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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.

**Lucile Turc et al.**

lucile.turc@helsinki.fi

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**We thank the referee for reviewing our manuscript and for providing detailed comments. The reviewer raised in particular several major concerns regarding the methodology employed in our study, which we address in detail below. As can be seen from our response, we feel that these issues can be resolved by better clarifying our methodology in the revised version of our manuscript. Our responses are marked in bold font in the text below, in between the reviewer's comments.**

Summary of the manuscript: Authors have studied magnetosheath dawn-dusk asym-



metries of the magnetic field (B), proton number density (n) and plasma flow speed(V) in the 2-D global Vlasiator simulation and compared the results with statistics from the THEMIS observations. The main conclusion made by the authors is that while the polarity of the asymmetries agrees with the THEMIS results, the magnitudes are in disagreement because Vlasiator is run with one set of conditions, whereas spacecraft observations show cumulation of the observations from different solar wind conditions and IMF orientations.

Overall evaluation of the manuscript: Unfortunately, in its present form I am unable to recommend this manuscript for publication in the scientific literature for the following reasons:

1) There are no original ideas or new scientifically valid results. There have been several past studies of the magnetosheath properties using both spacecraft data and different plasma approximation (e.g., MHD, hybrid, kinetic-simulations). Some of these have been cited but not all: The bow shock is not the only source for magnetosheath plasma. Also magnetopause processes are important that can transport magnetospheric particles into the magnetosheath. The study of the dawn-dusk asymmetries of B, n and V using spacecraft data has already been done. If the motivation is to solely test the code robustness, by using the study of dawn-dusk asymmetries as a validation effort against spacecraft data, a technical paper may be more suitable.

**We agree that there has been a number of observational studies of the dawn-dusk asymmetries of the parameters we selected for our study, as well as a few numerical studies using MHD models. However, we politely disagree with the reviewer regarding the lack of new results in our study.**

**In this manuscript, we present the first study of these asymmetries using a global hybrid-Vlasov model, which provides us with new information regarding those asymmetries. To our knowledge, this is the first in-depth quantification of these asymmetries using a hybrid-kinetic model. Part of our manuscript is indeed dedi-**

**cated to validating our simulation results based on the comparison with previous works, but we also present novel results:**

- **We show that foreshock kinetic processes have a strong impact on the magnetosheath density, thus providing an answer to the long-standing question of the variability of this asymmetry, and reconciling the vastly different results obtained in previous studies [Paularena et al., 2001; Walsh et al., 2012; Dimmock et al., 2016]**
- **We investigate the influence of the IMF cone angle on the asymmetries, which has not been studied before, neither with spacecraft measurements nor with models, and show that the magnetic field asymmetry and the variability of the magnetosheath density increase when the cone angle is reduced from $45°$ to $30°$.**
- **We investigate the influence of the Alfvén Mach number on the asymmetries, in a range of Mach numbers that is not easily accessible with observations, and show that the variability of the magnetosheath density and velocity is reduced at low Alfvén Mach numbers.**

**In the revised manuscript, we will reformulate part of the abstract and of the conclusions to better highlight these novel results.**

**Regarding the importance of magnetopause processes, we agree with the reviewer that they can indeed affect magnetosheath properties near the magnetopause. Please note however that the sentence in our introduction which the reviewer is referring to states that "the bow shock is the source of most *magnetosheath asymmetries*" (and not of most *magnetosheath plasma*), based on previous studies showing that most asymmetries are controlled by the IMF orientation [e.g., Dimmock et al., 2017]. In the revised manuscript, we will add a brief mention to magnetopause processes.**



2) For scientific paper "more in depth" analysis of the physical mechanisms is required to address what differences are due to numerical issues, what are due to kinetic physics, and what are the mechanisms. For example, how are the magnetosheath densities > 4 explained, if solar wind density is 1? How are these results affected by grid-resolution.

**According to MHD theory, the compression at the bow shock should indeed result in the magnetosheath density just downstream of the shock being at most four times larger than the solar wind density. This is what is observed downstream of the quasi-perpendicular portion of the bow shock in our numerical simulations (see the upper half of the top three panels in Fig. 6), where MHD theory mostly holds. At the quasi-parallel shock, on the other hand, kinetic processes become most prominent, and larger densities can be observed in the magnetosheath.**

**These large densities come essentially from density fluctuations in the foreshock, resulting in upstream densities that are already well above the plasma density in the pristine solar wind [see, for example, the numerical simulations presented in Omidi et al., 2014 and Turc et al., 2018; and the spacecraft measurements presented in the review by Eastwood et al., 2005]. When these patches of high density cross the bow shock, their fourfold compression results in downstream densities that exceed four times the solar wind density.**

**Such large densities in the magnetosheath, above the MHD limit, are a common feature in hybrid-kinetic simulations of the bow shock/magnetosheath system [see for example Figs. 9 and 10 in Omidi et al., 2014; Fig. 7 in Karimabadi et al., 2014]. We will add a few sentences in Section 3.3 of the manuscript to compare the magnetosheath density in our simulations with that in these previous numerical works.**

**Regarding the possible effects of grid resolution, the scale of these high den-**

**sity patches in the magnetosheath is much larger than the cell size, and thus they shouldn't be affected by the finite resolution in our simulations. Grid resolution, on the other hand, can impact which wave modes develop in the simulation [see Dubart et al., 2020, pre-print available in Annales Geophysicae Discussions: https://www.ann-geophys-discuss.net/angeo-2020-24/]. Previous works have shown that the compressional foreshock waves, the so-called 30 s waves, which are responsible for large-scale density fluctuations in the foreshock, are properly resolved in Vlasiator and their properties match those obtained from spacecraft measurements [Palmroth et al., 2015; Turc et al., 2018, 2019]. Also, foreshock transients such as cavitons and spontaneous hot flow anomalies, which can also result in density variations, develop as expected in the simulation [Blanco-Cano et al., 2018]. Therefore, the spatial resolution of our simulation is not expected to affect the plasma compression at the bow shock.**

**More discussion regarding the resolution is given below, as a response to another of the referee's comments. We will also add some discussion regarding the grid resolution in the revised manuscript.**

3) The Methodology of the present paper is flawed so no accurate scientific conclusions can be made at this time. The authors' conclusion, that the disagreement with the data and simulation is due to the fact that simulation is run for one set of conditions, whereas spacecraft data contains the history of IMF and solar wind, is only one possible reason. Paper fails to discuss the other, more plausible and likely more significant reasons listed below:

i) Code is run with 750 km/s solar wind speed. This condition occurs rarely as the average solar wind speed is slightly less than 400 km/s. Therefore, it is not logical or scientifically justified to compare the runs with 750 km/s solar wind velocity with the spacecraft statistics collected in the magnetosheath, when the solar wind flow preceding the THEMIS data collection is about 400 km/s. With higher solar wind speeds, the shock compression becomes stronger and one would expect higher magnetic field



strengths downstream of the quasi-perpendicular shock than for solar wind speeds of 400 km/s.

**While we agree with the reviewer that such fast speeds are rarely encountered in the solar wind at Earth, we will demonstrate that running the model with a 750 km/s solar wind speed is not an issue for the present study, and that our methodology is valid.**

**Firstly, the key parameter controlling the shock compression is the shock Mach number [e.g., Treumann et al., 2009], which indeed depends on the solar wind velocity, but also on other parameters such as the density, temperature and magnetic field strength, in the case of the magnetosonic Mach number. In our simulation, the upstream parameters are chosen such that the resulting Alfvén and magnetosonic Mach numbers have typical values for the solar wind at Earth: in our Runs 1 and 2A, the Alfvén Mach number $M_{\mathrm{A}}$ is 6.9 and the magnetosonic Mach number $M_{\mathrm{ms}}$ is 5.5, and our low Mach number run has $M_{\mathrm{A}} = 3.4$ and $M_{\mathrm{ms}} = 3.3$. Typical values for these Mach numbers at Earth are $2.5 < M_{\mathrm{A}} < 12$ and $2 < M_{\mathrm{ms}} < 7$ [Winterhalter Kivelson, 1988]. Therefore, despite the large solar wind speed, we have a typical compression ratio at the bow shock with our input parameters (see Fig. 5). We will add a sentence in Section 2.2, where the simulation runs are described, to indicate that the Mach number values in our runs are typical values at Earth.**

**Second, we would like to point out that all observational studies of magnetosheath asymmetries rely on the assumption that the variation of the shock compression is relatively small in the range of solar wind conditions encountered at Earth, and thus that magnetosheath parameters can be normalised to their solar wind counterparts to obtain the average distribution of magnetosheath properties. This normalisation is essential to observational studies, which are based on compilations of spacecraft measurements in the magnetosheath associated with a wide variety of solar wind conditions. Global maps of**

**normalised magnetosheath parameters are presented for example in Paularena et al. [2001], Longmore et al. [2005] and Dimmock et al. [2013-2017]. Walsh et al. [2012] present both raw and normalised magnetosheath parameters, and the latter are more narrowly-distributed around the results from MHD simulations. The only instance in which Dimmock et al. [2017] do not use a normalised parameter is for the ion temperature, because of cross-calibration issues when comparing temperature measurements from different spacecraft (THEMIS in the magnetosheath and ACE or Wind in the solar wind). Moreover, Dimmock et al. [2017] compare the levels of magnetosheath asymmetries for solar wind velocities below and above 400 km/s (splitting their data set into two halves), and find no significant change in the asymmetries between these two ranges of solar wind velocities. Large solar wind speeds may strongly affect the flank magnetosheath parameters, as large solar wind speeds are conducive to the development of the Kelvin-Helmholtz instability (KHI) at the magnetopause [e.g. Kavosi & Raeder, 2015]. However, our study concentrates on magnetosheath asymmetries in the plane containing the IMF vector, while KHI develops in the plane that is perpendicular to the IMF (e.g. in the equatorial plane for a northward IMF). Therefore, our results would not be affected by the KHI.**

**Therefore, the large solar wind speeds in our simulations are not an issue to quantify the magnetosheath asymmetry levels away from the magnetopause, and the normalisation of the data to the solar wind quantities together with the typical shock Mach numbers and compression ratio in our simulations ensure that the comparison with spacecraft observations is relevant. We will better explain our approach and its validity in the revised manuscript.**

ii) The runs use upstream solar wind density of 1/cc, which would result in a maximum downstream density of about 4/cc downstream of quasi-perp shock. Assuming the values of 1- 4/cc, the ion inertial length would be 228 km to 114 km in the magnetosheath, respectively, and for higher densities these scales get even smaller. The paper does



not describe what the coordinate-space resolution is used for the runs. In order to appropriately resolve the physical ion scales, the Vlasiator should use about 5 to 10 cells/ion inertial length, which requires coordinate space resolution at the minimum of about 20-40 km, otherwise the kinetic effects can artificially dominate at larger length scales than in the real system. Furthermore, if the ion inertial scale at the bow shock is not appropriately resolved, the results pertaining to kinetic shock physics are physically meaningless or exaggerated.

**The resolution of our grid in ordinary space is 228 km, which corresponds to one ion inertial length in the solar wind. As shown by numerous works, this resolution is sufficient to capture most ion kinetic processes in a simulation, and yields results that are in good agreement with spacecraft observations. In this, we respectfully disagree with the reviewer's statement that one would require 5-10 cells per ion inertial length in hybrid kinetic simulations.**

**We kindly refer the reviewer to the works of Omidi and colleagues [e.g., Omidi et al., 2014, 2016] and Blanco-Cano and colleagues [e.g., Blanco-Cano et al., 2006, 2009], in which a cell size of 1 solar wind ion inertial length is also used, allowing detailed investigations of ion kinetic processes in the foreshock and the magnetosheath. In the simulations of Shi et al. [2013, 2017] the spatial resolution is 1 to 2 cells per ion inertial length, depending on the position in the simulation domain. Karimabadi et al. [2014] present the results of 7 runs, most of them with a resolution of 2 cells per ion inertial length. The run with the best resolution has 4 cells per ion inertial length, but at the expense of the size of the simulation domain.**

**The results of these models (Vlasiator included) pertaining to ion kinetic processes have been extensively validated against spacecraft measurements [e.g., Sibeck et al., 2008, Blanco-Cano et al., 2011, Palmroth et al., 2015, Turc et al., 2019]. They have predicted kinetic phenomena such as foreshock bubbles [Omidi et al., 2010] and cavitons [Blanco-Cano et al., 2009] that have been later**

**on been confirmed in spacecraft measurements [Archer et al., 2015; Kajdic et al., 2011].**

**At the shock front, a cell size of 1 ion inertial length or larger may not correctly evaluate the gradient in the ramp. However, the hybrid-Vlasov formalism based on distribution functions enables the use of a slope limiter which allows for total variation diminishing evolution of discontinuities and steep slopes even at somewhat lower resolution. The shock transition is therefore well described in our simulations, and the downstream parameters are correctly modelled.**

**The study we present here focuses on the large-scale distribution of magnetosheath properties. Therefore, the spatial resolution of 1 cell per ion inertial length in our Vlasiator runs is sufficient to study global magnetosheath parameters and how they are impacted by ion kinetic physics. We will add a discussion on the spatial resolution in our simulations in the revised version of the manuscript.**

iii) Since the B, n and V are MHD quantities, authors should also run their case exactly with same parameters using the major global, state-of-the-art 3-D MHD codes available through Community Coordinated Modeling Center and compare their Vlasiator results with these.

**Magnetosheath asymmetries have been already studied using MHD models in previous studies, as described in the Introduction [Walsh et al., 2012; Dimmock et al., 2013]. The results of Walsh et al. [2012] show in particular that the magnitude of the asymmetries is larger in their MHD simulations than in the observations. Their interpretation is similar as ours: the asymmetries are larger in the simulations because they are run for a single IMF orientation, while the observations combine many different IMF orientations.**

**We will expand the comparison to previous MHD simulations in the Discussion section of the revised manuscript, but we do not feel that running new MHD sim-**



**ulations will bring novel information that is not already reported in the literature.**

Recommendation: While I cannot recommend this paper for publication at this time, I hope the authors will use this feedback as an opportunity to improve the paper, and for transparency include additional missing information (e.g., the grid-resolution etc.). This work requires significant further code validation efforts in a global scale, where the effects of spatial grid-resolution are systematically studied, so that the results can be correctly interpreted. Please see the specific comments below that need to be addressed after which the paper may eventually become suitable for scientific literature:

**We thank the reviewer for this very detailed set of suggestions on how to further proceed with this study. However, we believe that our methodology is appropriate for the present study, and that our conclusions are well supported by the analysis of our numerical results, as detailed in our responses to the reviewer's previous comments (see above).**

**Incidentally, we would like to mention that a typical Vlasiator run requires from a few to tens of million CPU hours. Performing a new set of runs as suggested by the reviewer is extremely costly, and thus cannot be done on a short notice, as it requires months of planning, application for computing resources, running and validation of the model's outputs.**

Specific comments:

1. Calculate the statistical solar wind and IMF condition from THEMIS statistics used in the paper.

2. Plot and show a spatial map in x-y -plane for each run of the i) ion inertial length, ii) ion gyro-radius and iii) plasma beta, and collect a mean, minimum and maximum values of these at the central magnetosheath where the statistics pertaining to study is being collected during the course of the simulation.

3. Re-run Vlasiator with the statistical conditions and with the appropriate resolution

(whichever length-scale is the smallest). For plasma beta of 1, the both length-scales should be the same. Compare the results with those in the present manuscript.

4. Add details and benchmarking how the phase space velocity distributions are processed to calculate n and V in 2-D-plane (as one can cut a 3-D velocity distribution in infinite ways). Show how the processing of the velocity distribution functions affects the results. Convince the reader of the validity of this processing at different regions in the magnetosheath.

**While our simulation domain is 2D in ordinary space, the velocity space, in which the velocity distribution functions evolve, is 3D in Vlasiator. Therefore, no 2D cut is performed in the ion velocity distribution functions. The density and velocity are calculated as the zeroth and first velocity moments of the distribution functions, i.e., by integrating the distribution function over the velocity space, based on plasma kinetic theory. This approach is valid everywhere in the simulation domain. To clarify this, we will add a sentence in Section 2.1 explaining that the macroscopic plasma parameters are obtained by integrating the velocity distribution functions.**

5. Re-run Vlasiator with a) old-set of parameters shown in this manuscript while appropriately resolving these length-scales and compare with the results from original resolution.

6. Ion and electron temperatures are an important quantity to demonstrate the dawn-dusk asymmetry. It will be very interesting to see these two parameters, and the perpendicular and parallel temperatures.

**Vlasiator is a hybrid model, which describes ion kinetic physics but treats electrons as a fluid. Therefore, it cannot be used to study electron temperatures in the magnetosheath. As concerns the ion temperature, we decided to leave it for future work, as we think its investigation warrants a paper of its own (as was done for example by Dimmock et al., 2015 for the ion temperature asymmetry**



**in the magnetosheath as observed by the THEMIS spacecraft). Here, we chose to concentrate on the magnetic field strength, plasma density and bulk velocity, and how they vary as a function of the cone angle and the Alfvén Mach number.**

7. Since the majority of the quantities compared in this study can also be obtained by the MHD global simulation, I suggest the authors also run the same solar input in the CCMC to compare with all the other three major MHD models and show the advantage of Vlasiator results.

**As mentioned earlier, MHD simulations of magnetosheath asymmetries have already been performed by Walsh et al. [2012] and provide results consistent with our findings.**

8. What is the "zebra stripes" structure on the dusk side, are those physical waves (which wave-mode) or a grid oscillation?

**These are physical oscillations, which are well resolved in the simulation as their wavelength is significantly larger than the cell size. The properties of these oscillations are consistent with that of the overshoot of the quasi-perpendicular bow shock, which has been observed for example by the ISEE and the Cluster spacecraft [Livesey et al., 1982; Bale et al., 2005]:**

- **their amplitude decays when moving further away from the shock front [Saxena et al., 2005].**
- **their wavelength is related to the ion gyroradius [Saxena et al., 2005]. This is evidenced by their smaller scale in Run 2B, where the IMF strength is doubled, and thus the gyroradius is smaller.**
- **their amplitude is related to the upstream Mach number [Livesey et al., 1982]. It is much smaller in Run 2B (low $M_A$ run), where the oscillations are barely visible in Figs 1, 3 and 6, than in the other two runs.**

**Investigating in more detail the properties of these oscillations and their relevance for magnetosheath transport processes is a study of its own, which is currently under way.**

9. From MHD the maximum shock compression ratio would give magnetosheath densities of 4/cc if the density in the solar wind is 1/cc. Here the maximum density in the magnetosheath is 6/cc. Is this a kinetic effect and what is the physical mechanism to generate that? How is the area of the > 4/cc density regions in the magnetosheath dependent on the ion gyro-radius/inertial scale and grid resolution when compared to MHD simulations that are run with the same parameters and same resolution?

**As discussed above, these high density patches in the magnetosheath are most likely due to density enhancements in the foreshock which are further compressed upon crossing the bow shock. The density enhancements in the foreshock are due to compressional waves and transient structures. These phenomena are not described in MHD models, as the foreshock is inherently a kinetic structure. These results are therefore not comparable with MHD, where such phenomena do not exist.**

**The scale of these density enhancements is related to that of the foreshock ULF waves waves, which modulate the foreshock parameters, including the density [e.g., Blanco-Cano et al., 2006; Turc et al., 2018]. In previous studies, we have shown that the properties of these waves in our simulations are described at their correct scales and are in excellent agreement with spacecraft observations [Palmroth et al., 2015; Turc et al., 2018, 2019].**

Minor comments:

1. The Discussion and Conclusions are repetitive. This could be made more concise.

**We will go through these parts again when revising the manuscript and we will trim them down where possible.**



2. The referencing is inadequate. Authors should extend their citations to include some of the following. Please see previous global hybrid simulation studies of the magnetosheath (e.g. by Y. Lin et al. (2001-2020), H. Karimabadi et al., N. Omidi et al,) and several missing studies related to spacecraft observations and statistics of the various foreshock transient that modify magnetosheath properties (e.g., F. Plaschke et al. (2013-2019), D. Turner at al., H. Hietala et al. (2009-2018), T. Liu et al.(2017-2019), H. Zhang et al. (2013-,) as well as leakage of magnetospheric particles into the magnetosheath by various processes (e.g., I. Cohen et al. 2017; K. Sorathia et al.,2019), and due to local magentosheath physics (e.g., P. Gary et al., 2006 A. Retino et al. 2007, D. Sundkvist et al. 2007, J. Soucek et al.(2008-2015), V. Genot et al.(2001-2009), T. Phan et al., 2018).

**We will add references regarding magnetosheath properties in the first paragraph of our introduction. We will also extend the paragraph of our introduction concerning hybrid simulations to include some of the references listed above.**

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