Unveiling the 3D Structure of Magnetosheath Jets

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December 10, 2023

Abstract

Magnetosheath jets represent localized enhancements in dynamic pressure observed within the magnetosheath. These energetic entities, carrying excess energy and momentum, can impact the magnetopause and disrupt the magnetosphere. Therefore, they play a vital role in coupling the solar wind and terrestrial magnetosphere. However, our understanding of the morphology and formation of these complex, transient events remains incomplete over two decades after their initial observation. Previous studies have relied on oversimplified assumptions, considering jets as elongated cylinders with dimensions ranging from 0.1 RE to 5.0 RE (Earth radii). In this study, we present simulation results obtained from Amitis, a high-performance hybrid-kinetic plasma framework (particle ions and fluid electrons) running in parallel on Graphics Processing Units (GPUs) for fast and more environmentally friendly computation compared to CPU-based models. Considering realistic scales, we present the first global, three-dimensional (3D in both configuration and velocity spaces) hybrid-kinetic simulation results of the interaction between solar wind plasma and Earth. Our high-resolution kinetic simulations reveal the 3D structure of magnetosheath jets, showing that jets are far from being simple cylinders. Instead, they exhibit intricate and highly interconnected structures with dynamic 3D characteristics. As they move through the magnetosheath, they wrinkle, fold, merge, and split in complex ways before a subset reaches the magnetopause.
a) X = +12.0 RE

b) X = +11.75 RE

c) X = +11.50 RE
d) X = +11.25 RE

Plasma density

Bulk flow speed

Plasma velocity (x-component)

Flux
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Key Points:

• We present the first 3D hybrid-kinetic simulation results of the solar wind interaction with the entire magnetosphere of Earth at physical scales

• We show the three-dimensional (3D) structure of the magnetosheath jets when the IMF is parallel to the solar wind flow direction

• Magnetosheath jets are not shaped like cylinders but are intricate, interconnected structures that split and merge in complex ways

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Abstract

Magnetosheath jets represent localized enhancements in dynamic pressure observed within the magnetosheath. These energetic entities, carrying excess energy and momentum, can impact the magnetopause and disrupt the magnetosphere. Therefore, they play a vital role in coupling the solar wind and terrestrial magnetosphere. However, our understanding of the morphology and formation of these complex, transient events remains incomplete over two decades after their initial observation. Previous studies have relied on oversimplified assumptions, considering jets as elongated cylinders with dimensions ranging from $0.1 R_E$ to $5 R_E$ (Earth radii). In this study, we present simulation results obtained from Amirtis, a high-performance hybrid-kinetic plasma framework (particle ions and fluid electrons) running in parallel on Graphics Processing Units (GPUs) for fast and more environmentally friendly computation compared to CPU-based models. Considering realistic scales, we present the first global, three-dimensional (3D in both configuration and velocity spaces) hybrid-kinetic simulation results of the interaction between solar wind plasma and Earth. Our high-resolution kinetic simulations reveal the 3D structure of magnetosheath jets, showing that jets are far from being simple cylinders. Instead, they exhibit intricate and highly interconnected structures with dynamic 3D characteristics. As they move through the magnetosheath, they wrinkle, fold, merge, and split in complex ways before a subset reaches the magnetopause.

1 Introduction

The magnetosheath is a region confined between the planetary bow shock (a boundary where the supersonic flow of the solar wind is decelerated, deflected, and heated) and the magnetopause (the outermost boundary of the magnetosphere). In this highly dynamic region, the properties of the solar wind plasma and magnetic field undergo significant changes due to compression and turbulence, making the magnetosheath a crucial region for understanding the interaction between the solar wind and planetary magnetosphere (recently reviewed by Narita et al. (2021)).

In the last two decades, spacecraft observations have frequently reported localized and temporary enhancements of plasma dynamic pressure in the magnetosheath of Earth, characterized by a sudden increase in plasma velocity and/or density compared to the surrounding magnetosheath plasma (Němeček et al., 1998; Savin et al., 2008; Hietala et al., 2009; Karlsson et al., 2012; Archer & Horbury, 2013; Hietala & Plaschke, 2013; Plaschke et al.,
2013; Gunell et al., 2014; Gutynska et al., 2015; Plaschke et al., 2017, 2020; Goncharov et al., 2020; Raptis et al., 2020). These enhancements have been observed more often at the sub-solar magnetosheath behind a quasi-parallel shock, i.e., when the interplanetary magnetic field (IMF) has a small cone angle (<30° with respect to the Earth-Sun line) (Archer & Horbury, 2013; Plaschke et al., 2013; Vuorinen et al., 2019; LaMoury et al., 2021). Similar phenomena have recently been observed in the magnetosheath of Mars (Gunell et al., 2023).

Currently, there is no general consensus on the nomenclature of these dynamic pressure enhancements, indicating a lack of comprehension of their underlying nature and characteristics. Throughout the years, various terminologies have been employed to describe these phenomena including “transient flux enhancements” (Némeček et al., 1998), “fast plasma streams” (Savin et al., 2012), “high energy density jets” (Savin et al., 2008), “plasmoids” (Karlsson et al., 2012; Gunell et al., 2014; Karlsson et al., 2015), and “magnetosheath jets” (Hietala et al., 2012; Plaschke et al., 2013; Dmitriev & Suvorova, 2015). We adopt the term “jets” in this study.

Previous analyses of the observed magnetosheath jets have provided different results regarding the morphology of the jets, particularly their sizes and structures (Plaschke et al., 2018). The early event studies indicated that the typical size of jets in the direction parallel to their flow motion is around 1 $R_E$ (Archer et al., 2012). However, large flow-parallel scale sizes ($5 R_E$) have also been observed (Dmitriev & Suvorova, 2012). Similarly, there is a wide spread in the flow-perpendicular dimension of jets, ranging from 0.2 $R_E$ to a few $R_E$ (Archer et al., 2012; Hietala et al., 2012; Gunell et al., 2014). Later, statistical analyses estimated 0.7 $R_E$ for the flow-parallel dimension and nearly twice as large for the flow-perpendicular dimension of the jets (Plaschke et al., 2013). Recent re-analysis of jets suggested that the scales of jets follow a log-normal distribution (Plaschke et al., 2020). This has led to a significant reduction in their estimated sizes, with median scales of 0.15 $R_E$ and 0.12 $R_E$ for the flow-parallel and flow-perpendicular dimensions, respectively (Plaschke et al., 2020).

Despite substantial adjustments in the estimation of jet sizes, the earlier findings concerning the rate of large jets (> 1 $R_E$) impacting the magnetopause (3 per hour, in general) remained unchanged (Plaschke et al., 2020).

In addition to observations, both local- and global-scale kinetic simulations of Earth’s magnetosheath have investigated the properties and scales of jets, and they have greatly advanced our understanding of these mysterious phenomena (Gutynska et al., 2015; Hao...
et al., 2016; Omidi et al., 2016; Palmroth et al., 2018; Voitcu & Echim, 2018; Preisser et al., 2020; Palmroth et al., 2021; Suni et al., 2021; Omelchenko et al., 2021; Guo et al., 2022). These simulations, similar to observations, revealed a broad range of sizes for jets from 0.2 \( R_E \) to a few \( R_E \) at various directions. Nonetheless, they consistently demonstrated that the size of jets is larger in flow-parallel compared to flow-perpendicular directions (Hao et al., 2016; Palmroth et al., 2018, 2021; Guo et al., 2022).

The uncertainties encountered in understanding the structure of these jets can be associated with oversimplified assumptions employed in their analyses. These assumptions often portray jets as either cylinder-, pancake-, or finger-like shapes, exhibiting diverse sizes aligned in parallel or perpendicular directions to the plasma flow or magnetic field orientation (Archer et al., 2012; Karlsson et al., 2012; Plaschke et al., 2016, 2018; Palmroth et al., 2021; Plaschke et al., 2020; Goncharov et al., 2020; Guo et al., 2022). In addition, all the previously applied kinetic models to investigate magnetosheath jets have either been two-dimensional (2D) models in the spatial domain (configuration space) (Gutynska et al., 2015; Hao et al., 2016; Omidi et al., 2016; Palmroth et al., 2018; Preisser et al., 2020; Palmroth et al., 2021; Suni et al., 2021; Guo et al., 2022) or three-dimensional (3D) models with reduced scales of Earth (Karimabadi et al., 2014; Omidi et al., 2016; Ng et al., 2021; Omelchenko et al., 2021) or focused on a small region in the magnetosheath (e.g., Voitcu & Echim, 2018). Furthermore, spacecraft observations at specific locations in the magnetosheath are unable to cover and probe a large spatial area at once, and therefore, provide a limited “1D snapshot” view of jets. Consequently, due to the lack of comprehension of the structure of the jets, several assumptions and simplifications have been made that can lead to uncertainties and ambiguities in our understanding of the morphology of these phenomena.

In addition to their sizes and structures, the formation mechanism of jets has also remained elusive (Plaschke et al., 2018, 2020). Observations suggest that the occurrence of jets downstream of the quasi-parallel shock is more frequent in proximity to the bow shock as compared to the magnetopause (Archer & Horbury, 2013; Plaschke et al., 2013; Goncharov et al., 2020). On the contrary, the occurrence frequency of jets increases toward the magnetopause downstream of the quasi-perpendicular shock (Archer & Horbury, 2013). It has been suggested that the formation of jets downstream of the quasi-parallel shock can be linked to the foreshock structures and/or the bow shock ripples, and reformation (Hietala & Plaschke, 2013; Omidi et al., 2016; Kajdič et al., 2017; Gutynska et al., 2015; Karlsson et al., 2015; Suni et al., 2021; Raptis, Karlsson, Vaivads, Pollock, et al., 2022). Moreover,
jets have been observed more frequently when the IMF exhibits a higher level of stability
(Savin et al., 2008; Hietala et al., 2009; Archer & Horbury, 2013; Plaschke et al., 2013).
This suggests that, in general, the formation of jets is not directly associated with IMF
discontinuities or transient events such as magnetic discontinuities and hot flow anomalies
(Hietala & Plaschke, 2013; Plaschke et al., 2013; Karimabadi et al., 2014; Suni et al., 2021;

Despite the lack of understanding of the nature and formation mechanism of magne-
tosheath jets, observations have found compelling evidence that jets play a crucial role in
coupling between the solar wind and planetary magnetospheres by transferring a significant
amount of energy and momentum towards and into the magnetosphere (Savin et al., 2008;
Shue et al., 2009; Savin et al., 2012; Gunell et al., 2012, 2014; Dmitriev & Suvorova, 2015;
Plaschke et al., 2016). They also contribute to various fundamental plasma processes, such
as wave generation (Karlsson et al., 2018; B. Wang et al., 2022; Krämer et al., 2023), plasma
acceleration (Lavraud et al., 2007; Liu et al., 2019), and magnetic reconnection (Phan et
al., 2007; Hietala et al., 2018; Ng et al., 2021). Beyond their impact on the magnetosphere,
these jets exhibit observable effects even on the ground, including geomagnetic disturbances,
enhancements in ionospheric outflow, and dayside aurora (Hietala et al., 2012; Han et al.,
2016; B. Wang et al., 2018; Norenius et al., 2021; B. Wang et al., 2022). Such far-reaching
influences highlight the significance of the jets in the solar wind coupling with the magneto-
sphere and ionosphere of Earth (Plaschke et al., 2018; Rakhmanova et al., 2023). However,
the extent of their impact remains uncertain, mainly due to our limited understanding of
their structure, dimensions, and formation mechanisms (Plaschke et al., 2018).

In this study, we present the first 3D configuration of magnetosheath jets using the
Amitis code, a state-of-the-art hybrid-kinetic plasma model (Fatemi et al., 2017). We have
successfully resolved, for the first time, the time-dependent, global 3D interaction (both
spatial and velocity domains) between the solar wind and Earth’s magnetosphere using the
physical scales of the Earth’s magnetosphere. By simulating typical solar wind conditions
near the orbit of Earth, we have achieved an unprecedented understanding of the structure
of jets forming within the magnetosheath.
2 Model and Methods

2.1 Amitis Model

In this study, we use an upgraded version of the Amitis code, a high-performance hybrid-kinetic plasma model that runs in parallel on multiple Graphics Processing Units (GPUs) instead of a single GPU (Fatemi et al., 2017, 2022). Amitis is 3D in both configuration and velocity spaces, time-dependent, and grid-based kinetic plasma framework (Fatemi et al., 2017). In this model, the ions are kinetic, charged macro-particles, and electrons are a massless, charge-neutralizing fluid. The model is the first of its kind that runs entirely on GPUs and it runs at least 10 times faster and more energy and cost-efficient (environmentally friendly) compared to its parallel CPU-based predecessors (Fatemi et al., 2017).

In our model, an ion position, \( r_i \), and velocity, \( v_i \), are obtained from the Lorentz equation of motion

\[
\frac{d v_i}{dt} = \frac{q_i}{m_i} (E + v_i \times B), \quad \frac{d r_i}{dt} = v_i, \tag{1}
\]

where \( q_i \) and \( m_i \) are the charge and mass of a macro-particle ion, respectively. \( E \) is the electric field and \( B \) is the magnetic field applied to the ion at its position. We calculate the electric field from the electron momentum equation for mass-less electrons (\( m_e = 0 \)), which is given by

\[
E = \frac{\text{Hall}}{\rho_i} + \frac{\text{Ohmic}}{\eta} + \frac{\text{Convective}}{\mathbf{u}_i \times \mathbf{B}} - \frac{\text{Ambipolar}}{\nabla p_e/\rho_i}, \tag{2}
\]

where \( \mathbf{J} \) is the electric current density calculated from Ampère’s law where displacement current is neglected (i.e., \( \mathbf{J} = \nabla \times \mathbf{B}/\mu_0 \)), \( \rho_i \) is the charge density of macro-particle ions, \( \eta \) is the resistivity, \( \mathbf{u}_i \) is the bulk flow velocity of ions, and \( p_e \) is the electron pressure. Different electric field terms including the Hall, ohmic, convective, and ambipolar electric fields are labeled in Equation 2. Amitis can solve electron pressure tensors, but for simplicity in this study, we assume that electrons are an ideal gas with \( p_e \propto n_i^\gamma \), where \( \gamma = 5/3 \) is the adiabatic index and \( n_i \) is the ion density. Therefore, the pressure gradient in Equation 2 is comparable to the ion density gradient in our model. We advance the magnetic field in time using Faraday’s law, \( \partial \mathbf{B}/\partial t = -\nabla \times \mathbf{E} \). The model principles are described in detail by Fatemi et al. (2017).

Amitis has been extensively applied to study plasma interactions with various planetary bodies including the Moon, Mercury, Ganymede, Mars, and several asteroids (e.g., Fatemi et al., 2017; Fuqua-Haviland et al., 2019; Fatemi et al., 2020; Aizawa et al., 2021; Poppe et al., 2021; Poppe et al., 2022).
al., 2021; Rasca et al., 2022; Fatemi et al., 2022; Shi et al., 2022; X.-D. Wang et al., 2023; Poppe & Fatemi, 2023). In addition, its results have been successfully validated through comparison with spacecraft observations (e.g., Fatemi et al., 2017, 2020; Aizawa et al., 2021; Rasca et al., 2022; Fatemi et al., 2022; X.-D. Wang et al., 2023), theories (Fuqua-Haviland et al., 2019), and other kinetic and Magnetohydrodynamic (MHD) models (Fatemi et al., 2017; Aizawa et al., 2021).

2.2 Coordinate System and Simulation Setup

In our analysis, we utilize the Geocentric Solar Magnetospheric (GSM) coordinate system, which is centered at Earth’s center of mass. In this coordinate system, the $+x$ axis is directed towards the Sun, representing the direction opposite to the flow direction of the solar wind. The $+z$ axis points to the northern magnetic pole and the $+y$ axis completes the right-handed coordinate system. To perform our simulations, we employ a simulation domain with dimensions $-19 R_E \leq x \leq +53 R_E$ and at smallest $-55 R_E \leq (y, z) \leq +55 R_E$, where $1 R_E = 6371$ km is the radius of Earth in our simulations. To discretize our simulation domain, we employ a regularly spaced Cartesian grid with cubic cells of size 500 km ($\approx 0.078 R_E$).

The focus of this study is on the structure of the solar wind interaction with the dayside magnetosphere, primarily the magnetosheath jets. Therefore, we exclude the simulation of Earth’s atmosphere, ionosphere, and exosphere by assuming that the inner boundary of the magnetosphere is a conductive sphere with a radius of 30,000 km ($\approx 4.7 R_E$), centered at the origin of our coordinate system. When a particle impacts this inner boundary, we remove that particle from the simulation domain. The choice for the size and configuration of the inner boundary aligns with previous simulations of Earth by the Vlasiator model (Palmroth et al., 2018, 2021).

The inflow boundary ($x = +53 R_E$) and the outflow boundary ($x = -19 R_E$) of our simulations act as a perfect plasma absorber. At the inflow boundary, kinetic macro-particles are continuously injected into the simulation domain, following a drifting Maxwellian velocity distribution function. Along the $y$- and $z$-axes, the boundaries are assumed to be periodic for both electromagnetic fields and particles. This means that electromagnetic fields and particles are replicated from one side to the other side of the simulation domain.
We incorporate the actual scales of the Earth’s magnetic field in our simulations. We adopt a magnetic dipole model with a magnetic moment $M = 8.22 \times 10^{22}$ A m$^2$ (Walt, 1994) positioned at the center of the Earth and oriented exactly along the $-z$ axis. This magnetic moment generates a surface equatorial magnetic field of $\sim 32 \mu$T at a distance of $1 R_E$, and $\sim 305$ nT at the inner boundary (plasma absorber) of our simulations at $4.7 R_E$.

At the inflow boundary where the solar wind enters our simulation domain, we employ 32 macro-particles per grid cell consisting exclusively of protons with mass $1.67 \times 10^{-27}$ kg and charge $1.60 \times 10^{-19}$ C. For simplicity, we do not include solar wind He$^{++}$ or heavier ions (e.g., O$^{++}$) in our simulations, explained in detail in Section 2.5. Within our simulation domain, we track the trajectories of over 50 billion macro-particle protons at every simulation time step. To achieve this, we utilize a time step of $\Delta t = 8 \times 10^{-3}$ s, which is $5 \times 10^{-4}$ of the upstream solar wind proton gyro-period away from magnetospheric disturbances and is $3 \times 10^{-2}$ of a proton gyro-period near magnetospheric poles at the inner boundary of our simulations. By employing such a small time step, we ensure that the gyromotion of the solar wind protons is fully resolved within the entire simulation domain.

Within our model, the plasma resistivity is uniformly set to $10^4 \Omega$ m wherever the ions exist. This resistivity is primarily required to damp numerical oscillations and to facilitate magnetic reconnection to occur in our simulations (Fatemi et al., 2017, 2020, 2022). To effectively handle the vacuum regions that arise in our simulations, such as those found in the magnetotail, we incorporate a vacuum resistivity of $0.2 \times 10^7 \Omega$ m, as described in Holmström (2013) and Fatemi et al. (2017). Whenever the density of a grid cell falls below 1% of the undisturbed (upstream) solar wind plasma density, we dynamically assign the vacuum resistivity to those cells. In these vacuum regions, we solve the magnetic diffusion equation instead of utilizing general Faraday’s law, as explained in detail by Holmström (2013) and Fatemi et al. (2017).

In this study, we perform a series of hybrid simulations using the Amitis code for the “typical” solar wind conditions near Earth, i.e., the solar wind speed of 400 km/s, plasma density of $7 \text{cm}^{-3}$, and magnetic field strength of 5 nT (Kivelson & Russell, 1995). The solar wind plasma and magnetic field configurations applied in our simulations are summarized in Table 1. In this table, the calculation for plasma dynamic pressure, represented as $P_{\text{dyn}}$, is given by $P_{\text{dyn}} = mnv^2$, where $m$ represents the proton mass, $n$ is the plasma density, and $v$ is the plasma flow velocity. In the solar wind, $P_{\text{sw}} = mn_{\text{sw}}v_{\text{sw}}^2$. The plasma $\beta$ denotes
the ratio between the solar wind thermal pressure and the magnetic pressure. \( M_A, M_s, \) and \( M_{ms} \) are the Alfvén, sonic, and magnetosonic Mach numbers, respectively.

Table 1. Solar wind plasma parameters and IMF configurations applied in our simulations. Only the IMF orientation is different between the simulation runs.

| Run | \( B_{\text{IMF}}(B_x, B_y, B_z) \) (nT) | \( |B| \) (nT) | \( n_{sw} \) (cm\(^{-3}\)) | \( \mathbf{v}_{sw}(v_x, v_y, v_z) \) (km/s) | \( T_i = T_e \) (eV) | \( P_{sw} \) (nPa) | \( \beta \) | \( M_A \) | \( M_s \) | \( M_{ms} \) |
|-----|---------------------------------|----------|----------------|--------------------------|-----------------|-------------|----------|----------|----------|----------|
| R1Y | (+4.83, +1.30, 0.0)            |          |                |                          |                 |             |          |          |          |          |
| R1S | (+4.83, 0.0, −1.30)            |          |                |                          |                 |             |          |          |          |          |
| R1N | (+4.83, 0.0, +1.30)            | 5.0      | 7.0            | (−400, 0, 0)             | 10.0            | 1.86        | 1.1      | 9.7      | 7.1      | 5.7      |
| R2  | (0.0, +5.0, 0.0)               |          |                |                          |                 |             |          |          |          |          |

Our simulations consisted of different scenarios. First, we conducted a simulation where the IMF is directed radially outward from the Sun (run R1), forming a 15° angle from the solar wind flow direction (i.e., quasi-parallel to the solar wind flow). Note that in this manuscript, the term “quasi-parallel IMF” refers to the direction of the IMF relative to the upstream solar wind flow direction, and not to the bow shock normal, unless stated otherwise. As outlined in Table 1, the R1 simulation run consists of three distinct IMF configurations. Initially, the IMF had only \( x \) and \( y \) components (run R1Y). After approximately 11 minutes of physical time, we changed the IMF orientation upstream in our simulations (i.e., the inflow boundary) and made it southward (R1S), propagating into the simulation domain while the magnitude and cone angle of the IMF remained unchanged. Subsequently, after nearly 35 minutes, we again changed the IMF to a northward orientation (R1N). This allowed us to simulate the passage of two consecutive current sheets (magnetic transients) through our simulations.

In the R1 simulation, the IMF changes occurred in the format of a step-function where the magnetic field orientation changed. For example, see time 12:30 in Figure S6d in the supplementary materials where the \( y \)-component of the magnetic field changes from +1.3 nT to zero, and the \( z \)-component of the magnetic field changes from zero to −1.3 nT. However, due to the non-zero plasma resistivity applied in our simulations \( (10^4 \Omega \text{m}) \), these changes formed a magnetic transient (current sheet) with a width of \( \approx 1 R_E \) propagating through the entire simulation domain, interacting with Earth. Choosing a smaller plasma resistivity
results in a narrower current sheet, but increases the numerical noise in our simulations. Before the arrival of the current sheet and after its passage, the solar wind parameters, and magnetic field configurations remained constant upstream of our simulation domain, indicating a relatively constant environment in terms of solar wind conditions and magnetic field configurations.

In addition to the R1 simulation series, we conducted one simulation with the IMF perpendicular to the solar wind flow direction (R2), listed in Table 1. Throughout this run, we maintained a fixed IMF orientation without making any changes. The solar wind plasma parameters including plasma density, velocity, and temperature remained unchanged during both R1 and R2 simulations.

The simulation results presented here (Figures 1–7) are taken before the arrival of the current sheets at $x = +25 R_E$ and/or long after the previous current sheet passed the dayside magnetosphere. This ensures that the dayside magnetosphere has responded to the magnetic transients and fully developed and is stable in the analyses presented in this manuscript. Detailed investigations on the response of the magnetosphere to magnetic transients and how the bow shock, magnetosheath jets, and magnetopause respond to IMF variations are beyond the scope of this study, saved for future research.

2.3 Jet Selection Criteria

Various methods have been applied to detect magnetosheath jets from observed spacecraft data, summarized in Plaschke et al. (2018). Among those, two general approaches are commonly used: (a) comparing observed features with time-averaged local background conditions in the magnetosheath (Archer & Horbury, 2013; Karlsson et al., 2012), and (b) comparing the observed features with undisturbed solar wind plasma and magnetic field upstream of the bow shock (Plaschke et al., 2013). However, both methods have limitations, as thoroughly reviewed by Plaschke et al. (2018). Utilizing a running average (often tens of minutes) to establish the local background imposes a limitation on the timescales of detectable transient events, like jets (Plaschke et al., 2013). The averaging timescales must be considerably longer than the duration of most transients and exceed their typical recurrence timescale (Archer & Horbury, 2013; Plaschke et al., 2013). Comparison with the upstream solar wind conditions allows for a broader range of timescales, but it requires information on the solar wind, which is often not readily available to a spacecraft located
downstream of the bow shock. Therefore, the solar wind observations by other satellites that continuously monitor the solar wind plasmas are used (e.g., ACE or Wind spacecraft data) and time-shifted to the nominal sub-solar bow shock (e.g., Plaschke et al., 2013, 2018). This time-shifting method can introduce complications and uncertainties in analyzing the data in the magnetosheath and the magnetosphere of Earth. However, this is not an issue in numerical simulations, because the upstream conditions are very well-known and can be accurately tracked in time in the simulations. Therefore, we use the latter approach in this study (i.e., method b).

One of the commonly employed thresholds using upstream solar wind conditions is $P_{\text{dyn},x} \geq 0.5P_{\text{sw}}$, where $P_{\text{dyn},x}$ is the dynamic pressure in the magnetosheath along the $x$ axis, and $P_{\text{sw}}$ is the solar wind dynamic pressure, explained by Plaschke et al. (2013). This threshold, referred to as the “Plaschke criterion” throughout this study, should only be applied to the sub-solar region (Plaschke et al., 2013). We use this criterion to select jets in the magnetosheath in our simulations. Since the IMF is nearly parallel to the solar wind flow direction during the R1 simulation run, and our focus is on the magnetosheath jets forming near the sub-solar region, the Plaschke criterion is a valid assumption in the presented analyses in this study. We limit our investigations spatially to the sub-solar region with a maximum $30^\circ$ deviation from the Earth-Sun line (Plaschke et al., 2013, 2018).

### 2.4 Magnetospheric Boundary Selection Criteria

Determining magnetospheric boundaries, such as the bow shock and the magnetopause, in the sub-solar region during quasi-parallel IMF configurations is not straightforward due to the disturbances associated with the foreshock. This complication holds for both simulations and spacecraft data. Our approach to select these boundaries in our simulations primarily relies on analyzing the intensity and direction of electric currents, $\mathbf{J}$, computed from Ampère’s law using our simulation data, a privilege available for 3D simulations. In previous studies, we successfully employed this method to identify magnetospheric boundaries at Mercury (Fatemi et al., 2018, 2020) and Ganymede (Fatemi et al., 2022). While the electric current density is our primary method to identify magnetospheric boundaries, for the R1 simulation series, however, the presence of the foreshock region makes it challenging to accurately pinpoint the bow shock’s location in the sub-solar region. To address this issue, we incorporate additional criteria in conjunction with the electric current density analysis. The criteria are as follows:
• The electric current intensity should exceed 3 nA/m$^2$ at the boundary,

• The plasma density downstream of the bow shock boundary should be higher than the upstream solar wind plasma density due to solar wind compression at the bow shock, and

• The bulk flow speed downstream of the bow shock boundary should be smaller than the solar wind plasma speed, due to the deceleration of plasma at the bow shock.

To identify the magnetopause boundary, we use the electric current density, and we choose 9 nA/m$^2$ as the minimum requirement for the current density at the magnetopause. Using these criteria, we selected the magnetopause and bow shock boundaries in our simulations. To validate our simulation results, we compare the location of the bow shock and magnetopause boundaries obtained from our simulations with an empirical model by Chao et al. (2002).

2.5 Limitations in Simulations

The presented results in this study come with certain limitations primarily due to the applied numerical method and the limited computational resources. The main limitations of this study are as follows:

• In our simulations, we focus exclusively on the solar wind protons and their impact on the overall interaction between the solar wind and Earth. Notably, the solar wind is comprised of various multiply charged heavy ion species like He$^{+2}$, O$^{+6}$, Si$^{+8}$, and Fe$^{+9}$ (Bame et al., 1970; Bochsler, 2007). However, protons are the dominant solar wind ion species (averaging over 95%), and for simplicity, we do not include heavy ions in this study. While the current version of Amitis is capable of handling over 10 ion species (e.g., Poppe et al., 2021), investigating the effect of the heavy ions in the formation, evolution, and morphology of the jets is an interesting research topic that remains for future investigation.

• The nature of hybrid models prevents us from including electron dynamics and their contributions to the interaction with the magnetosphere in this study. In addition, due to the lack of electron dynamics, our simulations underestimate the plasma acceleration associated with charge separation. As previously discussed by Fatemi et al. (2012), the ambipolar electric field in hybrid models, which is related to the electron pressure gradient shown in Equation 2, typically contributes less to plasma energiza-
tion compared to simulations that explicitly resolve electron dynamics. Currently, the space physics community lacks a kinetic plasma model that accurately handles electron dynamics and includes 3D plasma interaction with planetary bodies in their physical scales.

- Achieving extremely high simulation grid resolution (e.g., cell sizes smaller than 100 km to simulate the global 3D kinetic structure of the Earth’s magnetosphere using its physical scales), while very much desirable, remains impossible using kinetic models even using cutting-edge technologies like GPUs, at least with the current size of GPU’s internal memory (known as the global memory, which is maximum 80 GB on Nvidia A100 series at the time of this writing). Quantum computing shows promise for achieving such extremely high-resolution simulations, but this capability is not fully developed yet and will be accessible in the future.

While our presented results in this study shed light on important aspects of magnetosheath jets and unveil their structure, it is important to acknowledge the limitations of our simulations when interpreting and generalizing the results. Future research with enhanced numerical methods and computational capabilities will help to address some of these constraints and provide a more comprehensive understanding of the subject matter.

3 Results

Here, we present the first 3D simulation results of the structure of magnetosheath jets using physical scales of the Earth’s magnetosphere. This detailed representation is obtained from the Amitis model, explained in Section 2. In our simulations, we use the typical solar wind plasma conditions near Earth and a range of IMF orientations, outlined in Table 1. The spatial and temporal scales of the magnetosphere are physically represented in our model, and no scaling has been applied in our simulations.

3.1 Global 3D Structure of Earth’s Magnetosphere

First, we present the global, high-resolution, 3D kinetic interaction between the solar wind and Earth for various IMF configurations, showing our model correctly captures the physics of the interaction. Figure 1 presents a time-snapshot of the magnetic field obtained from our model for four distinct IMF configurations listed in Table 1: run R1Y for a quasi-parallel IMF to the solar wind flow without any $B_z$ component (Figure 1a), runs R1S
Figure 1. Time snapshot of the global, high-resolution, 3D structure of the solar wind interaction with Earth obtained from the Amitis hybrid model. The results are presented in the Geocentric Solar Magnetospheric (GSM) coordinate system for (a) a quasi-parallel IMF to the solar wind flow direction without any $B_z$ component, i.e., run R1Y, (b) a quasi-parallel IMF with a southward component, i.e., run R1S, (c) a quasi-parallel IMF with a northward component, i.e., run R1N, and (d) a perpendicular IMF where only the $B_y$ is non-zero, i.e., run R2. Note that the term “quasi-parallel” here refers to the orientation of the IMF with respect to the upstream solar wind plasma flow direction. The solar wind flows along the $-x$ axis. All simulation parameters are summarized in Table 1 and explained in Section 2. The background color shows the magnitude of the magnetic field in logarithmic scale in the $xy$ (equatorial) plane at $z = 0$, the $xz$ (mid-night meridian) plane at $y = 0$, and the $yz$ plane at $x \approx -18.5 \text{RE}$ in all panels. Streamlines shown in a few planes are magnetic field line tracing at that corresponding plane. For visualization purposes of the streamlines, we set the third component of the magnetic field to zero. The yellow arrows show the IMF orientation at each panel. The pink arrow in Figure 1a points to a flux rope in the magnetosheath over the northern cusp. Earth is shown by a small blue sphere, centered at the origin of the coordinate system, surrounded by a transparent sphere of radius $4.7 \text{RE}$, indicating the inner boundary of our simulations. The dashed white lines in Figures 1a and 1c are parallel to the ion foreshock boundaries, shown to guide the eyes, indicating the ion foreshock boundary is not aligned with the IMF. See Movies S4 and S5 in the supplementary materials for the time evolution of the magnetosphere during the R1Y and R1S simulations.
and R1N for a quasi-parallel IMF to the solar wind flow with a southward and northward component, respectively (Figures 1b and 1c), and run R2 for a perpendicular IMF to the solar wind flow (Figure 1d). Runs R1Y, R1S, and R1N are part of the same simulation sequence where the IMF orientation changes, as explained in Section 2. Note that the term “quasi-parallel” here refers to the orientation of the IMF with respect to the upstream solar wind flow and not the bow shock normal.

In addition to the global structure of the magnetosphere, one notable characteristic observed in Figures 1a–1c is the presence of a foreshock preceding the bow shock when the IMF is quasi-parallel to the solar wind (i.e., R1 simulation series). As marked in Figures 1a and 1c, the ion foreshock does not align with the IMF and instead, it remains behind the tangent field line, which is consistent with foreshock ion observations (Russell & Hoppe, 1983; Eastwood et al., 2005). However, when the IMF is perpendicular to the solar wind flow (Figure 1d), no foreshock is observed upstream of the bow shock. Instead, disturbances associated with the quasi-parallel shock are evident far downstream in the $yz$ plane at $x \approx -18.5 \, R_E$ and $y < -30 \, R_E$ (see the $yz$ plane in Figure 1d).

Our simulations, consistent with observations, suggest that the size of the magnetosheath is primarily influenced by the dynamic pressure of the solar wind and the angle between the IMF and the Sun-Earth line. When the IMF is aligned with the Sun-Earth line (parallel or antiparallel), the sub-solar bow shock gets highly disturbed and mixed into the foreshock, and consequently, the sub-solar magnetosheath region gets narrower (i.e., R1 series). Conversely, when the IMF is oriented at an oblique angle to the solar wind, the bow shock forms a well-confined boundary and the sub-solar magnetosheath region becomes thicker (i.e., run R2) compared to the quasi-parallel configurations.

Despite noticeable differences in the magnetic field structures presented in various panels in Figure 1, consistent features are visible in all panels, irrespective of the IMF configuration. These features include the collisionless bow shock, magnetopause, funnel-shaped magnetospheric cusps, and elongated magnetotail. Other fundamental magnetospheric phenomena (e.g., a flux rope over the dayside northern cusp in the magnetosheath at approximately $(+7.5, 0.0, +7.5) \, R_E$, marked with a pink arrow in Figure 1a and Kelvin-Helmholtz-like vortices marked in Figures S1a and S2e in the supplementary materials) have also been observed in our simulations, but analyzing them is beyond the scope of this study. In gen-
eral, Figure 1 indicates that our simulations provide a reasonable representation of the solar wind plasma interaction with Earth.

### 3.2 Magnetosheath Jets

Here, we focus on the magnetosheath jets and present their morphology for different IMF configurations. In Figure 2a, we present plasma dynamic pressure, $P_{\text{dyn}}$, normalized to the upstream solar wind dynamic pressure, $P_{\text{sw}} = 1.86 \text{nPa}$, in the equatorial ($xy$) plane at $z = 0$ for the R1Y simulation run (i.e., a quasi-parallel IMF to the solar wind flow with $B_z = 0$). The solid black contour lines in this Figure are obtained from the Plaschke criterion, highlighting $P_{\text{dyn},x} = 0.5 P_{\text{sw}}$. Additionally, we project the field-aligned current density, FAC, onto the inner boundary of our simulation at $4.7 R_E$. Different FAC regions are evident in Figure 2a, and their structure and current intensity are consistent with previous observations (Milan et al., 2017; Ganushkina et al., 2018). (See Movies S1 and S2 in the supplementary materials where we have shown the time evolution of the FACs as well as the plasma flux precipitation into the inner boundary of our simulations).

Our simulation presented in Figure 2a shows that the dynamic pressure is spatially variable in the foreshock region, ranging between $0.05 P_{\text{sw}}$ and $1.65 P_{\text{sw}}$ with the mean value of $0.95 P_{\text{sw}}$ and standard deviation of $0.18 P_{\text{sw}}$. For visualization purposes, we set the color bar range for the dynamic pressure between $0.083 P_{\text{sw}}$ and $3.0 P_{\text{sw}}$, centered at $0.5 P_{\text{sw}}$ (i.e., the Plaschke criterion explained in Section 2.3), while the local minimum and maximum values in our presented simulation results are $4.0 \times 10^{-4} P_{\text{sw}}$ and $3.77 P_{\text{sw}}$, respectively. We see from Figure 2a that in some places in the magnetosheath, the dynamic pressure reaches nearly twice the upstream solar wind dynamic pressure and it gets higher than $3.0 P_{\text{sw}}$ near the magnetospheric flanks. At the sub-solar region, a few magnetosheath jets with localized high dynamic pressure are apparent.

For better visualization, Figure 2b provides a closer view of the upstream magnetosheath region, where the presence of high dynamic pressure jets becomes evident. In this figure, similar to Figure 2a, the black contour lines highlight $P_{\text{dyn},x} = 0.5 P_{\text{sw}}$, i.e., the Plaschke criterion for identifying magnetosheath jets. Two jets with apparent classical “cylinder-like” (or finger-like) structures are marked with arrows, displaying significantly higher dynamic pressure compared to their surrounding environment in the magnetosheath ($P_{\text{dyn}} \geq 0.5 P_{\text{sw}}$). In addition, the magnetopause and bow shock boundaries estimated from
Figure 2. Amitis hybrid simulation results presented in the GSM coordinate system for the R1Y simulation at time $t = 744$ s in the $xy$ (equatorial) plane at $z = 0$. (a) Plasma dynamic pressure in logarithmic scale, normalized to the upstream solar wind dynamic pressure, $P_{sw} = 1.86$ nPa. The sphere centered at the origin of the coordinate system represents the inner boundary of our simulations at $4.7 R_E$ with a projected intensity of the field-aligned current (FAC). The solid black contour lines show $P_{\text{dyn, x}} = 0.5 P_{sw}$, i.e., the Plaschke criterion for identifying magnetosheath jets, explained in Section 2. (b) A zoomed-in region from the highlighted area with the white rectangle in panel a shows the normalized plasma dynamic pressure with two marked magnetosheath jets. The pink and green dots denote, respectively, the magnetopause (MP) and bow shock (BS) boundaries estimated from our simulations. The selection criteria for the MP and BS boundaries are explained in Section 2.4. The solid pink and green lines mark the corresponding boundaries obtained from the empirical model by Chao et al. (2002) for the plasma parameters applied in our simulations and listed in Table 1.
our simulations are shown, respectively, by the pink and green dots. Identifying the sub-
solar bow shock boundary when the IMF is quasi-parallel to the solar wind flow presents a
non-trivial task due to the influence of the foreshock disturbances. The bow shock boundary
obtained from our simulations (green dots) stands slightly closer to Earth compared to the
bow shock location estimated by Chao et al.’s empirical model for the bow shock (Chao et
al., 2002), illustrated by the solid green curve. However, the magnetopause boundary yields
a better agreement between our simulations (pink dots) and Chao’s empirical model for the
magnetopause (solid pink curve).

To further investigate the characteristics of the jets, Figure 3 shows the detailed electro-
magnetic and plasma environment obtained from our hybrid simulations, presented in the
same format as that shown in Figure 2b. We see the plasma density inside jets (especially
in the one closer to $y = 0$) is significantly higher compared to the density in the ambient
magnetosheath and in the upstream solar wind (Figure 3a). However, as later shown, this
is not necessarily valid for all jets, which is consistent with previous observations (Archer
& Horbury, 2013; Karlsson et al., 2015; Plaschke et al., 2018). The overall speed of the
plasma flow in the jets is approximately half of the upstream solar wind speed, and over two
times larger than the average plasma speed in the surrounding magnetosheath (Figure 3b).
For example, the averaged plasma speed of the jet closer to $y = 0$ is $\sim 250\, \text{km/s}$, which
is nearly 65% of the solar wind speed. However, as shown in Figure 3c, the surrounding
environment of both highlighted jets has a sunward flow motion with $v_x$ exceeding $0.15\, v_{sw}$
(i.e., $60\, \text{km/s}$ moving sunward along the $+x$ axis). Similar sunward flow motion has been
previously observed in both spacecraft data and numerical simulations (Shue et al., 2009;
Plaschke et al., 2017; Guo et al., 2022).

The proton flux within both jets exceeds 170% of the upstream solar wind flux (Fig-
ure 3d). In addition, at the time snapshot these results are taken, both jets advance to-
wards the magnetopause, shown by arrows in Figure 3d, extending predominantly in the
same direction as the upstream solar wind with some deviations. Their extension in the
flow-parallel direction surpasses their dimension in the flow-perpendicular direction, which
agrees with previous numerical simulations (Hao et al., 2016; Palmroth et al., 2018; Guo et
al., 2022). Both jets span the distance from the bow shock to the magnetopause, creating a
deformation to the magnetopause boundary, evident in the magnetopause current structure
shown in Figure 3e. Furthermore, the magnetic environment inside the jets shows noticeable
changes compared to their surrounding magnetic field in the magnetosheath. For example,
Figure 3. Hybrid simulation results for the R1Y simulation at time $t = 744$ s, presented in the same format as that shown in Figure 2b. (a) Proton density normalized to the upstream solar wind density, $n_{sw} = 7 \text{ cm}^{-3}$, (b) proton speed normalized to the upstream solar wind speed, $|v_{sw}| = 400 \text{ km/s}$, (c) normalized $x$-component of the proton velocity to the upstream solar wind speed where negative values show the anti-sunward and positive values show the sunward plasma motion, (d) proton flux normalized to the upstream solar wind flux, $F_{sw} = 2.8 \times 10^{12} \text{ m}^{-2} \text{ s}^{-1}$, and the colored arrows show the direction and magnitude of the proton flux, (e) the $y$-component of the electric current density, $J_y$, and (f) the magnitude of the magnetic field normalized to the strength of the IMF, $B_{IMF} = 5 \text{ nT}$. The arrows in Figures 3a and 3b mark the two magnetosheath jets highlighted in Figure 2. The inner and outer solid curves in all panels show, respectively, the magnetopause and bow shock boundaries obtained from the empirical model by Chao et al. (2002) for the plasma parameters applied to our simulations, listed in Table 1.

The magnetic field strength in the jet located closer to $y = 0$ reaches around $18 \text{ nT}$, i.e., over 3.5 times larger than the strength of the IMF (Figure 3f). More detailed structures of the plasma flow motion and magnetic field orientation are shown in Figure S1 in the supplementary materials. In addition, the time evolution of these jets and their incidence on the magnetopause are shown in Movies S1 and S2 as well as in Figure S2 in the supplementary materials.
3.3 The Third Dimension of the Jets

Up till here, we have presented two-dimensional (2D) views of the jet properties (Figures 2 and 3) as obtained from the 2D cross-sections of our simulation results, and we have shown that our results are consistent with earlier spacecraft observations (Nemeček et al., 1998; Savin et al., 2008; Hietala et al., 2009; Karlsson et al., 2012; Archer & Horbury, 2013; Hietala & Plaschke, 2013; Plaschke et al., 2013; Gunell et al., 2014; Gutynska et al., 2015; Plaschke et al., 2017, 2020; Goncharov et al., 2020; Raptis et al., 2020) and 2D kinetic simulations (Gutynska et al., 2015; Hao et al., 2016; Omidi et al., 2016; Palmroth et al., 2018; Preisser et al., 2020; Palmroth et al., 2021; Suni et al., 2021; Guo et al., 2022). However, in the following, we will unveil the 3D structure of the jets by including the third dimension and hereby show that the structure and properties of jets are much more complicated than previously thought.

Figure 4 illustrates the configuration of the magnetosheath jets for the R1Y simulation run in the $yz$ plane (perpendicular to the solar wind flow direction) at different distances from the center of Earth. Due to the geometry of these planes, the center of Figure 4a is closer to the sub-solar bow shock, and the center of Figure 4d is closer to the nose of the magnetopause. The black dots indicate the bow shock boundary obtained from our simulations, and the black solid contour lines highlight $P_{\text{dy},X} = 0.5P_{\text{sw}}$. As discussed earlier in Section 2, identifying the quasi-parallel shock (black dots scattered at $y < 0$ in all panels in Figure 4) is a non-trivial task, but the quasi-perpendicular bow shock boundary is well-preserved (black dots at $y > 0$ in all panels in Figure 4). The magnetosheath is the region surrounded by the bow shock boundary. All the high-dynamic pressure regions ($\geq 0.5P_{\text{sw}}$) with filamentary structures in the magnetosheath are jets (yellow and red color regions in the figure).

Contrary to previous hypotheses regarding jet morphology (Archer et al., 2012; Karlsson et al., 2012; Plaschke et al., 2016, 2018; Palmroth et al., 2021; Plaschke et al., 2020; Goncharov et al., 2020; Guo et al., 2022), our 3D kinetic simulations demonstrate that the magnetosheath jets do not exhibit simple geometries like cylinders, spheres, or pancakes. Instead, their structure is exceedingly intricate and interconnected. At closer distances to the bow shock (e.g., Figures 4a and 4b), the jets appear as interconnected regions. Moving further downstream from the bow shock and getting closer to the magnetopause (e.g., Figures 4c and 4d), the jets become increasingly fragmented and disconnected. The dynamic
Figure 4. Amitis hybrid simulation results obtained from run R1Y at time $t = 744s$ in the GSM coordinate system, presenting the dynamic pressure normalized to the upstream solar wind dynamic pressure, $P_{sw} = 1.86\text{nPa}$ in the $yz$ plane at different distances from the Earth’s center:
(a) $x = +12R_E$, (b) $x = +11.75R_E$, (c) $x = +11.5R_E$, and (d) $x = +11.25R_E$. The center of Figure 4a is closer to the sub-solar bow shock, and the center of Figure 4d is closer to the nose of the magnetopause. The black dots indicate the bow shock boundary obtained from our simulations, explained in Section 2. The magnetosheath is the area surrounded by the bow shock (black dots). The solid black contour lines highlight $P_{dyn,x} = 0.5P_{sw}$ (i.e., the Plaschke criterion for identifying magnetosheath jets). The magnetosheath jets are all the filamentary structures with dynamic pressure larger than $0.5P_{sw}$ in the magnetosheath (yellow and red in the figure). The Plaschke criterion is valid at the sub-solar region within an angle $<30^\circ$ from the Earth-Sun line (Plaschke et al., 2013), which is nearly the entire magnetosheath region presented here. All panels are viewed from the Sun, and therefore, the solar wind flows into the planes. The direction of the upstream solar wind flow and the orientation of the undisturbed IMF are the same for all panels and marked by arrows in Figure 4a.
Figure 5. Hybrid simulation results obtained from the R1Y simulation run at time $t = 744\text{s}$ in the $yz$ plane at $x = +11.5\text{R_E}$. The geometry of the cuts is the same as those described in Figure 4. (a) Proton density normalized to the upstream solar wind density, $n_{sw} = 7\text{cm}^{-3}$, (b) proton bulk flow speed normalized to the upstream solar wind plasma speed, $v_{sw} = 400\text{km/s}$, (c) the x-component of the plasma velocity normalized to the upstream solar wind plasma speed, $v_{sw} = 400\text{km/s}$, and (d) the proton flux normalized to the upstream solar wind flux, $F_{sw} = 2.8\times10^{12}\text{m}^{-2}\text{s}^{-1}$. The black contour lines show where $P_{\text{dyn},x} = 0.5 P_{sw}$. The jets are the filamentary structures in the magnetosheath, as described in Figure 4.

The pressure inside the jets spans over a wide range from $\sim 0.5 P_{sw}$ to over $3.0 P_{sw}$ in the planes shown in Figure 4.

More detailed characteristics of the jets in the $yz$ plane at $x = +11.5\text{R_E}$ are shown in Figure 5. In general, we see from Figure 5 that the plasma density and velocity of the jets (filamentary structures in the figure) are considerably higher than the surrounding magnetosheath plasma. The time evolution of the jets in the $yz$ plane at $x = +11.5\text{R_E}$ for the R1Y simulation is shown in the Movie S3 in the supplementary materials.
The structure of the magnetosheath jets in the $yz$ plane for the southward IMF con-
figuration (run R1S) is illustrated in Figure 6. In this simulation, both the magnetopause
and bow shock are positioned closer to the planet under the southward IMF orientation,
primarily due to magnetic reconnection eroding the dayside magnetosphere. This agrees
with previous observations and numerical simulations (e.g., Aubry et al., 1970; Wiltberger
et al., 2003; Le et al., 2016). Consequently, the planes shown in Figure 6 are located closer
to Earth compared to those shown in Figure 4. Similar to the results presented in Figure 4,
the magnetosheath jets exhibit intricate interconnections and form a complex geometry,
particularly in proximity to the bow shock (Figures 4a and 4b). In contrast to the results
shown in Figure 4, we observe that jets during the southward IMF appear less fragmented,
and spatially larger and more extended, which is associated with the IMF orientation that
alters the physics of the interaction. However, we did not observe any noticeable differences
in the average plasma dynamic pressure inside jets during the southward IMF compared to
those presented earlier in Figure 4. A similar conclusion also holds for the northward IMF
(see Figure S3 in the supplementary materials).

Similar to their structure, the evolution of jets is also complex and indeed a 3D problem.
Figure 7 illustrates the angle between the local plasma flow and the upstream solar wind in
the $yz$ plane at $x = +11.5 R_E$, taken at different times from the R1Y simulation. In this
figure, the zero degrees (white regions) mean the plasma flow direction is exactly parallel
to the upstream solar wind (i.e., along the $-x$ axis). Angles between 0 and 90 degrees
indicate an anti-sunward flow, and angles larger than 90 degrees show a sunward flow. In
general, this figure shows how large the plasma flow direction deviates from the undisturbed
solar wind flow direction in the shown planes. Similar to Figure 4, jets are the filamentary
structures mainly clustered at the center of each panel (see Figure S4 in the supplementary
materials for the time evolution of the dynamic pressure). Figure 7 indicates the dynamic
movement of jets and underscores their lively environment in the $yz$ plane. While the plasma
flow motion within jets predominantly follows the solar wind flow direction with nearly $10^\circ$
to $40^\circ$ deviation (seen by the light blue regions in Figure 7), the low dynamic pressure
regions encircling the jets in the magnetosheath move predominantly perpendicular to the
solar wind and often sunward, which is consistent with previous findings (Shue et al., 2009;
Plaschke et al., 2017; Guo et al., 2022).

As shown in Figure 7, the jets are highly dynamic, intermittently merging into and
splitting from each other. For instance, let’s consider a half-open loop jet positioned at
Figure 6. Hybrid simulation results obtained during the southward IMF (run R1S) at time $t = 2244$ s, presenting the dynamic pressure normalized to the upstream solar wind dynamic pressure, $P_{sw} = 1.86$ nPa in the $yz$ plane at different distances from the Earth’s center: (a) $x = +11.0 \, R_E$, (b) $x = +10.5 \, R_E$, (c) $x = +10.0 \, R_E$, and (d) $x = +9.5 \, R_E$. The figure format is the same as that shown in Figure 4.
Figure 7. Hybrid simulation results obtained from run R1Y in the $yz$ plane at $x = +11.5\, R_E$ at six different simulation times: (a) 672 s, (b) 696 s, (c) 720 s, (d) 744 s, (e) 768 s, and (f) 792 s. The last panel is taken at nearly 400 s prior to the arrival of the southward magnetic transient from the R1S simulation. The background color illustrates the angle between the localized plasma flow direction and the upstream solar wind flow direction. The zero degree means exactly parallel flow to the solar wind (i.e., along the $-x$ axis). Angles between 0 and 90 degrees are anti-sunward flow, angles larger than 90 degrees mean sunward flow, and consequently, 180 degrees means perfectly anti-parallel to the solar wind flow direction (i.e., along the $+x$ axis). The jets are the filamentary structures, and they have a flow angle of less than $\sim40$ degrees (light-blue colors). The black arrow in each panel points to one of the magnetosheath jets that gets connected to its neighboring jets at time 696 s and then gets disconnected again at time 744 s (see the text for more detail). The figure format is the same as that shown in Figure 4.
$(y, z) \approx (+3, +2) R_E$, pointed to by an arrow in Figure 7a. This jet experiences a phase of closure to another jet after 24 seconds (Figure 7b). Subsequently, it reopens after 72 seconds (Figure 7d) and then progresses towards the equatorial plane (Figures 7e and 7f).

As shown previously in Figure 2, and also Figure S2 in the supplementary materials, these jets have a third dimension along the $x$ axis, which makes their geometry not as simple as previously thought.

Consistent with previous observations, our simulations indicate that the low IMF cone angles relative to the solar wind flow direction are favorable for the generation of magnetosheath jets downstream of the quasi-parallel shock in the sub-solar region (i.e., where the local bow shock normal is quasi-parallel to the IMF) (Archer & Horbury, 2013; Plaschke et al., 2013, 2018). In the case of run R2 (i.e., a perpendicular IMF to the solar wind flow), we did not observe jets in the sub-solar region. Instead, as shown in Figure S5 in the supplementary materials, jet-like structures with various scales manifest downstream of the quasi-perpendicular shock at the magnetosheath flanks, marked with the white arrow in Figure S5. This finding is in agreement with some of the earlier observations (e.g., Archer & Horbury, 2013). Recent studies, however, have suggested that the jets observed downstream of the quasi-perpendicular shock are originally forming at the quasi-parallel shock and later transported downstream of the quasi-perpendicular shock (Raptis et al., 2020; Kajdič et al., 2021). While our preliminary analyses using our simulations (not shown here) do not support this idea, investigating the nature of the jets downstream of quasi-perpendicular shocks requires a separate study.

### 3.4 Stationary Virtual Spacecraft Observations

To further investigate the characteristics of jets in our model, we placed two stationary virtual observers in our simulations at two distinct locations within the magnetosheath, mimicking spacecraft observations. The first observer is positioned downstream near the nose of the bow shock at $(+11.5, 0.0, -1.0) R_E$, and the second observer is located in proximity to the magnetopause at $(+10.0, 0.0, +3.5) R_E$. The time series for various parameters derived from our kinetic simulations are shown in Figure 8. In addition to these two observers in the magnetosheath, we also placed one virtual observer as a reference point in the solar wind and far away from any terrestrial disturbances. The results from this observer are presented in Figure S6 in the supplementary materials.
The first 7.5 minutes of our simulations are highlighted as the “development phase” in Figure 8. This is the minimum time required for the dayside magnetosphere to be developed in our experiments during the nominal solar wind conditions at Earth (see Movies S4 and S5 in the supplementary materials). Subsequently, the magnetosphere attains a more developed state, and the simulation results reach a steady state. To introduce perturbations into the system, a magnetic transient in the form of a current sheet is applied upstream of our simulations (see Section 2 for more detail and also see time 12:30 in Figure S6d in the supplementary materials). This magnetic transient arrives to the first observer at time \( \sim 22:00 \), and to the second observer around 23:00. These instances of the magnetic transient are highlighted in red in Figure 8. Prior to the arrival of the magnetic transient and after its passage, the solar wind parameters, and magnetic field configurations remained constant upstream of our simulation domain, indicating a relatively constant environment in terms of solar wind conditions and magnetic field configurations for over 10 minutes.

In Figures 8a and 8f, the proton dynamic pressure, \( P_{\text{dyn}} = mnv^2 \), is shown by the solid black line, where \( m \) represents the proton mass, \( n \) is the plasma density, and \( v \) is the plasma flow velocity. The proton dynamic pressure along the solar wind flow direction, denoted as \( P_{\text{dyn,x}} = mnv_x^2 \), is shown by the solid red line, where \( v_x \) is the \( x \)-component of the plasma flow velocity. The dashed horizontal line indicates the upstream solar wind dynamic pressure (1.86 nPa) and the dash-dotted horizontal line indicates half of the solar wind dynamic pressure (0.93 nPa). According to the Plaschke criterion, the observed feature with \( P_{\text{dyn,x}} \geq 0.93 \) nPa are jets. In approximately 30 minutes after the development phase, we observed many jets passing through both observers in our simulations, some of them are labeled with numbers in the top panels in Figure 8. The identified jets vary in duration, ranging from a few seconds (e.g., jets #1, #6, and #9) to several minutes (e.g., jets #7, #8, and #10).

Nevertheless, it is essential to recognize that the intricate 3D structure of the jets, as obtained from our simulation results (illustrated in Figures 2–7 and the accompanying supplementary movies), indicates that some of the identified jets in Figure 8 could be components of the same jet. These components may undergo fragmentation and recombination, and appear as seemingly a new jet at later times in the “1D view” presented in Figure 8. This statement also holds for the previous spacecraft observations of magnetosheath jets.
Figure 8. The temporal evolution of various quantities examined at the position of two stationary virtual observers located within the magnetosheath in our hybrid simulations: (a–e) results at the first observer located downstream of the bow shock at (+11.5, 0.0, −1.0) \( R_E \), and (f–j) results at the second observer positioned upstream of the magnetopause at (+10.0, 0.0, +3.5) \( R_E \). (a, f) Proton dynamic pressure, \( P_{dyn} = m n_{sw} v^2 \), is shown by the solid black line, and the proton dynamic pressure along the solar wind flow direction, denoted as \( P_{dyn,x} = m n_{sw} v_{sw,x}^2 \), is shown in red. The dashed horizontal line shows the upstream solar wind dynamic pressure, 1.86 nPa, and the dash-dotted horizontal line marks half of the solar wind dynamic pressure, 0.93 nPa. Several magnetosheath jets, where their \( P_{dyn,x} \geq 0.93 \) nPa are labeled with numbers. (b, g) Proton density, (c, h) three components of the proton velocity, (d, i) three components of the magnetic field, and (e, j) differential proton energy flux (“Eflux”) as a function of energy and time. The initial phase of the magnetosphere development in our model is highlighted in green (i.e., the first 7.5 minutes). Subsequently, the IMF aligns quasi-parallel to the solar wind flow in the \( xy \) plane (run R1Y). After approximately 22 minutes the current sheet reaches the first observer, and nearly one minute later it arrives at the second observer. After this, the IMF exhibits a southward orientation for more than 15 minutes (run R1S). The period encompasses both the R1Y and R1S simulations, during which a current sheet (magnetic transient) traverses Earth’s magnetosphere is highlighted in red. Also, see Figure S6 in the supplementary materials for the upstream observer.
Comparing Figure 8a with Figure 8f, we observe more jets near the bow shock than near the magnetopause, which is consistent with previous observations (Archer & Horbury, 2013; Plaschke et al., 2013; Goncharov et al., 2020). In addition, our simulations demonstrate that jets can form during stable IMF configurations, which confirms earlier observations that did not directly relate the formation of the jets to magnetic transients (Archer & Horbury, 2013; Plaschke et al., 2013). For example, all labeled jets, except #5, formed during a constant and stable IMF. During the transient event, however, we also observe the passage of a jet through the first observer near the bow shock (i.e., jet #5), which may or may not have been formed by the transient event. Investigating the formation mechanism of the jets is beyond the topic of this research and will be conducted in a separate study.

Noteworthy characteristics of jets can be seen in the second and third rows in Figure 8. Consistent with previous observations (Archer & Horbury, 2013; Plaschke et al., 2018), some jets exhibit a substantial rise in plasma density (e.g., jets #3, #7, and #10), while others do not display significant changes (e.g., jets #2, #4 and #11). However, all identified jets shown in Figure 8 demonstrate a substantial increase in their flow velocity. In particular, the $x$-component of velocity during the passage of nearly all jets, as shown by the red lines in Figures 8c and 8h, reaches $\sim 200 \text{ km/s}$ and beyond, which aligns with earlier observations (Archer & Horbury, 2013; Plaschke et al., 2013; Gunell et al., 2014; Karlsson et al., 2015). Furthermore, Figures 8d and 8i illustrate magnetic field variations, which may be associated with jets, as observed in spacecraft data (Plaschke et al., 2020). However, we collected the simulated magnetic field data at the location of our virtual observers with a frequency of 0.33 Hz, which is not high enough to pursue wave analysis. The energetic behavior of jets can also be distinguished in the energy-time spectrogram obtained from our kinetic simulations, shown in Figures 8e and 8j. Consistent with previous spacecraft observations (Hietala et al., 2009; Archer et al., 2012; Archer & Horbury, 2013; Plaschke et al., 2013; Dmitriev & Suvorova, 2012; Plaschke et al., 2018; Raptis, Karlsson, Vaivads, Lindberg, et al., 2022), the identified jets in our simulations exhibit a higher energy flux and lower plasma heating compared to the classical structure of the magnetosheath plasma without jets.

4 Discussion and Conclusions

We present the first 3D, global, hybrid-kinetic plasma interaction between the solar wind plasma and Earth’s magnetosphere at its physical scales using Amitis, a high-performance GPU-based hybrid-kinetic plasma framework (Fatemi et al., 2017). While MHD models
have been extensively applied for decades to study the solar wind interaction with Earth
(e.g., Den et al., 2006; Lopez et al., 2011), the kinetic nature of the interaction, for example,
the formation of an extensive foreshock during quasi-parallel IMF configurations cannot be
explained by MHD models. Moreover, earlier kinetic simulations applied to this problem
are either 2D models (e.g., Hao et al., 2016; Omidi et al., 2016; Palmroth et al., 2018; Suni
et al., 2021; Guo et al., 2022) and/or have scaled down the size of the magnetosphere or
the solar wind parameters to reduce the computational costs (e.g., Karimabadi et al., 2014;
Omidi et al., 2016; Ng et al., 2021; Omelchenko et al., 2021).

In addition, we present the first 3D structure of magnetosheath jets. Consistent with
previous observations and numerical simulations, we show that magnetosheath jets appear
during stable IMF configurations, and therefore, should not be merely related to transient
events in the solar wind. In contrast to earlier findings and analyses, our investigation
demonstrates that these jets do not have a simple geometry like a cylinder, sphere, or
pancake. Instead, they exhibit a complex 3D and dynamic structure, interlinked in a highly
intricate manner. They repeatedly merge into and split from each other, encompassing a
broad spectrum of dimensions, and reach the magnetopause over a spatially large area (see
Movie S1, S2, and S3 in the supplementary materials for more details).

Previous 2D simulations of the magnetosheath jets (Gutynska et al., 2015; Hao et al.,
2016; Palmroth et al., 2018; Preisser et al., 2020; Palmroth et al., 2021; Suni et al., 2021;
Guo et al., 2022) may provide a misleading impression of the structure, size, and time-
evolution of jets due to their 2D perspective and the lack of the third dimension. Moreover,
3D simulations without realistic scales for Earth (Omelchenko et al., 2021) did not yield
definitive findings concerning the morphology of jets, primarily due to scaling factors applied
to the size of Earth and/or the strength of Earth's magnetic dipole. However, our simulations
with physical scaling of Earth's magnetosphere reveal that jets are intricate, dynamic, and
indeed, 3D structures.

By analyzing the results from our single-point measurements, presented in Figure 8,
we lack additional information about the 3D spatial arrangement of jets. This arrangement
resembles spacecraft observations that probe only a small spatial area at once, and therefore,
provide a limited “1D snapshot” view of jets. Consequently, by using the spacecraft data
we cannot definitively determine if the observed jets are numerous individual entities, or
if they are fewer in number with some being components of an interconnected structure,
akin to the examples illustrated in Figures 4–7. This indicates the significance of utilizing 3D kinetic simulations for the magnetosphere to comprehensively explore the morphology of the jets.

Through the exploration of the 3D structure of magnetosheath jets, we can improve our knowledge of the Earth’s magnetosphere and its interaction with the solar wind. In addition, recent studies have provided compelling evidence for the formation of magnetosheath jets in planetary magnetospheres beyond our own (Gunell et al., 2023). Therefore, our research not only advances our understanding of magnetosheath jets within the magnetosphere of Earth but also offers valuable insights into analogous phenomena occurring in other planetary magnetospheres. This can open new windows for comparative planetary research.

Open Research Section

The simulation data presented in this manuscript is archived at Zenodo, and publicly accessible via https://doi.org/10.5281/zenodo.8421137. In addition, simulation data other than those shown in the article and archived on Zenodo, if available, are readily accessible upon request to the corresponding author.

Acknowledgments

Funding: The authors acknowledge financial support from the Swedish National Space Agency (SNSA) grant 2022-00138. S.F. also acknowledges financial support from SNSA grant 115/18, the Swedish Research Council (VR) grant 2018-03454, and Nvidia’s Academic Hardware Program, grant RTX-A6000. M.H. & E.K. also acknowledge financial support from VR grant 2018-03623.

Computation resources: The computations were primarily enabled by the Berzelius resource provided by the Knut and Alice Wallenberg Foundation (KAW) at the National Supercomputer Centre (NSC), Linköping, Sweden. They were partly conducted through computation and data storage resources at the High Performance Computing Center North (HPC2N), Umeå University, Sweden, and partly through infrastructure and hardware grants awarded through “Kempestiftelserna” and “medeldyr utrustning” at Umeå University, Sweden. S.F. acknowledges Prof. Paolo Bientinesi, Mr. Åke Sandgren, and Mr. Björn Torkels-
son at HPC2N for their unconditional support and assistance in providing hardware for running the Amitis code on the Kebnekaise supercomputer.

**Author contributions:** S.F. is the developer of the Amitis code, planned and ran all the simulations, performed the analyses, made the figures, and wrote the first draft of the paper. S.F. and E.K. developed the post-processing and visualization tools for Amitis simulations. All authors contributed to the discussions and interpretation of the results and improvement of the analyses. They also contributed to editing and improving the text of this manuscript.

**References**


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Shue, J.-H., Chao, J.-K., Song, P., McFadden, J., Suvorova, A., Angelopoulos, V., ...


Figure 2.
Figure 3.
Figure 4.
Figure 7.
Figure 8.
Supporting Information for “Unveiling the 3D Structure of Magnetosheath Jets”

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1. Figures S1 to S6

Additional Supporting Information (Files uploaded separately)

1. Captions for Movies S1 to S5

Introduction Here, we present figures and movies that provide supporting information to the main text and figures in our manuscript.

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Movie S1.

Amitis hybrid-kinetic simulation results presented in the GSM coordinate system for the R1Y simulation from time 640 s (i.e., 10:40) to 1200 s (i.e., 20:00) in the $xy$ (equatorial) plane at $z = 0$. The background color, similar to Figure 2 in the main text, shows plasma dynamic pressure in logarithmic scale, normalized to the upstream solar wind dynamic pressure, $P_{sw} = 1.86 \text{nPa}$. The sphere centered at the origin of the coordinate system represents the inner boundary of our simulation at 4.7 $R_E$ with a projected plasma flux precipitating into the inner boundary, normalized to the solar wind flux $F_{sw} = 2.8 \times 10^{12} \text{m}^{-2} \text{s}^{-1}$. The solid black contour lines show $P_{dyn,x} = 0.5 P_{sw}$, i.e., the Plaschke criterion for identifying magnetosheath jets, explained in the Model and Methods section in the main text.

Movie S2.

Similar to Movie S1, but showing different quantities. In this movie, the background color shown in the $xy$ plan illustrates the $y$-component of the electric current density, $J_y$ in the units of $nA/m^2$. The sphere shows the inner boundary of our simulation at 4.7 $R_E$ with projected field-aligned currents (FAC) at the boundary.

Movie S3.

Amitis hybrid simulation results obtained from run R1Y from time 640 s (i.e., 10:40) to 1200 s (i.e., 20:00) in the GSM coordinate system, presenting the dynamic pressure normalized to the upstream solar wind dynamic pressure, $P_{sw} = 1.86 \text{nPa}$ in the $yz$ plane at $x = +11.5 R_E$, similar to the time snapshot shown in Figure 4c in the main text. The
geometry of the plan is similar to those shown in Figure 4 in the main text.

**Movie S4.**

Amitis hybrid-kinetic simulation results show the global structure of the solar wind plasma interaction with Earth. The background color shows the magnitude of the magnetic field in logarithmic scale in (left) the $xy$ plane at $z = 0$ and (right) the $xz$ plane at $y = 0$, both presented in the GSM coordinate system. The presented planes are perpendicular to each other, showing the 3D structure of the magnetic fields. The solar wind flows along the $-x$ axis (from right to left), shown by the yellow arrows. The orientation of the IMF is also shown by the white arrow on each plane. This movie shows in total 40 minutes of real-time solar wind interaction with Earth, covering the R1Y and R1S simulations. From time 00:00 to 14:20, the IMF is on the $xy$ plane with $B_z = 0$ (i.e., run R1Y). At time 14:20, a current sheet arrives at $x = +40 R_E$, where the IMF orientation changes southward without changing its initial magnitude (i.e., run R1S). After $\approx 7$ minutes, the current sheet reaches the dayside magnetosphere. Before the arrival of the current sheet, the ion foreshock region is visible upstream of the bow shock on the $xy$ plane. During the passage of the current sheet, the entire system including the foreshock, bow shock, and the magnetosphere, responds to the changes in the IMF orientation. After that, the foreshock region is mainly visible in the $xz$ plane. Since the magnitude of the IMF and solar wind plasma parameters remain unchanged during the entire simulation, no signature of the current sheet is evident in this movie. The IMF magnitude is 5 nT, marked as $|B_{\text{IMF}}|$ on the color bar.
Movie S5.

Amitis hybrid-kinetic simulation results show the global structure of the solar wind plasma interaction with Earth. The background color shows the plasma density in logarithmic scale in (left) the $xy$ plane at $z = 0$ and (right) the $xz$ plane at $y = 0$, both presented in the GSM coordinate system. The geometry of the planes is similar to those presented in Movie S4. The solar wind plasma density is $7 \text{ cm}^{-3}$, marked as $n_{\text{sw}}$ on the color bar.
Figure S1. Hybrid simulation results in the $xy$ (equatorial) plane from a zoomed-in region to the white rectangle in Figure 2a in the main text. The geometry of the cuts is the same as those described in Figure 2. Both panels here were previously shown in Figure 3. Here, we have added more details to them that could not become apparent in Figure 3. (a) Similar to Figure 3c. The background color shows the $x$-component of the solar wind velocity, $v_x$, normalized to the upstream solar wind speed, $v_{sw} = 400 \text{ km/s}$. The streamlines show the direction of the plasma flow motion. Both jets have a forward velocity component towards the magnetopause, and a few Kelvin-Helmholtz-like vortices are visible in this panel, marked by arrows. (b) Similar to Figure 3f. The background color shows the magnitude of the magnetic field normalized to the strength of the IMF, $B_{IMF} = 5 \text{nT}$. The background streamlines together with arrows show the direction of the magnetic field. Inside the magnetosphere ($x \lesssim 9 R_E$), the magnetic field lines primarily point northward (outward in the plane shown), and therefore, only the arrowheads are visible.
Figure S2. Time evolution of the magnetosheath jets in the $xy$ plane at $z = 0$ obtained from our hybrid plasma model for the R1Y simulation setup. Background color is the normalized proton flux on a logarithmic scale. The streamlines show the direction of the plasma flow. The solid contour lines mark $P_{\text{dyn}} = 0.5 P_{\text{SW}}$. Several jets can be seen at different times, and, for example, two of them are marked by yellow arrows in panels c and d. In addition, a few Kelvin-Helmholtz-like vortices are apparent in several panels, and three of them are marked by pink arrows in panel e. The cyan dots denote the magnetopause boundary estimated from our simulations. The solid cyan and white lines, respectively, mark the magnetopause and bow shock boundaries from the empirical model by Chao et al. (2002). The geometry of the planes is similar to those presented in Figure 3 in the main text.
Figure S3. Hybrid simulation results obtained during the northward IMF (run R1N) at time $t = 3060 \text{s}$, presenting the dynamic pressure normalized to the upstream solar wind dynamic pressure in the $yz$ plane at different distances from the Earth’s center: (a) $x = +11.25 \, R_E$, (b) $x = +11.0 \, R_E$, (c) $x = +10.75 \, R_E$, and (d) $x = +10.5 \, R_E$. The figure format is the same as that shown in Figures 4 and 6 in the main text.
Figure S4. Hybrid simulation results obtained from run R1Y in the yz plane at $x = +11.5\, R_E$ at six different simulation times: (a) 672 s, (b) 696 s, (c) 720 s, (d) 744 s, (e) 768 s, and (f) 792 s. The background color illustrates the normalized dynamic pressure. The solid black contour lines highlight $P_{\text{dyn,x}} = 0.5\, P_{\text{sw}}$ (i.e., the Plaschke criterion for identifying magnetosheath jets), and the black dots indicate the bow shock boundary obtained from our simulations, explained in the Materials and Methods section. The magnetosheath is the region surrounded by the bow shock boundary, and the jets are the filamentary structures with dynamic pressure $\geq 0.5\, P_{\text{sw}}$ in the magnetosheath. The figure format is the same as that shown in Figure 7.
Figure S5. Hybrid simulation results when the IMF is perpendicular to the solar wind (run R2), obtained at time $t = 900$ s, presenting the dynamic pressure normalized to the upstream solar wind dynamic pressure, $P_{sw} = 1.86$ nPa in the (a) $xy$ plane at $z = 0$ and in the (b) $xz$ plane at $y = 0$. The solar wind and IMF orientations at different planes are shown by gray arrows. In panel b, the solar wind convective electric field, $\mathbf{E} = -\mathbf{v} \times \mathbf{B}$, is pointing upward along the $+z$ axis. The white arrow in panel b points to the quasi-perpendicular shock where many small irregular filamentary features, somewhat similar to the magnetosheath jets, are evident downstream of the quasi-perpendicular shock at the $+E$ hemisphere of the magnetosphere. Identifying the nature and characteristics of these filamentary structures are outside the scope of the current study, and will be investigated in a separate research.
Figure S6. The temporal evolution of (a) plasma dynamic pressure, (b) proton density, (c) proton velocity, (d) magnetic field, and (e) differential proton flux, examined at the position of a stationary virtual observer located in the solar wind and far away from any magnetospheric and foreshock disturbances at (+47.1, +18.8, 0.0) $R_E$. The magnetic transient (current sheet) arrives at the observer at time $\approx 12:30$, highlighted in red. The description of different panels is the same as that shown in Figure 8 in the main text. We intentionally did not place the observer only along the $x$ axis to ensure the terrestrial disturbances do not reach the observer during the magnetic transients.