MHD simulation results presented in Walsh et al. [2012] and Dimmock et al. [2013], and found them to be in good qualitative agreement. The only apparent discrepancy with MHD theory was the variation of the asymmetry level as a function of the Alfvén Mach number. However, when revisiting those results once the standard deviation of the asymmetry levels was taken into account, based on the suggestion from Reviewer 2, we found that the variation was not conclusive, and thus did not contradict MHD theory (see our response to the third major point of Reviewer 3). We will amend this paragraph (lines 295-300) when revising the manuscript. For these reasons, we feel that the present paper

does not call for an extensive comparison with MHD simulations.

3. I also note that the solar wind conditions in the hybrid simulations are different from the typical solar wind conditions at L1. I am satisfied with the author's reply to Reviewer 1 that the Mach numbers in the solar wind stay in the typical interval and therefore the bow shock-magnetosheath properties may not be changed in comparison with those in observations. However, I would emphasize that the solar wind density of 1 cm^{-3} is significantly smaller than the average in observations (usually between 5 and 10 cm^{-3}). I think the paper should clearly explain this because I guess that the low solar wind density may be a reason for the stronger fluctuations in the magnetosheath than those in the data.

In the same manner as the high solar wind speed would not influence our results because of the typical Mach numbers in our simulations, the low density should not affect the bow shock-magnetosheath properties either, because the density compression ratio stays within its typical range at Earth. The low solar wind density does not result in large uncertainties in the density in our simulation because the hybrid-Vlasov formalism allows to describe accurately low density plasma, even in regions as tenuous as the magnetotail lobes. This low density does not affect either the development of wave activity in the magnetosheath, which is home to mirror modes [Hoilijoki et al., 2016] and EMIC waves [Dubart et al., 2020].

It would be helpful if the reviewer could provide us with a reference regarding the influence of solar wind density on the variability of magnetosheath properties, as it is not clear to us which other physical processes this could affect. This would be an interesting item to add to the discussion.

4. Since the authors use average parameters both in the simulations and observations, I think it would be possible to add standard deviations to the figures, e.g. in the form of error bars. This would be helpful when comparing the differences between the runs

(how significant is the difference with respect to the standard deviations). Besides, the authors mention in the text that they calculated longer time average intervals (line 290). How long are they and does this make any difference to their conclusions?

Thank you for this suggestion. In the revised manuscript, we will add error bars to the asymmetry plots (line plots in Figures 1, 3, 6 and 7). As done in Dimmock et al. [2017], we estimate the error on the magnetosheath parameters as the standard error of the mean (standard deviation divided by the square root of the size of the bin sample). We then use this error to calculate the minimum and maximum values of the asymmetry in each bin, which determines the extent of the error bars in the asymmetry plots. A few example plots with error bars are included in our response to Reviewer 2.

We performed time averages over 50 s, 100 s and 150 s. We did not find any significant differences in the results we obtained. While the exact value of the asymmetry level varied in each bin (especially for the density), the polarity of the asymmetry remained identical, and the range of the asymmetry level over the whole magnetosheath was essentially unchanged.

Minor remarks 1. The bibliography list in the paper is long, but I would like to mention two more papers, Zwan and Wolf (https://doi.org/10.1029/JA081i010p01636) who first mentioned the plasma depletion layer and Samsonov et al. (https://doi.org/10.1029/2000JA900150) who compared magnetosheath profiles downstream of the parallel and perpendicular bow shock using the anisotropic MHD model.

Thank you for these references, we will add them in the introduction.

2. Line 83. "These processes would thus favour the quasi-parallel flank." But the results in the paper show the $Q_\perp$ -favoured velocity asymmetry. How is this consistent?

Our results focus on the bulk velocity, which is larger in the quasi-perpendicular

magnetosheath. In contrast, the studies of Dimmock et al. [2016a] and Nykyri et al. [2017] show that velocity fluctuations in the Pc 3 range (22 – 100 mHz) are stronger on the quasi-parallel flank and are favourable to the development of the Kelvin-Helmholtz instability. The difference in bulk velocity between the quasi-parallel and quasi-perpendicular flanks is probably not large enough to counteract the effect of the larger velocity fluctuations in the quasi-parallel sector, as it has been shown that the Kelvin-Helmholtz instability is more frequently observed on the quasi-parallel flank [Henry et al., 2017]. We will extend this paragraph of the introduction and add the reference to the study by Henry et al. [2017].

3. Lines 149-152. The figures in the paper show that the spatial bins are asymmetric with respect to the Sun-Earth line. Please, explain how this asymmetry is taken into account if you use the same shape as Shue et al.'s model which is symmetrical.

We used a different flaring parameter for the outer magnetosheath boundary on the quasi-parallel and quasi-perpendicular flank, to account for the different magnetosheath thicknesses. We will add an explanation for this in the revised manuscript.

4. Caption to Figure 2. Please, define θ_{Bn}.

We will add the definition of θ_{Bn} in the figure caption.

5. Lines 233-235. Is θ_{Bn} equal to $0°$ and $90°$ near the terminator plane?

Yes. We will reformulate this sentence to better clarify this.

6. Lines 265-266. I think it is better "density compression ratio" instead of "shock compression ratio".

We agree that "density compression ratio" is less ambiguous. We will correct this in the revised manuscript.

7. Label on Figure 5 says that the lines correspond to runs 1 & 2A and 2B but this contradicts the text (lines 265-266).

The text mentions only Runs 2A and 2B, as they are the two runs under discussion at this point in the text. We will add a mention to Run 1 as well to make it clear that the caption and the text are consistent with each other.

8. Figure 4. The author may add an arrow to indicate the stagnation point.

Thank you for this suggestion, we will add an arrow on this figure.

9. Lines 367-369. Is it better to say about an increase in the magnetic field on the quasi-perpendicular flank than about a decrease on the quasi-parallel flank?

This sentence refers to the low magnetic field strength downstream of the quasi-parallel shock, which remains equally low in the central magnetosheath as in the outer magnetosheath when the cone angle is reduced to 30°. In contrast, the magnetic field strength is higher in the central magnetosheath than in the outer magnetosheath for a 45° cone angle in Run 1 (see Figure 1a and 1b). On the quasi-perpendicular flank, the magnetic field strength is also lower in Run 2A than in Run 1 because of the lower θ_{Bn} value due to the more radial IMF orientation. The field line draping does not cause an increase of the magnetic field strength on the quasi-perpendicular flank in this run. We will reformulate this sentence to clarify this.

Additional references (not previously included in the manuscript bibliography)

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- **Gordeev, E., Sergeev, V., Honkonen, I., Kuznetsova, M., Rastätter, L., Palm-

roth, M., Janhunen, P., Tóth, G., Lyon, J., Wiltberger, M.: Assessing the performance of community-available global MHD models using key system parameters and empirical relationships, Space Weather, 13, 868, doi:10.1002/2015SW001307, 2015.**
- **Henry, Z. W., Nykyri, K., Moore, T. W., Dimmock, A. P., Ma, X.: On the Dawn-Dusk Asymmetry of the Kelvin-Helmholtz Instability Between 2007 and 2013, Journal of Geophysical Research (Space Physics), 122, 11,888, doi:10.1002/2017JA024548, 2017.**
- **Hoilijoki, S., Palmroth, M., Walsh, B. M., Pfau-Kempf, Y., von Alfthan, S., Ganse, U., Hannuksela, O., Vainio, R.: Mirror modes in the Earth's magnetosheath: Results from a global hybrid-Vlasov simulation, Journal of Geophysical Research (Space Physics), 121, 4191, doi:10.1002/2015JA022026, 2016.**

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