Helsinki, June 13, 2018

Dear Referee #1,

Thank you for your thorough review of our paper. We have addressed all of your very good points that have significantly improved the quality of the paper. Below, we go through the points in detail; the original Referee questions are marked with italics.

The authors used a global hybrid-Vlasov simulation to study magnetosheath jets. They identified one magnetosheath jet that satisfies all the selection criteria of Plaschke et al. (2013), Archer and Horbury (2013), and Karlsson et al. (2015). They conclude that the size of magnetosheath jet is ~ 2.3 x 0.5 Re and the jet is generated because of an interaction of the foreshock ULF waves and the bow shock surface. These conclusions are neither substantial nor supported by the provided evidence. Therefore, the referee cannot recommend its publication in AG.

We would like to maintain that the size of the jet and its generation are important results warranting publication. Even with multi-spacecraft data, the scale-size observations have been indirect and inferred, based on statistics rather than individual structures. We think it is important to establish with a model that there is indeed a coherent structure, with generation and decay, whose size is in agreement with the interpretation of spacecraft data. Since this has not been done before, it is important to first do this rigorously and compare to different observational criteria, leading to a proof-of-concept that can then in the future be used more easily, without having to verify all different jet-like structures separately. The fact that we get similar scale sizes as compared to observations lends credibility to the observations as well, needed to properly interpret the observational studies so far. Further, the jet generation has not been verified with a model before. We further emphasize that the jet size and the generation mechanism are not the only results of the manuscript, as we also clarify how the different criteria in the literature are related, and verify that they can occur for steady IMF.

Detailed comments:

1. With just a short description about the foreshock ULF waves in the Discussion, it is difficult to understand how the high dynamic pressure is associated with the waves. The authors are required to do a detailed analysis, like what they did for an identification and validation of the magnetosheath jet.

We agree with this, and thank the Reviewer for pointing this out. We have added a Figure 9 and a detailed description of the upstream structure that caused the jet, on page 7, lines 25-32.

2. The authors chose 1 cm⁻³ and 750 km/s for the solar wind density and velocity. The equivalent dynamic pressure is 0.94 nPa, which is considered a special solar wind condition. The authors need to explain why they chose such a condition. Can the magnetosheath only be seen in this condition or any other condition? Readers will be interesting in knowing about it.

This is due to the run conditions we originally chose. Vlasiator is a supercomputing code requiring a large computer to be run, and therefore for each run we need to separately ask for resources from different supercomputing centres. The 750 km/s is originally chosen because we have needed the solar wind to flush through the simulation box rather quickly so that the initialized magnetosphere appears without too much waiting. The density is chosen such that the combination of the density and velocity yields such an Alfvén Mach number that the foreshock will be representative of the reality. Thus we can trust the foreshock physics and consequently its bow shock interactions. The magnetosheath appears in our other runs as well, and has been verified in other peer-reviewed papers

to represent reality, e.g., Hoilijoki et al., 2016 JGR.

A dynamic pressure of ≤ 0.94 nPa occurs 16% of the time throughout the solar cycle and 23% of the time under quasi-radial IMF, based on OMNI solar wind data for the last solar cycle. While our case does not represent the median conditions, it is not an outlier. A recently accepted review paper by Plaschke et al. (2018) states that observational statistics show a slight tendency in the jet occurrence for higher solar wind speeds and lower densities than usual. Full statistics of jet occurrence with conditions are not possible to be carried out with Vlasiator due to the computational demand, but may be possible with a limited number of runs. We are enthusiastic that such statistics could be carried out, however, first we need a detailed comparison of the different jet criteria so that we can run such a statistical study in practice.

We have added this information in the revised version, on page 4, lines 25 onwards.

3. A dynamic pressure of 0.94 nPa results in the subsolar magnetopause standoff distance of 11.5 Re. But the standoff distance derived from the model is about 7 Re, as seen in Figure 1. The same problem occurs for the position of the bow shock. From the movies S1 and S2, the bow shock is gradually expanding and the magnetopause is gradually shrinking. The locations of the bow shock and magnetopause never reach a steady state. This problem has made the referee think that this hybrid Vlasov model might not stable, giving unrealistic positions of the bow shock and magnetopause. To a validation of the hybrid Vlasov model, the authors are strongly suggested to add the locations of the bow shock and magnetopause to their simulation results using an empirical model.

Thank you for making this comment, this is very helpful indeed.

Regarding the expansion of the magnetopause and the bow shock, we would like to point out that in all hybrid-kinetic simulations, hybrid-PIC included, there is a gradual increase of the bow shock position for two reasons. First is the magnetic field pile-up due to the 2D setup of the run. The field piles up around the magnetosphere because it cannot slip towards the nightside as in reality. We emphasize that this is a feature in all 2D simulations, and there is not much one can do about it. There are several other peer-reviewed papers showing this feature, indicating that it should not be regarded as a showstopper. Second, and smaller issue in our case is the artificial heating in the hybrid-kinetic simulations due to numerical diffusion. We have managed to develop such a good solver that the numerical heating stays at a tolerable level and does not largely contribute to the gradual expansion. This is now mentioned on page 5, lines 4-8 in the revised version.

The simulation is initialized with the geomagnetic dipole field and the IMF pervading the box, while the plasma flows with the solar wind parameters. This causes the magnetosphere and bow shock structures to develop self-consistently during the initialization of the run. Regarding the magnetopause, the first thing to note is that one should not expect it to agree exactly with the proxies in a 2D simulation. However, we have looked more closely at the magnetopause position in Figure 1. First of all, in simulations (3D included), the magnetopause position is determined by 1) gradient of density, magnetic field or current density, 2) last closed field line, or 3) the so-called fluopause method introduced by Palmroth et al., 2003 (JGR). These parameters often do not agree with each other, while it has been shown that the fluopause gives the closest agreement with empirical models, as shown e.g., in Palmroth et al. 2003. The gradients of the abovementioned parameters vary between 2 Re in Figure 1, while the fluopause method puts the subsolar magnetopause into about 10 Re. The density enhancements that are shown closer to the earth, at about 7 Re are due to the pile-up, and they are not related to the magnetopause according to the above criteria. They originate from plasma that has been brought there before and is being squeezed by the new incoming plasma.

The revised Figure 1 now includes streamlines to help identifying the magnetopause and a line showing the bow shock position. The text reflects the above issues on page 5, lines 10-23.

4. The definition of a magnetosheath jet is a bit confusing. In my opinion, it should go with a criterion of flow speed, but the selection criteria of Plaschke et al. (2013), Archer and Horbury (2013), and Karlsson et al. (2015) are all related with the dynamic pressure or density. The authors need to classify this issue and add a definition of the magnetosheath jets to the beginning of the Introduction.

The Reviewer is right in that especially the early observations are more related to the flow speed, while especially in the later years the vast majority of previous studies have used dynamic pressure and not velocity as the key quantity. However, since the flow speed appears quadratically in the dynamic pressure, it is also strongly reflected in the used criteria. We have highlighted this in the Introduction on page 2, line 26-27 as the Referee suggests.

5. In Figure 3a, it shows that the geometry of the magnetosheath jets by Archer and Horbury (2013) is well aligned with the surface of the magnetopause. Are they really jets? The jets found by Karlsson et al. (2015), as shown in Figure 4a, look tiny and sporadic. Are they really jets? The features, which are shown in Figure 2 by Plaschke et al. (2013), are jets-like. But these jets never touch the surface of the magnetopause, which is different from the results by Plaschke et al. (2016).

We would like to point here that the observational community has adopted the term "jet", which has a connotation of an elongated feature. However, without proper modelling of them, we cannot actually say, based on the observations, what their dimensions are and what is their time evolution. It is true that some of them reach the magnetopause (while others probably do not, we cannot say this based on observations, either), indicating that at least some of them could be elongated features. However, observations nearer the shock have not estimated the sizes/shapes of jets, and therefore they may be more like "blobs" there. It is exactly the simulations that allow more detailed comparison of some of their properties (like size/shape and how large a fraction of them reach the magnetopause) that observations may be limited in inferring. We have mentioned this in the Discussion, on page 8, lines 26-32.

We also note that there is a magnetopause effect caused by the jet, visible in the S1 movie. We omitted this discussion because we tend to avoid making conclusions at the magnetopause due to the pileup effect. The other Reviewer urged us to add this in the manuscript and describe the magnetopause effect as well. We have now included this discussion on page 5, on lines 26-33.

6. The X and Y scales in Figures 3, 4, and 5 should be the same.

This is corrected, thank you for this suggestion.

In summary, only one conclusion about the size of the magnetosheath jet is not substantial for a publication in AG. The authors are required to add more conclusions, such as a proof on the association between the high dynamic pressure and the foreshock ULF waves (Item 1), and the solar wind condition for an occurrence of the jet (Item 2). In addition, the authors are required to clarify the potential problem in their model (Item 3) and the issue in the definition and features of the jets (Items 4 and 5).

These are corrected according to the above answers. Thank you again for your very helpful and constructive comments, which will significantly increase the quality of the manuscript, we appreciate the time you spent on our work.

On behalf of all the co-authors, Minna Palmroth

Helsinki, June 13, 2018

Dear Referee #2,

Thank you for your thorough review of our paper. We have addressed all of your very good points that have significantly improved the quality of the paper. Below, we go through the points in detail; the original Referee questions are marked with italics.

Summary: This manuscript examines the physics of magnetosheath jets, using the results of a 5D vlasov simulation of the solar wind – magnetosphere interaction performed using the Vlasiator code. The simulation set up uses steady solar wind conditions, and several magnetosheath jets are reported to occur. The manuscript provides a detailed analysis of one jet in particular that is relatively large, and examines how three different identification criteria, previously published, capture the structure. The size of the jet is quantified, and is found to be consistent with experimental observations. Finally, the magnetosheath jet is shown to be associated with a variation in the upstream pressure that is caused by foreshock waves. The work provides a useful counterpoint to observational studies by showing for the first time that the different signatures adopted in different studies can in fact identify the same event, and therefore help to unify understanding of what these structures are. It also provides a global view of the phenomenon, and contact is made with observations by estimating the size of the jet.

Overall, my primary concern with the manuscript is that it does not do full justice to what is a very interesting and important simulation result. It is important to compare the three identification criteria, but I think there is more that should be done. This relates to the physics questions about how the jets are formed and their impact on the magnetopause, which will be of wider interest. I would be unwilling to recommend the manuscript for publication without addressing the following two points:

1) There is some limited discussion about the source of the magnetosheath jet, but the Vlasiator data surely allows for a much more detailed examination of the proposed formation mechanism and the nature of the ULF waves. In particular, it should be possible to generate some virtual spacecraft data for the upstream ULF waves (e.g. placed just upstream of the shock from where the jet arises) and see immediately if it is the formation of a SLAMS that happens here. Showing and discussing the data would significantly strengthen the manuscript. Similarly, how does the profile of the shock change as the ULF wave pressure front arrives and the jet begins to penetrate into the magnetosheath? Providing more information about the formation mechanism would significantly strengthen the two be too difficult to extract this information.

We fully agree with the Reviewer, and note that also the other Reviewer made this same point. We have added analysis, Figure 9, and a more detailed discussion about the origin of the jet on page 7, lines 25-32.

2) I was surprised that there is no discussion about the impact of the jet on the magnetopause. In supplementary movie 1, at around t = 325 - 340 s, there is an oscillation of the magnetopause at x = 7.5, y = -4 (very roughly) which seems to follow directly from the arrival of the remnant of the jet. Two pulses traveling away from the impact point along the magnetopause are visible, and I wonder if this is reconnection triggered by the jet. Again I think it would significantly strengthen the paper to add information about the fate of the jet and its impact on the magnetopause.

Again, the Reviewer is absolutely right. We omitted this discussion because we tend to avoid making conclusions at the magnetopause due to the pileup effect (see our answer to the other Reviewer, point #3). We agree with the Reviewer and think that the magnetopause oscillation is caused by the jet. We added this information, along with a proper discussion about the pileup effect on page 5, lines 5-33.

3) Evolution of the jet size. The jet size is quoted for one particular time, but it would be very good to provide more information about how the jet size changes. In particular, does the length parallel to the flow change more than the length perpendicular? This should be possible to extract from the simulation as well.

We added a Figure 6 and analysis on page 6, lines 35-36, and page 7, lines 1-8.

4) Jet occurrence. Watching the movies in the supplementary information, it seems that other jets do occur. Given the fact that the simulation is scaled to the Earth, is it possible to say anything about the occurrence rate and if this is consistent with observations?

Yes, indeed it is. However, we chose not to do this in this manuscript. This is because we would first like a proof-of-concept paper, where we verify the methodology, so that we can trust the results. Once this has been carried out, we can adopt the methodology to all our runs, to all our jets, leading to possibly (tens of) thousands of observation points in space and time, given that we have now several runs with varying conditions that can be used. It would be impractical to verify this many jets in this detail, and therefore we thought it is good to verify one first.

5) Change in jet profile. It would be very useful from a spacecraft observation point of view to know how the profile of the jet - as would be observed by the spacecraft – changes with distance from the shock. Again this is something that Vlasiator would be able to show more clearly, and would be able to be extracted from the data.

This is an excellent suggestion. Both the Karlsson, and Archer and Horbury criteria are determined from the peak values, and the full-width-at-half-maximum approximation when analyzing the spatial scales. We added Figure 7 along with analysis on page 7, lines 9-18

Thank you again for your very helpful and constructive comments, which will significantly increase the quality of the manuscript, we appreciate the time you spent on our work.

On behalf of all the co-authors, Minna Palmroth

Magnetosheath jet properties and evolution as determined by a global hybrid-Vlasov simulation

Minna Palmroth^{1,2}, Heli Hietala³, Ferdinand Plaschke^{4,5}, Martin Archer^{6,7}, Tomas Karlsson⁸, Xóchitl Blanco-Cano⁹, David Sibeck¹⁰, Primož Kajdič⁹, Urs Ganse¹, Yann Pfau-Kempf¹, Markus Battarbee¹, and Lucile Turc¹

¹Department of Physics, University of Helsinki, Helsinki, Finland

²Space and Earth Observation Centre, Finnish Meteorological Institute, Helsinki, Finland

³Department of Physics and Astronomy, University of Turku, Finland

⁴Institute of Physics, University of Graz, Graz, Austria.

⁵Space Research Institute, Austrian Academy of Sciences, Graz, Austria.

⁶The Blackett Laboratory, Imperial College London, London, UK

⁷School of Physics and Astronomy, Queen Mary University of London, London, UK

⁸School of electrical engineering and computer science, KTH Royal Institute of Technology, Stockholm, Sweden.

⁹Instituto de Geofísica, Universidad Nacional Autónoma de México, Mexico City, Mexico

¹⁰Code 674, NASA/GSFC, Greenbelt, MD, USA

Correspondence to: Minna Palmroth (minna.palmroth@helsinki.fi)

Abstract. We use a global hybrid-Vlasov simulation for the magnetosphere, Vlasiator, to investigate magnetosheath highspeed jets. Unlike many other hybrid-kinetic simulations, Vlasiator includes an unscaled geomagnetic dipole, indicating that the simulation spatial and temporal dimensions can be given in <u>SI units</u> without scaling. Thus, for the first time, this allows investigating the magnetosheath jet properties and comparing them directly with the observed jets within the Earth's magne-

- 5 tosheath. In the run shown in this paper, the interplanetary magnetic field (IMF) cone angle is 30°, and a foreshock develops upstream of the quasi-parallel magnetosheath. We visually detect a structure with high dynamic pressure propagating from the bow shock towards the magnetopausethrough the magnetosheath. The structure is confirmed as a jet using three different criteria, which have been adopted in previous observational studies. We compare these criteria against the simulation results. We find that the magnetosheath jet is an elongated structure extending Earthward of earthward from the bow shock by ~2.3-2.6
- 10 R_E , while its size perpendicular to the direction of propagation is ~0.5 R_E . We also investigate the jet evolution, and find that the jet originates due to the interaction of the foreshoek Ultra Low Frequency (ULF) waves with the bow shock surfacebow shock with a high dynamic pressure structure that reproduces observational features associated with a short, large-amplitude magnetic structure (SLAMS). The simulation shows that magnetosheath jets can develop also under steady IMF, as inferred by observational studies. To our knowledge, this paper therefore shows the first global kinetic simulation of a magnetosheath jet,
- 15 which is in accordance with three observational jet criteria, and is caused by a SLAMS advecting towards the bow shock.

1 Introduction

Solar wind plasma encompasses the Earth's magnetic domain with a region of turbulent magnetosheath, consisting of shocked plasma magnetosphere is surrounded by the magnetosheath, which consists of shocked and turbulent plasma of solar wind origin. The sunward boundary of this region is the bow shock through which the <u>solar wind</u> plasma flows into the magnetosheath. The earthward boundary of the magnetosheath is the magnetopause, the outer edge of Earth's <u>magnetic domain magnetosphere</u>.

- 5 The bow shock and magnetosheath plasma properties relative to those in the upstream pristine solar wind depend broadly on the interplanetary magnetic field (IMF) direction. One of the most important parameters is the defining conditions within the magnetosheath is the angle between the bow shock normal direction the IMF. In portions of the bow shock, where the bow shock normal is-lie more or less parallel to the IMF direction, the bow shock is said to be *quasi-parallel*. At the quasi-parallel shock, part of the solar wind particles reflect back towards the Sun (Schwartz et al., 1983; Meziane et al., 2004),
- 10 causing instabilities and waves upstream, and forming a so-called foreshock. The downstream part of region downstream from the quasi-parallel shock is called the quasi-parallel magnetosheath, where the plasma properties are highly turbulent (e.g., Fuselier et al. 1991; Gutynska et al. 2012). On the other hand, the region downstream from the quasi-perpendicular side of the bow shock is less turbulent, and there. There is no foreshock upstream because from the quasi-perpendicular bow shock because IMF lines keep the reflected particles keep close to the bow shock and the waves do not have time to grow. The
- 15 magnetosheath downstream of Nevertheless, the magnetosheath downstream from the quasi-perpendicular bow shock hosts a variety of locally-generated waves, e.g., mirror mode waves (Soucek et al., 2015; Hoilijoki et al., 2016). Němeček et al. (1998) reported observations of peaks in the ion fluxes within the quasi-parallel magnetosheath, which they termed transient flux enhancements. Hietala et al. (2009) reported observations of similar high velocities near the magnetopause, and proposed a mechanism to produce these velocities by a rippled bow shock surface. In this mechanism the distorted bow
- 20 shock surface collimates particles into a structure termed a magnetosheath jet. Several studies have since investigated the properties of these jets high-speed structures that have been termed as magnetosheath jets, and demonstrated their importance in terms of geoefficiency, as they. They can for example distort the magnetopause (Shue et al., 2009; Plaschke et al., 2016). Jets are also important for, and drive magnetospheric dynamics because they can trigger magnetopause reconnection (Hietala et al., 2018). Statistical investigations of the jets show that they are clearly associated with the foreshock and the quasi-parallel
- 25 magnetosheath (e.g., Archer and Horbury 2013; Plaschke et al. 2013). Omidi et al. (2016) therefore suggested that foreshock waves may be related to the origin of the jets. Hietala et al. (2009) proposed a mechanism to produce the jets by a rippled bow shock, which collimates particles into a high-speed structure. Karlsson et al. (2015) suggested that the jets could be associated with foreshock short, large amplitude magnetic structures (SLAMS, Lucek et al. 2002, 2004) originating from steepening foreshock waves, and travelling through the bow shock.
- The jets have later been identified using a variety of measurement criteria. Since the jets exhibit high velocities and/or densities, Originally, the jets were observationally identified by high velocities (e.g., Němeček et al., 1998; Hietala et al., 2009). In recent years the vast majority of observational studies have used dynamic pressure and not velocity as the key quantity, although a level of agreement is expected due to the quadratic dependence of the velocity in the dynamic pressure. Plaschke et al. (2013) devised a criterion C_P , defined as the ratio of the magnetosheath dynamic pressure in the X direction and to

the upstream solar wind dynamic pressure. Plaschke et al. (2013) defined that in order to represent jets, C_P had to fulfil the condition

$$C_P = \frac{\rho v_X^2}{\rho_{sw} v_{sw}^2} > 0.25,$$
(1)

5 where ρ is the density, v_X is the velocity component in the X X direction, the numerator refers to the conditions in the magnetosheath while the denominator represents solar wind conditions, with the subscript sw denoting the solar wind. The coordinate system that they used was Geocentric Solar Ecliptic (GSE), where X is sunward, Z is perpendicular to the ecliptic plane and is positive northward, and Y completes the righthanded system. The Plaschke criterion C_P defines the jet as the entire region where Eq. (1) holds, and requires that the dynamic pressure peak is >0.5 times the solar wind value. Further, the 10 criterion is applied only for solar zenith angles less than 30°.

Archer and Horbury (2013) used the total dynamic pressure but divided by a 20-minute temporal average of the dynamic pressure within the surrounding magnetosheath, and required that

$$C_A = \frac{\rho v^2}{\langle \rho_{sh} v_{sh}^2 \rangle_{20min}} > 2.$$
⁽²⁾

where the brackets indicate a temporal average. Karlsson et al. (2012) investigated enhancements in the magnetosheath density,
which they called plasmoids. They separated the plasmoids according to their speed, and observed remarked that the fast plasmoids have whose local velocity increased at least 10% increase in local velocity, and that therefore they % could be associated with jets. They defined the events by taking ratios of the magnetosheath electron density to a 15-minute temporal average within the magnetosheath as

$$C_K = \frac{n_e}{< n_e >_{15min}} > 1.5,$$
(3)

- 20 where n_e is the electron density in the magnetosheath. Both C_A and C_K are only defined to identify peak values of the relevant parameters, and when durations or spatial scales were identified the full-width-at-half-maximum was used. Jets identified with the three criteria are in broad agreement with respect to occurrence and properties, suggesting that the criteria identify similar phenomena. This motivates a modelling study to test how similar the three criteria in fact are and whether they all are associated with magnetosheath jets.
- Hao et al. (2016) performed local hybrid-particle-in-cell (PIC) simulations within a limited spatial extent, and found that the solar wind Alfvén Mach number is important in determining how far the jets can penetrate within the magnetosheath. Using a 2D hybrid-PIC code, Karimabadi et al. (2014) observed jet-like structures penetrating clongated structures with higher magnetic field and plasma density traversing from the foreshock to the magnetosheath. The structures were clongated regions of higher magnetic field and plasma density. However, since Karimabadi et al. (2014) use a scaled dipole strength in the
- 30 hybrid-PIC model, representative of roughly a Mercury-sized magnetosphere, deducing the scale sizes of the structures from

the simulation results is not straightforward, and their direct comparison to the jets observed in the Earth's magnetosheath is difficult. Nevertheless, Karimabadi et al. (2014) reported that jet scales parallel to the direction of propagation could be ~2.4 R_E , and in the perpendicular direction ~0.3 R_E within the Earth's magnetosheath. Plaschke et al. (2016) estimate observationally that the Observationally, Plaschke et al. (2016) estimate that the characteristic jet sizes are 1.34 R_E by 0.71 R_E in the parallel and perpendicular direction, respectively.

- In this paper, we use This paper employs the hybrid-Vlasov simulation code Vlasiator to investigate the jet properties. Vlasiator includes ion-kinetic features similar to hybrid-PIC codes, but unlike hybrid-PIC codes, does not include sampling noise in the results due to a different modelling approach. Further, Vlasiator uses the actual unscaled geomagnetic dipole strength as a boundary condition, and therefore the results can be given in R_E and seconds without scaling, indicating that the length and time scales can be directly compared to spacecraft observations of jets. In this paper, we first introduce Vlasiator, and the run used to examine the magnetosheath jets. We visually identify a candidate jet, after which we show that our candidate jet
- 10 fulfils all three jet criteria described above. We then examine the jet properties and evolution, and end the analyse the process that generates the jet, before ending the paper with discussion and conclusions.

2 Model

Vlasiator is a hybrid-Vlasov model targeted for global simulations of the Earth's magnetosphere. Vlasiator solvers treat protons as a distribution function $f(\mathbf{r}, \mathbf{v}, t)$ in phase space, and electrons as a massless charge-neutralizing fluid (Palmroth et al., 2013;

- 15 von Alfthan et al., 2014; Palmroth et al., 2015; Pfau-Kempf, 2016). Electron kinetic effects are neglected by the solvers, but the ion kinetic effects are solved without numerical noise. The time-evolution of $f(\mathbf{r}, \mathbf{v}, t)$ is controlled by the Vlasov equation, propagated by a fifth-order accurate semi-Lagrangian approach (Zerroukat and Allen, 2012; White and Adcroft, 2008). Maxwell's equations neglecting the displacement current in the Ampère-Maxwell law are used to solve the electromagnetic fields. Maxwell's equations are supplemented by Ohm's law, including the Hall term. The technical features of the code includ-
- 20 ing the closure scheme, the numerical approach, and the parallelization techniques are described by von Alfthan et al. (2014) in the previous version using the Finite Volume Method, while here and in Palmroth et al. (2015) an updated Semi-Lagrangian scheme is used (see also Pfau-Kempf 2016).

The run investigated in this paper is carried out in the ecliptic XY plane of the Geocentric Solar Ecliptic (GSE) coordinate system, representing a two-dimensional (2D) approach in ordinary space. Each ordinary space simulation cell includes a

3D velocity space used to describe the proton velocity distribution. Therefore the approach here is $\frac{5D-2D-3V}{2D-3V}$ in total. The simulation plane in the run used in this paper ranges from $-7.9 R_E$ to 46.8 R_E in X, and $\pm 31.3 R_E$ in Y, with a resolution of 228 km corresponding to the typical ion inertial length in the solar wind. The velocity space resolution is 30 km/s. The solar wind parameters are given as an input at the sunward wall of the simulation box, while copy conditions are applied at other boundaries. The Z direction in ordinary space applies periodic conditions. The inner edge of the magnetospheric domain is a

30

circle with a radius of 5 R_E , while the ionosphere is a perfect conductor in the present version of the code. The same run has

also been used to examine magnetosheath mirror mode waves by Hoilijoki et al. (2016), with a general agreement to existing knowledge of the phenomenon.

The solar wind parameters in this run are as follows: Solar wind distribution functions are assumed Maxwellian, with an initial temperature of 0.5 MK. The IMF has a cone angle of 30°, the IMF x component is -4.33 nT, IMF y is 2.5 nT, while the total magnetic field intensity is 5 nT. The solar wind density is 1 cm⁻³, and velocity 750 kms⁻¹ in the -X direction. Solar wind distribution functions are assumed Maxwellian, with an initial temperature of 0.5 MK. This same run has previously been used to investigate magnetosheath mirror mode waves by Hoilijoki et al. (2016) The combination of the solar wind parameters have

- 5 been chosen to facilitate on one hand the relatively fast initialisation of the simulation to save in the total computational load, and on the other hand the realistic representation of the foreshock. With these solar wind parameters, the upstream Alfvén Mach number becomes 7, well inside the normal range of Alfvén Mach numbers at the Earth (Winterhalter and Kivelson, 1988). Thus we can trust the foreshock physics and consequently its interactions with the bow shock. The combination of solar wind values yields a relatively low dynamic pressure of about 1 nPa, however, this dynamic pressure or lower are observed about
- 10 23% of the time under quasi-radial IMF throughout the solar cycle, based on OMNI solar wind data. Observational statistics show a slight tendency for jets to occur for higher solar wind speeds and lower densities than usual (Plaschke et al., 2018), indicating that our solar wind parameter set represents the conditions under which the magnetosheath jets occur.

Before going to the results, we note that the bow shock moves gradually upstream in all 2D hybrid-kinetic models. There are two reasons for this. First, the magnetosheath magnetic field piles up in front of the magnetopause because in 2D it cannot

15 slip around the magnetosphere towards the nightside as in reality. Secondly, there is an artificial heating in the hybrid-kinetic simulations due to numerical diffusion. This feature is relatively minor in Vlasiator, and the numerical heating does not contribute significantly to the gradual expansion of the bow shock (e.g., von Alfthan et al., 2014; Palmroth et al., 2015).

3 Results

Figure 1a shows a close-up of the Vlasiator simulation domain investigated in this paper. It shows a snapshot of a supplementary 20 movie S1, depicting the dynamic pressure at time t = 305.5 s from the beginning of the run. Colour-coding shows the dynamic pressure. To guide the eye, Fig. 1a also includes the bow shock position as a white solid line, depicting the location where the density is twice the solar wind density. The shock compression ratio is about 3-4 at Earth, making the density gradient at the shock quite sharp, and therefore the bow shock position can be shown in this simple manner. As for the magnetopause position, we first note that in this 2D-3V simulation it is not realistic to expect that the magnetopause position agrees exactly with the

25 empirical proxies. Further, in magnetohydrodynamic (MHD) simulations, such as in GUMICS-4 (Janhunen et al., 2012), the location of the magnetopause depends upon the parameter by which it is defined. The so called fluopause, determined by an average of solar wind streamlines deflecting around the magnetosphere, is a good proxy for the magnetopause, well in accordance with empirical proxies (Palmroth et al., 2003). Therefore we also show the streamlines in Figure 1a to illustrate roughly the dimensions of the magnetosheath in this run. Following Palmroth et al. (2003), the subsolar magnetopause would

30 be determined by neglecting the innermost streamline at around 7 R_E , and by taking an average of the next ones towards upstream, placing the magnetopause using this proxy to somewhere around 10 R_E .

Based on movie S1, we visually identified a high-pressure structure emerging from the bow shock surface and extending through the magnetosheath, marked with a white arrow -in Fig. 1a. The supplementary movie S1 shows both the beginning and the end of the visually identified feature. As we shall describe in this paper, the feature is associated with a higher dynamic pressure advecting towards the bow shock, and reaching it at around t = 282 s. On the other hand, at t = 325 - 340 s, the visually identified feature seems to be associated with a transient wave or an oscillation, which originates approximately at X, Y = [7.5, -4]. This transient follows from the arrival of the remnant of the visually identified feature, and two pulses

- 5 traveling away from the impact point are visible. In a 2D-3V simulation, we do not wish to confirm whether features close to the magnetopause are realistic due to the pile-up effect described above. However, from Supplementary movie S1 it is clear that the visually identified feature is certainly a transient event having a distinct lifetime. It has such a large dynamic pressure that it pushes ambient plasma and has an impact downstream. Therefore we take this feature into a closer scrutiny in order to conclude about its relevance to the magnetosheath jets.
- 10 The white dot in Fig. 1a at $X, Y = [9.5, -4.2]R_E$, shows the earthward edge of this structure, from which we show virtual spacecraft data in Fig. 1b. The virtual spacecraft data in Fig. 1b shows that the velocity increased roughly by 20%, density roughly by 50%, while the dynamic pressure roughly doubled at the time of the structure in panel 1a, marked by a vertical dashed line.

Figure 2 shows the Plaschke criterion C_P defined in Eq. (1), where in a spatially limited zoom of Fig. 1. The colour-coding shows the dynamic pressure ratio between the magnetosheath and solar wind, using the X component of the velocity v_X . The black contour shows where this quantity exceeds 0.25, while the white contour shows the area where the quantity exceeds 0.5 in line with Plaschke et al. (2013). The structure in Fig. 1 can be observed as an elongated feature starting from the bow shock and extending to the left towards the magnetopause in Fig. 2 approximately at $X, Y = [10, -4]R_E$.

- Figure Using the same zoom as Fig. 2, Fig. 3 shows the Archer and Horbury criterion C_A (Eq. 2), which is a ratio of the 20 dynamic pressure and the temporal average of dynamic pressure. Panel 3a shows this ratio, panel 3b is presents the dynamic 20 pressure (the numerator of the criterion), and panel 3c shows the temporal average of dynamic pressure (the denominator 20 of the criterion). While Archer and Horbury (2013) originally used a 20-minute average in the denominator, here we use a 20 three-minute temporal average, centered on time t = 305.5 s. This is solely because the simulation interval does not last for 20 minutes, and while testing different values this three-minute average was found to be the shortest period identifying the 25 structure, while having a manageable amount of data. The contours in panel 3a show where the Archer and Horbury criterion
- exceeds 2, and where therefore the dynamic pressure is twice the temporal average. The largest area satisfying this criterion can be found near the location $X, Y = [109, -4]R_E$.

Figure 4 shows the Karlsson criterion C_K (Eq. 3), namely the ratio of the instantaneous density to the temporal average of the density. Panel 4a shows this ratio. Panels 4b and 4c show the density and the temporal average of density over three minutes, centered on the time t = 305.5 s, respectively. The contour in panel 4a shows locations where the ratio exceeds 1.5., that is

30

where the density is 50% greater than the temporal average. Figure 4a shows that the Karlsson criterion is fulfilled mostly at the surface of the bow shock, while a small area of higher density can be found at location $X, Y = [9, -4]R_E$.

Finally, Fig. 5 compares results for all the criteria, the Karlsson criterion C_K in Eq. (3) with magenta, Archer and Horbury criterion C_A in Eq. (2) with blue, and the Plaschke criterion in Eq. (1) with a black contour. The region we visually identified

- from the movie S1, and which is indicated by an arrow in Fig. 1a fulfils all three criteria approximately at $X, Y = [10, -4]R_E$. Since the criteria agree, we call the feature a magnetosheath jet, and identify its physical dimensions and evolution in time. We adopt an inclusive strategy, and determine that the jet originates at the bow shock with enhanced C_K (magenta) criterion, at $X = 11.6 R_E$, and reaches a location with enhanced C_A (blue) criterion at $X = 9.1 R_E$. Taking into account the angle at which the magnetosheath jet propagates from the bow shock towards the magnetopause, its length is approximately 2.3-2.6 R_E in
- 5 the direction of propagation. In the perpendicular direction, the jet size varies from 0.6 R_E at the bow shock, to 0.3 R_E in the mid-jet area, to ~0.5 R_E at the magnetopause end. Since Fig. 5 represents a snapshot, we emphasise that these dimensions are instantaneous values.

Next we examine the jet evolution in timeNext we investigate the evolution of the jet size in time in Fig. 6, continuing with the inclusive strategy. The panels of Fig. 6 present the jet area, radial size, and tangential size, respectively. The area has been

- 10 calculated such that both the Archer and Horbury as well as the Plaschke criteria delimit the jet, and the area is the sum of the areas of the grid cells within the jet boundaries. The radial size is simply the subtraction of the maximum and minimum radial distance of the jet boundary positions, while the tangential size is the jet area divided by the radial distance. Figure 6 indicates that the area increases and decreases during the jet lifetime, and reaches its maximum just before the time of the jet in Fig. 5. The radial size increases first as the jet emerges from the bow shock, but then stays constant as it propagates through
- 15 the magnetosheath before the jet disperses away. The tangential size remains below $1 R_E$ on average for the most part of the jet lifetime, but the increase of the tangential size at the end of the jet lifetime suggests that it disperses into the tangential direction.

Figure 7 investigates how the jet profile changes as a function of distance from the bow shock. Figure 7a shows an overview plot, with both Plaschke, and Archer and Horbury criteria used to delimit the jet. Figure 7a shows three coloured stars

20 in positions: green = [9.2, -3.7], red = [10.0, -4.4], cyan = [10.8, -5.2]. Figure 7b shows velocity, density, and dynamic pressure as a function of time at these three locations, with similar colour-coding as the stars are given in panel 7a. The full-width-at-half-maximum, which would be measured by a spacecraft, changes from 14 s to 8 s and 9 s from the bow shock to the mid-jet, and to the earthward tip, respectively. Converting these to spatial scales with multiplying with the average velocity yields a spatial size of $0.7 R_E - 0.3 R_E$, respectively. Clearly, the velocities and the dynamic pressures are greatest

25 nearest the shock, and decrease as the jet propagates towards the magnetopause. The dynamic pressure decreases by 70% from the bow shock to the vicinity of the magnetopause, indicating that the origin of the jet may be related to the dynamic pressure outside the bow shock.

Figure 8 examines what causes the jet, using the Plaschke criterion. Figures 8a-d show the total dynamic pressure in the background, and the Plaschke criterion as a eyan-black contour at four times near the time shown in Fig. 5. The panels are snapshots from Supplementary movie S2. In Fig. 8a, a high-pressure area shown by the white arrow approaches the bow shock.

30

This area, which is associated with 30-second ULF waves in the foreshock (Palmroth et al., 2015), high-pressure structure steepens towards the bow shock surface within a matter of seconds. At time t = 295 s the higher dynamic pressure area structure has hit the bow shock, shown by the arrow in Fig. 8b. In panels 8c and 8d this bulge extends towards the magnetopause, and at time t = 310 s it is already fading away. Supplementary movie S2 shows this time sequence in a more dynamic fashion. Figure

35 8 shows that the jet is at its prime at the time shown-

Finally, we investigate the high-pressure structure that causes the jet in more detail. Figure 9a shows the high-pressure feature advecting towards the bow shock with the solar wind. The black dot near the centre of the high-pressure structure shows a point at which we take virtual spacecraft data in Fig. 5, indicating that the jet dimensions given above are to be taken as maximum values at least for driving parameters similar to 9b. The parameters in Fig. 9b are chosen to facilitate a comparison to a SLAMS.

5 which shows an increase in the magnetic field by a factor of 2 or more, and contains a rotation of the magnetic field vector (Lucek et al., 2002, 2004). Figure 9b shows a twofold increase of both the density and the magnetic field intensity when the structure passes the virtual spacecraft location. The components of the magnetic field indicate that the structure includes a clear rotation in the ones in this run. XZ plane. Therefore we conclude that the high-pressure structure that causes the jet reproduces the observational criteria (Lucek et al., 2002, 2004), suggesting that it is indeed a SLAMS.

10 4 Discussion

In this paper, we We have presented a Vlasiator simulation run in the ecliptic plane with a 30° IMF cone angle. We identify and study a magnetosheath jet, and verify its properties by comparing them to three observational criteria (Plaschke et al., 2013; Archer and Horbury, 2013; Karlsson et al., 2012, 2015). The fact that the structure we observed fulfilled all three observational criteria indicates that the observations of Plaschke et al. (2013); Archer and Horbury (2013); Karlsson et al. (2015) indeed

- 15 concern similar phenomena within the magnetosheath. The fact most supporting the idea that our visually selected event is indeed a magnetosheath jet is that all three criteria agree spatially within the jet, and that the identified region is continuous starting from the shock surface and reaching towards the magnetopause. Further, it has a limited lifetime during which the criteria are met within the same region, suggesting that the origin has to do with temporal changes that are connected by the three criteria. While we have concentrated on one jet, there are many more candidate jets in this Vlasiator run that satisfy the
- 20 different criteria, as shown by the Supplementary movies S1 and S2. This and other runs carried out with Vlasiator will allow statistical investigations looking into the evolution of the jets as a function of their position inside within the magnetosheath, and how this depends their size distribution, and how these parameters depend on the driving conditions.

We find that the jet size in the direction of propagation is 2.3 at maximum 2.6 R_E , while in the perpendicular direction it is ~0.5 R_E in size. These dimensions are in agreement with previous scaled results given in ion inertial lengths within a phybrid-PIC simulation with roughly a Mercury-size magnetic dipole, assuming typical magnetosheath properties in order to

convert the results into Earth radii (Karimabadi et al., 2014). Plaschke et al. (2016) estimate the characteristic size of the jets to be 1.34 R_E by 0.71 R_E . The difference to our results may be because we selected the most prominently visible jet, which reached deepest into the magnetosheath, and we measured the dimensions at the prime, while the jet in this paper is within

the range of the jet - In the simulation, sizes reported by them. Contrary to observations, in the simulation the entire jet can

30

be measured and the flow parallel direction can be identified. Spacecraft instead will rarely cross the jet along that the axis of largest extension. Thus the jet in our results may be more elongated than the ones in Plaschke et al. (2016), although the Supplementary movies S1 and S2 indicate many other smaller jet-like structures with dimensions better in accordance with extent. Thus an exact match between observationally identified and modelled jets are not to be expected, but the fact that they broadly agree suggest that the modelled jet can be examined in more detail, and conclusions about its properties can be related to the observations.

It is interesting to compare the different observational criteria in Eqs. (1-3) in light of the simulation results shown here. According to Plaschke et al. (2018), the Archer and Horbury criterion is most inclusive, identifying a large amount the largest

- 5 <u>number</u> of jets, while the Karlsson criterion is most strict identifying small amounts the smallest number of jets (or plasmoids). We have not rigorously tested how large areas the three criteria in fact concern within the magnetosheath, as we have concentrated in on finding a structure that could be identified as a jet with the present observational criteria. We note however that based on Fig. 5 both the Archer and Horbury (2013) and the Plaschke et al. (2013) criteria identify larger regions than the Karlsson criterion, which indeed seems to be the most strict in the simulation overall. It is also interesting to
- 10 note that while the widely accepted term "jet" has a connotation of an elongated feature, according to the results shown here, the Archer and Horbury (2013) and Karlsson et al. (2012, 2015) criteria delineate features shaped more like "blobs". Without vast fleets of observing satellites, it falls on a combination of observational and simulational efforts to infer the shapes and dimensions of jets. Further modelling studies of the jet size distributions will be necessary in order to assess this point.
- We find that the Karlsson criterion is mostly <u>enhanced_fulfilled</u> near the bow shock surface, and it seldom reaches the 15 magnetosheath portions close to the magnetopause. On the contrary, the Archer and Horbury (2013) criterion identifies regions closest to the magnetopause but can be found to be satisfied throughout the magnetosheath, agreeing with the observational statistics. These characteristics might be associated with the solar wind driving conditions in our run. Neither Karlsson et al. (2012) nor Karlsson et al. (2015) specify the solar wind conditions for their events, while our event is associated with the a solar wind density value of 1 cm⁻³. The Archer and Horbury criterion is determined by the dynamic pressuredepending
- 20 quadratically on the , which depends on the square of the velocity, which in our simulation is rather high in the solar wind, 750 kms⁻¹. While both criteria concern ratios that can be enhanced during a variety of driving conditions, it is possible that in the conditions of this run, the Karlsson high-density plasmoids are either not properly generated or cannot propagate deep in the magnetosheath, while the Archer and Horbury pressure enhancements could traverse further towards the magnetopause due to the faster general velocities in the magnetosheath. In accordance with Plaschke et al. (2013), the Plaschke criterion in
- 25 our results is most enhanced near the bow shock. This may be because it is based on the X component of dynamic pressure: The general magnetosheath flow pattern starts to deviate from the X direction rather soon after near the shock. Further, the jets push ambient magnetosheath plasma out of their way in order to reach the magnetopause, decelerating them to a level where they no longer satify level that no longer satisfies the Plaschke criterion. Therefore, in order to observe more jets close As we also show that the dynamic pressure rapidly decreases as a function of distance from the bow shock, to observe jets closer to
- 30 the magnetopause , it may be better to choose the Archer and Horbury (2013) criterion.

Both ULF waves and SLAMS are common in the foreshock, where they advect towards the bow shock (e.g. Eastwood et al., 2005, and re By looking at the Supplementary movie S2 and Fig. 8 Figs. 8 and 9, we find that the jet in question is formed by the interaction of a steepened foreshock ULF wave with the bow shock surface. These ULF waves are common in the foreshock, where they advect towards the bow shock near which they are steepened, acquiring a high dynamic pressure (e.g. Eastwood et al., 2005, and references The ULF pressure fluctuations within the foreshock convecting towards the bow shockarrive there with a variety of properties. The foreshock pressure enhancement associated with the selected jet high pressure structure with the bow shock. The pressure enhancement has a larger pressure than its neighbours. It is also, and it is elongated along the X axis, and wider in Y than other foreshock fluctuations within the run sequence. Further, the Based on virtual spacecraft data taken from the structure,

- 5 we conclude that its characteristics reproduce the main features of a SLAMS. As the bow shock already shows an initial dent before the pressure front arrivesthere. Therefore, the pressure enhancement passes SLAMS arrives, the SLAMS can pass the bow shock with little braking and can propagate deep into the magnetosheath. In contrast, we refer to another larger pressure fluctuation that reaches the bow shock at about t = 351 s (at $X, Y \approx [11, -3.5]R_E$, see movie S2). The bow shock is not dented upon the arrival of this fluctuation and therefore the resulting jet-like structure does not grow large or propagate very
- 10 deep within the magnetosheath. Since there is only one larger jet in this run sequence, we cannot yet say how common this ULF wave interaction is, but shall certainly come back to the connection in future runs.

Both Omidi et al. (2016) and Hao et al. (2016), using Omidi et al. (2016) used a 2D hybrid-PIC simulation, to associate magnetosheath jet-like structures to with foreshock ULF waves. The jets in Omidi et al. (2016) are also reported by Omidi et al. (2016) alm reach the magnetopause, and they are associated with high dynamic pressures, and they reach close towards the magnetopause.

- 15 They. The authors note that "these regions are not associated with high flow speeds and are instead caused by the density enhancements associated with the magnetosheath filamentary structures". Without a rigorous comparison to the data in Omidi et al. (2016) we cannot be sure that the features in their simulation and the ones shown here concern the same physics and whether therefore the origins of the structures can be related. However, we do note that in our simulations the higher dynamic pressure regions within the magnetosheath, which we call the magnetosheath jets, are associated with high velocities.
- 20 Further, Hao et al. (2016) carried out a local 2D hybrid-PIC simulation with a planar shock to investigate a jet-like feature. They associated the jet-like feature with the upstream ULF waves, and made a note that it may originate due to a "SLAMS-like" feature interacting with the bow shock. The present study takes further these previous numerical works by providing a global simulation of the formation and evolution of magnetosheath jets in the real magnetospheric scales, directly comparable to those observed by Earth-orbiting spacecraft. This allows us to rigorously compare the jet with existing observational criteria, and
- 25 also to identify the structure causing the jet as a SLAMS. To our knowledge, this is the first time this type of study has been carried out.

For As for the generation of the jets, Hietala et al. (2009) suggested a mechanism, which relies on an assumption of a rippled shock surface that actively funnels particles into a collimated structure having a high velocity, propagating towards the magnetopause. Hietala et al. (2009) discussed the origins of such a ripple and remarked that while rippling is inherent to

30 the quasi-parallel shock, one possible origin for the ripple would be a short, large-amplitude magnetic structure (SLAMS) (e.g. Lucek et al., 2002) SLAMS convecting towards the bow shock and interacting with it. FurtherIn contrast, Karlsson et al. (2015) suggested that SLAMS interaction with foreshock SLAMS could essentially travel through the bow shock could lead to the formation of their plasmoid observations and maintain its higher pressure, if there is an original dent or corrugation at the bow shock surface to which that SLAMS hits. The jet generation we have investigated here is directly associated with a high-pressure foreshock structure interacting with the bow shock. While we do not take a position whether our high-pressure structure causing the jet is indeed a SLAMS, we note that our result presents evidence that the origin of the ripple may be caused by an interaction of the bow shock with the foreshock. As the foreshock ULF wave interaction with the bow shock has also been suggested to provide seed perturbations for the mirror mode waves within the quasi-perpendicular magnetosheath (Hoilijoki et al., 2016), we note that it is becoming vital to understand the foreshock processes as a driver for many kinetic phenomena within the magnetosheath SLAMS coming into a contact with a dented bow shock, after which that SLAMS essentially continues through the magnetosheath as a structure that resembles a jet, which fulfils the jet observational criteria.

Therefore our results confirm the Karlsson et al. (2015) scenario for this single jet. However, this does not rule out other 10 possible generation mechanisms that may also be in action.

5 Conclusions

5

5

We investigated magnetosheath high-speed jets in a hybrid -Vlasov simulation done at scales directly comparable to the Earth's magnetosphere. We identify structures in the simulation that can be related to the magnetosheath jets using three different observational criteria. We examine one such jet in more detail and find that its maximum size is 2.3 - 2.6 R_E and ~ 0.5 R_E in the direction parallel and perpendicular to the propagation direction, respectively. The jet originates from the interaction of the foreshock ULF waves with the is caused by a SLAMS structure travelling through the bow shock.

Acknowledgements. We acknowledge The European Research Council for Starting grant 200141-QuESpace, with which Vlasiator (http: //physics.helsinki.fi/vlasiator) was developed, and Consolidator grant 682068-PRESTISSIMO awarded to further develop Vlasiator and use it for scientific investigations. We gratefully also acknowledge the Finnish Centre of Excellence in Research of Sustainable Space (Academy of Finland grant numbers 267144, and 309937. PK's work was supported by DGAPA/PAPIIT

10 grant IA104416. The CSC – IT Center for Science in Finland is acknowledged for the Grand Challenge award leading to the results shown in here. We acknowledge valuable discussions within the International Space Science Institute (ISSI) team 350, called "Jets downstream of collisionless shocks", led by FP and HH. LT acknowledges Marie Sklodowska-Curie grant 704681. We thank Mr Jonas Suni for producing data for the figures in the revised version.

References

- 15 von Alfthan, S., Pokhotelov, D., Kempf, Y. ., Hoilijoki, S., Honkonen, I., Sandroos, A. and Palmroth, M.: Vlasiator: First global hybrid-Vlasov simulations of Earth's foreshock and magnetosheath, J. Atmos. Solar Terr. Phys., 120, 24-35, doi:10.1016/j.jastp.2014.08.012, 2014.
 - Archer, M. O., and Horbury, T. S.: Magnetosheath dynamic pressure enhancements: occurrence and typical properties, Ann. Geophys. 31, 319-331, doi:10.5194/angeo-31-319-2013, 2013
- 20 Eastwood, J. P., Balogh, A., Lucek, E. A., Mazelle, C., and Dandouras, I., Quasi-monochromatic ULF foreshock waves as observed by the four-spacecraft Cluster mission: 1. Statistical properties, J. Geophys. Res., 110, A11219, doi:10.1029/2004JA010617, 2005
 - Fuselier, S., Klumpar, D., and Shelley, E.: On the origins of energetic ions in the Earth's dayside magnetosheath, J. Geophys. Res., 96, 47-56, 1991.
- Gutynska, O., Šimunek, J., Šafránková, J., N?meček, Z., and Přech, V.: Multipoint study of magnetosheath magnetic field fluctuations and
 their relation to the foreshock, J. Geophys. Res., 117, A04214, doi:10.1029/2011JA017240, 2012
 - Hao, Y., Lembege, B., Lu, Q., and Guo, F., Formation of downstream high-speed jets by a rippled nonstationary quasi-parallel shock: 2-D hybrid simulations, J. Geophys. Res., 121, 2080-2094, doi:10.1002/2015JA021419, 2016
 - Hietala, H., Laitinen, T. V., Andréeová, K., Vainio, R., Vaivads, A., Palmroth, M., Pulkkinen, T. I., Koskinen, H. E. J., Lucek,E. A., Rème, H.: Supermagnetosonic Jets behind a Collisionless Quasiparallel Shock, Phys. Rev. Lett. 103(24), 245001,

doi:10.1103/PhysRevLett.103.245001, 2009

- Hietala, H., Phan, T.D., Angelopoulos, V., Oieroset, M., Archer, M. O., Karlsson, T., and Plaschke, F.: In situ observations of a magnetosheath high-speed jet triggering magnetopause reconnection, Geophys. Res. Lett., 45, doi:10.1002/2017GL076525, 2018
- Hoilijoki, S., Palmroth, M., Walsh, B. M., Pfau-Kempf, Y., von Alfthan, S., Ganse, U., Hannuksela, O. and Vainio, R.: Mirror modes in the Earth's magnetosheath: Results from a global hybrid-Vlasov simulation, *J. Geophys. Res. Space Physics*, 121, doi:10.1002/2015JA022026, 2016.
 - Janhunen, P., Palmroth, M., Laitinen, T. V., Honkonen, I., Juusola, L., Facsko, G., and Pulkkinen, T. I., The GUMICS-4 global MHD magnetosphere ionosphere coupling simulation, J. Atm. Solar-Terr. Phys., 80, 48-59, doi: 10.1016/j.jastp.2012.03.006, 2012.
 - Karimabadi, H., Roytershteyn, V., Vu, H. X., Omelchenko, Y. A., Scudder, J., Daughton, W., Dimmock, A., Nykyri, K., Wan, M., Sibeck, D. G., Tatineni, M., Majumdar, A., Loring, B., and Geveci, B.: The link between shocks, turbulence, and magnetic reconnection in collisionless plasmas, Phys. of Plasmas, 21, 062308, doi: 10.1063/1.4882875, 2014
- Karlsson, T., Brenning, N., Nilsson, H., Trotignon, J.-G., Vallières, X., and Facsko, G.: Localized density enhancements in the magnetosheath: Three-dimensional morphology and possible importance for impulsive penetration, J. Geophys. Res. 117, 03227, doi:10.1029/2011JA017059, 2012
 - Karlsson, T., Kullen, A., Liljeblad, E., Brenning, N., Nilsson, H., Gunell, H., and Hamrin, M.: On the origin of magnetosheath plasmoids and their relation to magnetosheath jets, J. Geophys. Res. 120, 7390-7403, doi:10.1002/2015JA021487, 2015

Lucek, E. A., Horbury, T. S., Dunlop, M. W., Cargill, P. J., Schwartz, S. J., Balogh, A., Brown, P., Carr, C., Fornacon, K.-H., and Georgescu,

- E.: Cluster magnetic field observations at a quasi-parallel bow shock, Ann. Geophys., 20, 1699-1710, https://doi.org/10.5194/angeo-20-1699-2002, 2002.
 - Lucek, E. A., Horbury, T. S., Balogh, A., Dandouras, I., and Rème, H.: Cluster observations of structures at quasi-parallel bow shocks, Ann. Geophys., 22, 2309-2314, https://doi.org/10.5194/angeo-22-2309-2004, 2004.

Meziane, K., Mazelle, C., Wilber, M., LeQuéau, D., Eastwood, J. P., Rème, H., Dandouras, I., Sauvaud, J. A., Bosqued, J. M., Parks,

- 15 G. K., Kistler, L. M., McCarthy, M., Klecker, B., Korth, A., Bavassano-Cattaneo, M.-B., Lundin, R., and Balogh, A.: Bow shock specularly reflected ions in the presence of low-frequency electromagnetic waves: a case study, Ann. Geophys., 22, 2325-2335, https://doi.org/10.5194/angeo-22-2325-2004, 2004.
 - Němeček, Z., Săfránková, J., Přech, L., Sibeck, D. G., Kokubun, S., Mukai, T.: Transient flux enhancements in the magnetosheath, Geophys. Res. Lett. 25, 1273-1276, doi:10.1029/98GL50873, 1998
- 20 Omidi, N., Berchem, J., Sibeck, D., and Zhang, H.: Impacts of spontaneous hot flow anomalies on the magnetosheath and magnetopause, J. Geophys. Res. Space Physics, 121, 3155-3169, doi:10.1002/2015JA022170, 2016.
 - Palmroth, M., Pulkkinen, T. I., Janhunen, P., and Wu, C.-C., Stormtime energy transfer in global MHD simulation, J. Geophys. Res., 108, 1048, doi:101029/2002JA009446, 2003.
 - Palmroth, M., Honkonen, I., Sandroos, A., Kempf, Y., von Alfthan, S. and Pokhotelov, D.: Preliminary testing of global hybrid-
- 25 Vlasov simulation: Magnetosheath and cusps under northward interplanetary magnetic field, J. Atmos. Solar Terr. Phys., 99, 41-46, doi:10.1016/j.jastp.2012.09.013, 2013.
 - Palmroth, M., Archer, O., Vainio, R., Hietala, H., Pfau-Kempf, Y., Hoilijoki, S., Hannuksela, O., Ganse, U., Sandroos, A., von Alfthan, S. and Eastwood, J.: ULF foreshock under radial IMF: THEMIS observations and global kinetic simulation Vlasiator results compared, J. Geophys. Res., doi:10.1002/2015JA021526, 2015.
- 30 Pfau-Kempf, Y., Vlasiator: From local to global magnetospheric hybrid-Vlasov simulations, Doctoral thesis, University of Helsinki, URN:ISBN:978-952-336-001-3, http://urn.fi/URN:ISBN:978-952-336-001-3, 2016
 - Plaschke, F., Hietala, H., Angelopoulos, V.: Anti-sunward high-speed jets in the subsolar magnetosheath, Ann. Geophys. 31, 1877-1889, doi:10.5194/angeo-31-1877-2013, 2013
- Plaschke, F., Hietala, H., Angelopoulos, V., and Nakamura, R.,: Geoeffective jets impacting the magnetopause are very common, J. Geophys.
 Res. Space Physics, 121, 3240-3253, doi:10.1002/2016JA022534, 2016
 - Plaschke, F., Hietala, H., Archer, M., Blanco-Cano, X., Kajdič, P., Karlsson, T., Lee, S.-H., Omidi, N., Palmroth, M., Roytershteyn, V., Schmid, D., Sergeev, V., and Sibeck, D., Jets downstream of collisionless shocks, submitted to accepted, Space Sci. Rev., 2018

Schwartz, S. J., Thomsen, M. F., and Gosling, J. T., Ions upstream of the Earth's bow shock: A theoretical comparison of alternative source populations, J. Geophys. Res., 88(A3), 2039-2047, doi:10.1029/JA088iA03p02039, 1983

- 405 Shue, J.-H., Chao, J.-K., Song, P., McFadden, J. P., Suvorova, A., Angelopoulos, V., Glassmeier, K. H., and Plaschke, F.,: Anomalous magnetosheath flows and distorted subsolar magnetopause for radial interplanetary magnetic fields, Geophys. Res. Lett., 36, L18112, doi:10.1029/2009GL039842, 2009.
 - Soucek, J., Escoubet, C. P., and Grison, B.,: Magnetosheath plasma stability and ULF wave occurrence as a function of location in the magnetosheath and upstream bow shock parameters, J. Geophys. Res. Space Physics, 120, 2838-2850, doi:10.1002/2015JA021087, 2015.
- 410 White, L. and Adcroft, A.: A high-order finite volume remapping scheme for nonuniform grids: The piecewise quartic method (PQM), J. Comp. Phys., 227, 7394-7422, doi:10.1016/j.jcp.2008.04.026, 2008.

Winterhalter, D., and Kivelson, M. G.: Observations of the Earth's bow shock under high Mach number/high plasma beta solar wind conditions, Geophys. Res. Lett., 15, 1161-1164, doi:10.1029/GL015i010p01161, 1988.

Zerroukat, M. and Allen, T.: A three-dimensional monotone and conservative semi-Lagrangian scheme (SLICE-3D) for transport problems,

415 Q.J.R. Meteorol. Soc., 138: 1640-1651. doi: 10.1002/qj.1902, 2012



Figure 1. a) Dynamic pressure within Vlasiator simulation domain. <u>Bow shock position is identified with white solid line</u>. The <u>black dashed</u> lines are solar wind streamlines illustrating the magnetopause position roughly (see text for details). The figure is a snapshot of Supplementary movie S1, which does not include the bow shock position or the streamlines. The arrow indicates the visually detected magnetosheath jet under scrutiny in this paper. b) Virtual spacecraft data from the location marked with a white dot in panel a): Magnetic field, velocity, density and dynamic pressure as a function of time. The dashed vertical line shows the time of the visually identified jet in panel a).



Figure 2. Colour-coding shows the dynamic pressure calculated using the X-component of velocity, v_X , divided by the solar wind dynamic pressure using the solar wind v_X . The black contour shows where this Plaschke criterion exceeds 0.25, and white where it exceeds 0.5, as defined in Plaschke et al. (2013).



Figure 3. a) The Archer and Horbury (2013) criterion defined in Eq. (2), devised from the ratio of b) the dynamic pressure and c) the temporal average of dynamic pressure over three minutes centered at the time showing the jet-like feature in Fig. 1a. Panel a) shows a contour marking the locations where the ratio of panel b) and c) exceeds 2. Panels b) and c) have the same scale, from 0 to 1.5 nanopascals.



Figure 4. a) The Karlsson criterion in Eq. (3) (Karlsson et al., 2012, 2015), devised from the ratio of b) the density at t = 305.5 s, and the c) temporal average of density over three minutes, centered at the time showing the jet-like feature in Fig. 1a. Panel a) shows a contour marking locations where the ratio of panel b) and c) exceeds 1.5. Panels b) and c) have the same scale, from 0 to 6 particles in a cubic centimetre.



Figure 5. All criteria with density colour-coded at t = 305.5 s. The Karlsson criterion C_K in Eq. (3) is given with magenta, Archer and Horbury criterion C_A in Eq. (2) with blue, and the Plaschke criterion C_P in Eq. (1) with black.



Figure 6. Time evolution of the The jet area, radial, and tangential size as a function of time. The color coding in area has been calculated based on both the background shows Archer and Horbury as well as the total dynamic pressurePlaschke criteria, while the evan contour shows radial size is the Plaschke criterion C_P computed using the X component subtraction of the velocity v_X in dynamic pressure. Panels a) to d) show times 275, 295, 300, maximum and 310 seconds, respectively, from the start minimum radial distance of the simulation. The time of jet boundary positions, reflecting the jet at its prime is shown in Figmaximum extent. 5. The arrows show tangential size is the effective jet generation width, and are referred to in it is calculated by dividing the textjet area by the radial size. The panels are snapshots of Supplementary movie S2.



Figure 7. Jet evolution in time as a function of distance from the bow shock. a) An overview plot of the dynamic pressure with the Plaschke criterion with black contour, at time t = 305 s. The panel a) shows three locations with a green, red and cyan stars, at which virtual spacecraft data are given in panel b), showing from top to bottom the velocity, density and dynamic pressure against time. Colour coding shows the data from the similarly coloured stars in panel a).



Figure 8. Time evolution of the jet. The colour coding in the background shows the total dynamic pressure, while the black contour shows the Plaschke criterion C_P computed using the X component of the velocity v_X in dynamic pressure. Panels a) to d) show times 275, 295, 300, and 310 seconds, respectively, from the start of the simulation. The time of the jet at its prime is shown in Fig. 5. The white arrows show the jet generation and are referred to in the text. The panels are snapshots of Supplementary movie S2.



Figure 9. a) An overview plot of the high-pressure structure that causes the jet, colour-coding shows the dynamic pressure. The black dot marked by the arrow shows the virtual spacecraft location, for which different parameters are shown in panel b). From top to bottom the virtual spacecraft parameters are X, Y, and Z components of the magnetic field, magnetic field intensity B, density ρ , total speed v and the dynamic pressure p_{dyn} . The parameters are plotted against time, and the time shown in the panel a) is given by a dashed vertical line.