Modeling Star–Planet Interactions in Far-out Planetary and Exoplanetary Systems

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Abstract

The magnetized wind from a host star plays a vital role in shaping the magnetospheric configuration of the planets it harvests. We carry out three-dimensional (3D) compressible magnetohydrodynamic simulations of the interactions between magnetized stellar winds and planetary magnetospheres corresponding to a far-out star–planet system, with and without planetary dipole obliquity. We identify the pathways that lead to the formation of a dynamical steady-state magnetosphere and find that magnetic reconnection plays a fundamental role in the process. The magnetic energy density is found to be greater on the nightside than on the dayside, and the magnetotail is comparatively more dynamic. It is found that stellar wind plasma injection into the inner magnetosphere is possible through the magnetotail. We further study magnetospheres with extreme tilt angles, keeping in perspective the examples of Uranus and Neptune. High dipole obliquities may also manifest due to polarity excursions during planetary field reversals. We find that global magnetospheric reconnection sites change for large planetary dipole obliquity, and more complex current sheet structures are generated. We discuss the implications of these findings for atmospheric erosion, the introduction of stellar and interplanetary species that modify the composition of the atmosphere, auroral activity, and magnetospheric radio emission. This study is relevant for exploring star–planet interactions and its consequence on atmospheric dynamics and habitability in solar system planets and exoplanets.

Key words: magnetic reconnection – magnetohydrodynamics (MHD) – stars: winds, outflows

1. Introduction

The fate of a planetary system rests in the hands of the harboring star. The principal mode of interaction of a star with the planets it hosts is via the stellar wind (Matt et al. 2012; Alvarado-Gómez et al. 2016). The variability of the stellar wind strength—which is related to the stellar activity and position of the planet with respect to the star—is an important factor in dictating planetary effects. Adhering to the planetary classification convention (close-in or far-out) of Shkolnik (2013) based on the distance of the planet from the star, it has been found that planets in close-in orbits (<0.1 au) with their host star are subject to electromagnetic as well as gravitational interactions, i.e., tidal effects (Cuntz et al. 2000), which can make the planets move either inward or outward, due to the transfer of angular momentum (Strugarek et al. 2014, 2017). Cohen et al. (2009) showed that close-in star–planet interactions (SPIs henceforth) prevent the expansion of the stellar coronal magnetic field and the acceleration of the stellar wind. In order to study SPIs for the case of close-in planets using numerical simulations, both the planet and its host star are needed to be included in the computational domain (Cohen et al. 2009, 2011; Matsakos et al. 2015; Strugarek et al. 2015, 2017), as the magnetic fields of both entities get modified as a result of the interactions. The plasmoid loops trapped in between the solar and the planetary magnetic fields then tend to modify the coronal magnetic fields as well (Kashyap et al. 2008; Lanza 2009; Miller et al. 2012). For the case of fairly distant planets (≥0.5 au, e.g., Earth-like and beyond), the coronal magnetic field of the star is hardly affected, and only the planetary magnetosphere is expected to deform. For this scenario, the stellar wind can be approximated as an independent physical entity that affects the planetary dynamics (Tóth et al. 2004; Dong et al. 2015).

The planetary effects of SPIs are numerous (for a detailed review, see Strugarek 2017). The habitability of a planet depends on whether it is capable of retaining a sustainable atmosphere around itself (Seki et al. 2001; Barabash et al. 2007). The planetary magnetosphere serves as an invisible shield protecting the atmosphere. If the stellar wind is strong enough to penetrate the magnetosphere via magnetic reconnections, it might erode away a significant part of the atmosphere from the planet (Dong et al. 2017; Garraffo et al. 2017; Nortmann et al. 2019). The dynamic ram pressure of the wind is crucial in determining the distance from the planet at which reconnection events are possible. A larger ram pressure would sustain a smaller magnetopause and vice versa. Because the region outside the magnetopause is not shielded, any atmosphere (which we consider to be charge neutral) can be ionized and taken away by the energetic stellar wind. So, as the wind grows stronger, the ram pressure increases and therefore allows greater stellar wind penetration, first due to the compression of the magnetosphere, and second, due to the opening up of more closed field lines. Zendejas et al. (2010) presented an analytical model for the interaction between atmospheres of nonmagnetized planets and stellar winds from main-sequence M stars and was able to provide a prediction of the timescale for complete atmospheric loss. The magnetized SPIs might lead to enhanced radio emissions in the deformed magnetosphere of the planet (Zarka 2007). If the interplanetary magnetic field is able to penetrate the planet as a consequence of the interaction, ohmic dissipation may also lead to planetary heating (Laine et al. 2008).

The motivation for investigating interactions between Sun-like stars and Earth-like planets is based on practical considerations as well. The activity of the Sun affects our planet and, indirectly, our lives as well. Solar activity evolution
is of utmost importance as it controls the features of the solar wind. How the Sun changes over time (Nandy & Martens 2007; O’Fionnagain & Vidotto 2018; Pognan et al. 2018), and how evolving changes impact planets, is an important question. Observations have shown that very strong modulations in the solar wind occur over a period of roughly 1.3 yr (Richardson et al. 1994). In the near vicinity of the planet, variations in the solar wind intensity also depend on the position of the planet in its own orbit (Gómez et al. 1993) as well as its orientation with respect to the Sun (McComas et al. 2008). Prominent fluctuations in the planetary geomagnetic field orientation occur within a time range of less than 10 yr to periods of about $10^6$ yr (Cox & Doell 1964). Although geomagnetic field reversal is a rare event, the timescale of the duration of geomagnetic field reversals is only about 1000–6000 yr (Glatzmaier et al. 1999). Polarity excursions vastly affect the nature of magnetospheric deformation and magnetic reconnections during the interaction with the solar wind. The consequent effects are relevant for space weather variations (Schwenn 2006; Polkkinen 2007), geomagnetic storms (Dal Lago et al. 2006), aurora formation (Liou et al. 1998), and space missions (Kumar 2014).

Driven by the above motivations, we study the interactions between the wind from a Sun-like star and the magnetosphere of an Earth-like planet using three-dimensional (3D) compressible magnetohydrodynamic (MHD) simulations. As discussed earlier, keeping in mind the separation distance (~1.0 au) between the Sun and the Earth, the system can be considered to be a “far-out” system. Therefore, it is prudent to keep the star out of the computational domain and only consider interactions between an incoming stellar wind and the planetary magnetosphere, which is embedded in an interplanetary medium. The wind is assumed to be a pure shock and may have its intrinsic magnetic field oriented either northward or southward with respect to the direction of the planetary dipole axis. We use different values of the shock speed, which replicates the variability of the solar wind intensity over time. We also consider different inclinations, including the present Earth-like obliquity (referred to as “tilt” henceforth), of the planetary dipole axis with respect to the equatorial plane in order to mimic planets with highly tilted axes (such as Uranus and Neptune) or stages of polarity excursions during geomagnetic field reversals. Our main aim here is to perform a parameter space study to illustrate how SPI depends on the physical properties of the system and analyze the nature of magnetic reconnections that take place for different configurations of the star–planet system.

The structure of the paper is as follows. In Section 2, we describe the compressible MHD equations, which we use to simulate the plasma system along with estimates of the physical quantities that are used. The numerical setup and description of the entire computational domain are also briefly described in this same section. In Section 3, we present our results. In Section 4, we present the conclusions of this study.

### 2. SPI Model

The plasma system that we are simulating is governed by the adiabatic equation of state and the following set of resistive MHD equations:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \quad (1)$$

$$\frac{\partial \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) = \frac{1}{4\pi\rho} \mathbf{B} \times (\nabla \times \mathbf{B}) + \frac{1}{\rho} \nabla P = \mathbf{g}, \quad (2)$$

$$\frac{\partial E}{\partial t} + \nabla \cdot [(E + P) \mathbf{v} - \mathbf{B} (\nabla \times \mathbf{v}) + (\eta \cdot \mathbf{J}) \times \mathbf{B}] = \rho \mathbf{v} \cdot \mathbf{g}, \quad (3)$$

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \times (\mathbf{B} \times \mathbf{v}) + \nabla \times (\eta \cdot \mathbf{J}) = 0. \quad (4)$$

The variables $\rho$, $\mathbf{v}$, $\mathbf{B}$, $P$, and $E$ denote the density, velocity, magnetic field, pressure, and total energy density, respectively. The pressure $P$ is the sum total of the thermal pressure ($p_\text{th}$) and the magnetic pressure ($p_m = \mathbf{B}^2/(8\pi)$). $E$ stands for the sum total of the internal energy density, kinetic energy density, and magnetic energy density. The vector $\mathbf{g}$ is the acceleration experienced by the fluid due to the gravitational field of the planet. $\mathbf{J}$ is the current density given by $\nabla \times \mathbf{B}$, ignoring the displacement current. In our study, for simplicity, we consider a finite and isotropic magnetic diffusivity $\eta$, which is constant in space and time. Table 1 shows typical values of all the physical quantities used in our reference simulation and their corresponding notations. As shown in the table, we choose a value of magnetic diffusivity that falls within the range of realistic values as shown in earlier studies (Lyon et al. 1986; Wiechen et al. 1996; Raeder 1999).

In this study, we simulate the interaction of magnetized stellar wind with a planet hosting an intrinsic dipolar magnetic field. We use the 3D compressible MHD code software PLUTO (ver. 4.3; Mignone et al. 2007) to create an SPI module (SPIM) and solve the full set of resistive MHD equations (Equations (1)–(4)) in a Cartesian box filled with a magnetized ambient medium including a planet placed at the origin. For the Cartesian grid, the following axis convention was used: (a) the $x$-axis is taken to be aligned with the line connecting the centers of the star and the planet with the positive $x$-direction directed along the line connecting the star to the planet, (b) the $z$-axis is aligned with the zero-tilt dipole axis along the N to S magnetic poles (vertically up), and (c) the $y$-axis is obtained by considering a right-handed Cartesian system with the information from the $x$- and $z$-axis orientations. The origin (0, 0, 0) is chosen to be the center of the planet. Figure 1(a) shows a schematic representation of the computational domain and the

| Physical Quantity | Notation | Value Used |
|-------------------|----------|------------|
| Density in ambient medium | $\rho_{\text{amb}}$ | $1.5 \times 10^{-21}$ g cm$^{-3}$ |
| Pressure in ambient medium | $P_{\text{amb}}$ | $1.35 \times 10^{-3}$ dyne cm$^{-2}$ |
| Density in stellar wind | $\rho_{\text{sw}}$ | $4 \times 10^{-19}$ g cm$^{-3}$ |
| Stellar wind velocity | $v_{\text{sw}}$ | $11.8 \times 10^5$ cm s$^{-1}$ |
| Ambient medium velocity | $v_{\text{amb}}$ | 0.0 |
| Temperature | $T_0$ | $4 \times 10^4$ K |
| Adiabatic index | $\gamma$ | 5/3 |
| Orbital separation | $d_{\text{orb}}$ | 1.0 au |
| Planetary mass | $M_\text{pl}$ | $5.972 \times 10^{24}$ g |
| Planetary radius | $r_\text{pl}$ | $6.371 \times 10^6$ cm |
| Planetary dipole moment | $B_0$ | 0.31 G |
| Magnetospheric tilt angle | $\Theta_{\text{pl}}$ | 0°, 11°, 45°, 90° |
| Stellar wind magnetic field | $B_{\text{sw}}$ | $4 \times 10^{-5}$ G |
| Magnetic diffusivity | $\eta$ | $10^{13}$ cm$^2$ s$^{-1}$ |
coordinate convention chosen. The dashes at the midpoint of the edges of the box along the z-axis indicate that the dimensions are not to scale. The diagram simply serves the purpose of qualitatively representing the axial orientation for ease of understanding the various directionalities that we use in the rest of the paper. We simulate our system until it reaches a steady state. We have used an HLL Riemann solver with linear interpolation in space, a MINMOD limiter, and a second-order Runge–Kutta for temporal update. We impose the \( \nabla \cdot \mathbf{B} = 0 \) condition by using the divergence-cleaning method, an approach based on the generalized Lagrange multiplier formulation (Dedner et al. 2002). A constant value of magnetic resistivity \( \eta \) is used in our model as the causal mechanism for non-ideal processes like magnetic reconnections that are prevalent in regions of interaction of winds with the planetary atmosphere. A super-time-stepping scheme is implemented for our simulations (Vaidya et al. 2017).

2.1. Grid Configuration

The computational domain extends from \(-45R_E\) to \(225R_E\) in the x-direction, from \(-25R_E\) to \(25R_E\) in the y-direction, and from \(-225R_E\) to \(225R_E\) in the z-direction. Static mesh refinement is implemented in all three directions near the vicinity of the planet of radius \(1.0R_E\) placed at the origin \((0, 0, 0)\). The grids marked in white, pink, and green are square grids while those marked in yellow and blue are rectangular grids. Maximum grid resolution is obtained in a cube of dimension \(4.0R_E\) containing the planet.

Figure 1. (a) Schematic diagram of the computational domain used for our star–planet interaction simulation. The planet lies within the domain while the stellar wind comes in through the left boundary (yz plane) with a velocity perpendicular to the plane of entrance. (b) Grid configuration in a zoomed-in portion of the computational box is shown (xz slice at \(y = 0\)). The x- and z-axes are in units of \(R_E\). Static mesh refinement is implemented in all three directions near the vicinity of the planet of radius \(1.0R_E\) placed at the origin \((0, 0, 0)\). The grids marked in white, pink, and green are square grids while those marked in yellow and blue are rectangular grids.
some parts of the computational domain as shown in Figure 1(b). The grids in the vicinity of the planet are always square in shape.

2.2. The Planet and Its Atmosphere

Within the sphere, defined by the planetary radius $r_{\text{pl}}$, we maintain a steady density profile ($\rho_{\text{pl}}$), which is $10^6$ times the density of the ambient medium ($\rho_{\text{amb}}$):

$$\rho_{\text{pl}} = 10^6 \rho_{\text{amb}}, \text{ for } r \leq r_{\text{pl}}.$$  

(5)

Beyond the planetary radius, we set an atmosphere that extends up to $r = 3r_{\text{pl}}$. The density profile in the planetary atmosphere is chosen to ensure a smooth transition between the density values at the boundaries $r = r_{\text{pl}}$ and $r = 3r_{\text{pl}}$.

$$\rho_{\text{atm}}(r) = \rho_{\text{pl}} + \frac{(\rho_{\text{amb}} - \rho_{\text{pl}})}{2} \left[\tanh \left(9 \frac{r}{r_{\text{pl}}} \right) - 2 \right] + 1 \text{ for } r_{\text{pl}} \leq r \leq 3r_{\text{pl}},$$  

(6)

where $\rho_{\text{pl}}$ and $\rho_{\text{amb}}$ are the densities of the planet and the ambient medium, respectively. The above choice of density results in a planetary atmosphere with a mass equal to $2.8 \times 10^{10}$ g. The gravitational field in the entire computational domain is due to the total mass of the planet (which is the same as the mass of the Earth) as given in Table 1. The mass is assumed to be a point mass kept at the center of the planet (at $r = 0$), and accordingly, the gravity is given by

$$g(r) = -\frac{GM_{\text{pl}}}{r^2}.\quad (7)$$

The pressure distribution in the atmosphere is found by numerical integration of the equation

$$\frac{dP}{dr} = -\rho_{\text{atm}}(r)g(r).\quad (8)$$

The pressure inside the planet is evaluated by extrapolating the value of pressure at the planet–atmosphere boundary as found from the numerical integration. Figure 2 shows the density and pressure profiles that are fed as initial conditions. In the density profile in Figure 2(a), the function (6) has been plotted in the atmosphere. The density in the planet ($\rho_{\text{pl}}$), however, is not that of the actual Earth, but is kept continuous with the density of the atmosphere at the planet–atmosphere boundary so as to avoid any spurious simulation results, due to sharp density jumps. The atmospheric pressure profile in Figure 2(b) is a result of numerical integration of Equation (8), while that inside the planet is a simple extrapolation. It is important to note here that the planet is treated as an internal boundary, and therefore, all of the physical quantities inside the planet are essentially held at constant values as provided by the initial conditions. The above equations describe a gravitationally stratified atmosphere in hydrostatic balance with the planet and the ambient medium. We emphasize therefore that this atmosphere obtained is physical and a close approximation of that of an Earth-like planet.

A dipolar planetary magnetic field aligned along the $z$-axis is initialized throughout the domain. For zero-tilt ($\Theta_{\text{pl}} = 0$), the magnetic dipole axis is aligned with the geographical axis that passes through the north and south poles of the planet. The following equations are used to initialize the three components of the dipolar magnetic field on the surface of the planet and outward:

$$B_x = -B_0 r_{\text{pl}}^3 \left(\frac{3xz - r^2}{r^5}\right) \cos \Theta_{\text{pl}} - B_0 r_{\text{pl}}^3 \left(\frac{3y^2 - r^2}{r^5}\right) \sin \Theta_{\text{pl}},$$

(9)

$$B_y = -B_0 r_{\text{pl}}^3 \left(\frac{3y^2}{r^5}\right).$$

(10)

$$B_z = -B_0 r_{\text{pl}}^3 \left(\frac{3xz - r^2}{r^5}\right) \cos \Theta_{\text{pl}} + B_0 r_{\text{pl}}^3 \left(\frac{3xz}{r^5}\right) \sin \Theta_{\text{pl}}.$$  

(11)

Here, $B_0$ denotes the magnetic dipole moment; $B_x$, $B_y$, and $B_z$ denote the three components of the 3D magnetic field vector; $r$ is the radial distance from the center of the planet; and $r_{\text{pl}}$ is the radius of the Earth-like planet (same size as that of Earth, $R_{\text{pl}} = 6.37 \times 10^8$ cm). The static mesh refinement is shifted by a small offset to avoid singularities in the magnetic fields at the origin $x = y = z = 0$. The unperturbed planetary dipole magnetic field is applied as a background field, and additionally, the region inside the planet is treated as an internal boundary where the dynamical equations are not evolved. For the purpose of this study, we use $\Theta_{\text{pl}} = 0^\circ, 11^\circ,$
45°, and 90°. It is to be noted here that for nonzero dipole tilt, the magnetic dipole axis of the planet does not pass through its geographic north and south poles but with an angle the magnetic dipole axis of the planet does not pass through its geographic axis using its left-hand direction (i.e., internal to its surface). Within the planet, the magnetic field is not allowed to evolve over time. This allows us to keep a steady planetary dipole throughout the duration of our simulation as we are not considering planetary dynamo action in our simulations.

2.3. Ambient Medium

We refer to the region \( r > 3r_{pl} \) to be the ambient medium. To model the initial magnetic field in this region, we use the same expression as the planetary dipole (see Equations (9) through (11)). The density is initialized throughout the ambient medium to be \( \rho_{amb} = \rho_{sw} \) while the pressure is set to the thermal pressure in this region as given in Table 1 for \( p_{amb} \). We start our simulation with the planet and its perfectly dipolar magnetic field in a static interplanetary medium. The evolution of the plasma properties of the ambient medium and consequent magnetospheric changes can therefore be induced only by the impact of the magnetized stellar wind.

2.4. Stellar Wind

The stellar wind is injected from the left boundary perpendicular to the \( yz \) plane (\( x = -45R_G \)). For all other boundary faces of the Cartesian box, we implement the free-flowing boundary conditions. The wind may have its magnetic field oriented either southward (S-IMF) or northward (N-IMF) with respect to the planetary geographical axis (along the \( z \)-direction). The input parameters at the stellar wind injection boundary are obtained by solving the Rankine–Hugoniot jump conditions for the given shock velocity.

3. Results

3.1. Benchmarking the Model: Magnetopause Standoff Distance

To check the robustness of the model, we carry out some sanity checks and reproduce certain theoretically expected features. We first explore the path to a steady-state magnetospheric configuration attained by the system in a particular simulation. Figure 3 shows the temporal evolution of global quantities such as kinetic, thermal, and magnetic energies normalized by their respective equilibrium values at \( t = 76 \) minutes. It is observed that all quantities attain steady state after about 30 minutes of dynamics. The magnetic energy evolution is due to the deviation in the magnetic field from the unperturbed planetary dipole profile. The primary feature of the magnetosphere that dictates the protective environment around the planet is the magnetopause. The magnetopause surface is demarcated by the zones where the pressure balance condition is satisfied between the ram pressure of the wind and the magnetic pressure of the planetary field. According to the model suggested in Mead (1964), we use the following expression (Pudovkin et al. 1998):

\[
r_0 = \left( \frac{f^2 \mu_{pl}^2}{8k\pi nm_p v^2} \right)^{1/6},
\]

which quantifies the geocentric distance of the substellar magnetopause standoff distance. Here, \( f \) is used to account for the strengthening of the planetary dipolar field due to the magnetopause currents, and \( k \) is a correction factor introduced by Spreiter et al. (1968) to account for the nature of interaction of the stellar wind with the magnetopause and has been successively used in other studies (Pudovkin et al. 1998). The value of \( k \) as stated in Spreiter et al. (1968) is 0.88. The parameter \( \mu_{pl} \) stands for the planetary dipole moment, \( n \) and \( v \) are the number density and uniform velocity of the stellar wind particles, respectively, and \( m_p \) is the mass of proton.

Figure 4(a) shows a comparison between the theoretically expected values of magnetopause standoff distance obtained...
from its analytical expression (Equation (12)) and the results from our simulations. For this analysis, we have taken a range of stellar wind velocities obtained by varying the shock speed between $V_{\text{shock}} \approx V_0$ and $V_{\text{shock}} \approx 8V_0$. Here, $V_0 = 350 \text{ km s}^{-1}$ is the value of the slow solar wind at 1 au.

So, in effect, we explore a range of speeds almost an order of magnitude in spread (i.e., for more active stars, e.g., a younger Sun). The S-IMF and N-IMF cases are plotted for the same wind speed. The plot shows that the results from both the N-IMF and S-IMF cases follow the same trend as shown by the analytical expression (Equation (12)). However, for all values of wind velocities, the standoff distance obtained from simulating the S-IMF case is seen to be slightly shorter than the theoretical expectation. On the other hand, N-IMF data...
points are consistently slightly above the theoretically expected values (Pudovkin et al. 1998). For the S-IMF case, this can be attributed to the inward shift of the magnetopause layer due to magnetic reconnection at the substellar point, which allows for greater penetration on the dayside magnetosphere. For N-IMF, on the other hand, the outward migration is on account of the clustering and external pressure of parallel magnetic field lines. Nevertheless, the points for each wind velocity are very close to the expected value. The theoretically expected standoff distance is approximately equal to the mean of the two simulated distances (from the N-IMF and S-IMF cases).

The trace of the magnetopause (in the \(xz\) plane) for different wind velocities for the S-IMF case is shown in Figure 4(b). As expected, we find that the magnetopause location migrates inwards toward the planet with an increase in wind velocity, which is also consistent with the result shown in Figure 4(a).

3.2. Magnetospheric Dynamics for Earth-like Tilt

In this subsection, we present results of the effect of stellar wind on a planetary magnetosphere with an Earth-like tilt for our reference simulation using \(V_{\text{shock}} = 4.5V_0\) (corresponding parameters are given in Table 1), i.e., for a somewhat active star compared to the present-day Sun. Furthermore, we study the possibility of any plasma injection from the stellar wind into the planetary atmosphere, which might be important for its evolution. We also investigate the extent of atmospheric mass loss as a result of the interaction.

3.2.1. Evolution Leading to the Establishment of a Steady-state Magnetosphere

Figure 5 presents the temporal evolution of the interaction between the stellar wind and the planetary magnetosphere. We start from an unperturbed planetary dipole in the computational domain (as described in Section 2) and impose the stellar wind at \(t = 0\). The magnetospheric evolution for S-IMF (left column) and N-IMF (right column) for the same time instants are depicted. The 3D volume rendering depicts the density, while the magnetic field streamlines are plotted in black. It is to be noted here that while plotting the streamlines, their sources of origin have been kept on the \(xz\) plane (please refer to Section 2 for the coordinate convention used) with no constraint on their integration.

Let us discuss the S-IMF case first. At \(t = 6.1\) minutes (Figure 5(a)), the wind has just crossed the planetary magnetosphere. The opposite orientations of the stellar and planetary field lines facilitate easy reconnections near the polar region. The nightside lobe at the far end remains unaffected. At \(t = 30.3\) minutes (Figure 5(b)), the wind has traversed the entire length of the computational box. The volume plot shows the slow spread in density due to the interaction. On the nightside just behind the planet, a small magnetotail is formed, due to pinching of planetary field lines. This magnetic reconnection also results in the formation of plasma blobs that are advected out of the domain by the outgoing wind. The field lines leaving the upper and lower boundaries of the box originate from the planet due to reconstructions. In Figure 5(c) \((t = 54.6\) minutes\), purely stellar field lines are now found at the right end. The system approaches steady-state configuration in Figure 5(d) at \(t = 76\) minutes. The magnetotail stretches out longer in the nightside. Steady-state 2D profiles of pressure, magnetic field strength, and velocity for the S-IMF case are given in the left column of Figure 6.

The N-IMF case is more complicated. At \(t = 6.1\) minutes (Figure 5(e)), the dayside lobe gets compressed by the incoming wind, and no reconnections occur in this region as the stellar and planetary field lines are oriented in the same direction. At \(t = 30.3\) minutes (Figure 5(f)), pinching of planetary field lines on the nightside gives rise to a magnetotail and a plasma blob at the far-right end of the domain. The stellar field lines enter from the lower boundary, curl around the magnetosphere, and leave the upper boundary. The reconstructions of these stellar field lines occur with the upper and lower planetary lobes. At \(t = 54.6\) minutes (Figure 5(g)), the magnetosphere reaches a compact form, surrounded by purely stellar field lines. At the steady state in Figure 5(h) \((t = 76\) minutes\), the configuration remains almost similar to the earlier state. However, at the nightside near the planet, the field lines get strongly twisted before leaving the domain. Steady-state 2D profiles of pressure, magnetic field strength, and velocity for the N-IMF case are given in the right column of Figure 6. For both the S-IMF and N-IMF cases as presented in Figure 6, we observe a bow shock in front of the dayside magnetospheric lobe of the planet at about \(-20R_E\). The \(x\)-component of velocity decreases suddenly just right of the bow shock and then increases gradually as we move farther away from the planet at the nightside. The asymmetry about the equatorial plane in all profiles is introduced due to the dipole tilt. Further illustration regarding the steady-state field dynamics can be found in Section 3.3.

Figure 7 shows the spatial distribution of the three components of the deviation \((B_{\text{dev}})\) from the unperturbed dipolar magnetic field vector \((B_{\text{dipole}})\) as a result of the stellar wind interaction, \(B_{\text{total}} = B_{\text{dipole}} + B_{\text{dev}}\). For the \(B_{\text{dev}}\) profiles along \(x\)-axis, we keep \(y = z = 0\). Similarly, for plotting along \(y\)-axis, \(x = z = 0\) and for plotting along the \(z\)-axis, \(x = y = 0\). Therefore, if a satellite carrying a magnetometer moves along the \(x\)-axis, the deviations of the total recorded magnetic field from the tilted dipole are expected to approximately match those in the profiles shown in the topmost plots in Figures 7(a) and (b). Similarly, while moving along the \(y\)- and \(z\)-axes, the profiles should resemble the middle and bottom plots, respectively, in Figures 7(a) and (b). The profiles along the \(x\)-axis show a considerable asymmetry about the origin (those along the \(y\)- or \(z\)-axis are either a mirror image about the plane perpendicular to the respective axis or a mirror image about the origin). Along the \(x\)-axis, the deviation of the \(x\)-component of the magnetic field \(B_x_{\text{dev}}\) is quite large in the nightside as compared to the deviation in the other two components. However, the profile of \(B_x_{\text{dev}}\) is entirely different for the S-IMF and N-IMF cases. Starting from \(x = 0\) and moving along \(+x\), \(B_x_{\text{dev}}\) remains positive for S-IMF, due to the open field lines at the far end (please see Figure 5(d)). On the other hand, for N-IMF, \(B_x_{\text{dev}}\) flips sign at the position where planetary field lines wrap around and purely stellar field lines begin at the right end (please see Figure 5(h)). The deviations in the other two components of the magnetic field are large near the vicinity of the planet in all three directions.

We also calculate the magnetic energy density \(\epsilon_{\text{Earth-like}}\) for the Earth-like case (S-IMF) with respect to an unperturbed dipole for no wind \(f_{\text{no-wind}}\) as a function of radial distance from the center of the planet. To facilitate the understanding of our
Figure 5. Temporal evolution of the planetary magnetosphere with 11° inclination (Earth-like tilt) on the way to the steady state as a result of interaction with stellar wind for the S-IMF and N-IMF cases. The colormap of the 3D volume rendering depicts density in units of $1.5 \times 10^{-23}$ g cm$^{-3}$. The color bar applies to all the subplots in the figure.
output, we use a normalized energy density \( \epsilon^{(\text{norm})} = \epsilon_{\text{Earth-like}}/\epsilon_{\text{no-wind}} \). For our analysis, we consider concentric spheres \( (S_i) \) of incremental radius \( r = (3 + i)R_E \) around the Earth-like planet with \( i \in (0, 19) \). So, the innermost sphere has a radius of \( 3R_E \), while the outermost one is of radius \( 22R_E \). For the analysis of Figure 8, let us suppose that \( \phi \) denotes the azimuthal angle with \( \phi = 0 \) being along \( +\hat{\xi} \) and \( \phi = \pi \) along \( -\hat{\xi} \). Now, we find the space-averaged magnetic energy density \( \epsilon_i \) in each shell formed between two consecutive spheres \( (S_i \text{ and } S_{i+1}) \). We consider three kinds of shells: (a) \( Sh_{\text{day}} \): half shell in the dayside \( (\pi < \phi < 2\pi) \), (b) \( Sh_{\text{night}} \): half shell in the nightside \( (0 < \phi < \pi) \), and (c) \( Sh_{\text{total}} \): full shell \( (0 < \phi < 2\pi) \). This allows us to find the changes in relative contributions in energy density from the dayside sphere and nightside sphere as a function of radial distance. For \( Sh_{\text{day}} \), \( \epsilon^{(\text{norm})} - 1 \) decreases until around \( 12R_E \) and then becomes almost constant in the region outside the magnetopause. For \( Sh_{\text{night}} \), the magnetic energy density steadily increases and becomes proportional to radial distance \( [(\epsilon^{(\text{norm})} - 1) \sim r] \) from about \( 12R_E \). Thus, the contribution from dayside magnetic

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**Figure 6.** Steady-state 2D profiles of pressure (top row; in units of \( 1.844 \times 10^{-8} \) dyne cm\(^{-2}\)), magnetic field strength (second row; in units of \( 4.814 \times 10^{-4} \) G), and \( x \) (third row) and \( z \) (fourth row) components of velocity (in units of \( 3.5 \times 10^7 \) cm s\(^{-1}\)) for the S-IMF and N-IMF cases (Earth-like dipole tilt).
energy is much lower compared to that from the nightside. So, the plot of \( e_{\text{norm}} - 1 \) for a full shell, \( S_{\text{total}} \), follows a linear dependence on shell radius just as \( S_{\text{night}} \) but is shifted to lower values due to the subdued contribution from dayside. Kindly note that to evaluate the contribution for the full shell, the sum of the day- and nightside contributions has been normalized. On the dayside, the magnetospheric lobe is heavily compressed very near the planetary surface, due to the impact of the stellar wind. As a result, if we increase the shell radius, the magnetic energy density decreases and then eventually becomes constant outside the magnetopause, where only the stellar wind magnetic field is present. However, at the nightside, planetary field lines extend much beyond the magnetotail, due to advection by the wind, giving rise to relatively more complex and dynamic reconnections at the far-right end. Thus, the magnetic energy density increases with increasing shell radius on the nightside. Note that the value of \( e_{\text{norm}} - 1 \) determines whether the magnetic energy density as a result of the interaction is greater or lesser than that of an unperturbed dipole. For instance, if the value is positive, the energy density is greater than that of a dipole and vice versa. For a perfect dipolar profile, the value of \( e_{\text{norm}} - 1 \) will be zero. In the dayside, as the distance from the planet increases, the value falls slowly and then saturates to a negative value, which denotes the region where only stellar wind magnetic field lines are present. This is because the magnetic energy density of a purely stellar field is less than that of a planetary dipole. On the other hand, the value on the nightside increases slowly above zero with increasing distance because we have contributions from both stellar and planetary magnetic fields resulting from the interaction dynamics. Far away at the nightside where there are purely stellar field lines (with no contribution from the planetary magnetosphere), the value is expected to slowly drop with increasing distance and become constant at the negative value attained in the dayside. To capture this decay of magnetic energy density to the ambient value, one would require a much larger domain in the nightside, which is computationally prohibitive.

### 3.2.2. Atmospheric Mass Loss and Inner Magnetospheric Plasma Injection

The effects of SPIs are numerous. Important consequences are planetary atmospheric mass loss (Penz et al. 2008; Nortmann et al. 2019) and injection of stellar wind particles into the magnetosphere (Li et al. 2003; Atkinson 2004; Hietala et al. 2017). In our simulations, we have explored the possibility of plasma injection by analyzing large-scale flows but not particle motion. We initialize the stellar wind and atmosphere with independent passive scalars normalized to unity and then, study the evolution of the stellar wind as well as the atmosphere. The atmosphere shows mass loss due to the interaction while the inflow of wind plasma material is possible through the magnetotail.

Figure 9 shows different stages in the phenomenon of atmospheric mass loss, due to the impact of the stellar wind. The quantity plotted using 3D volume rendering is the product of density and atmospheric passive scalar. The frame at \( t = 0 \) (Figure 9(a)) shows the planet and its unperturbed atmosphere as the initial condition. As the incoming stellar wind interacts with the planetary magnetosphere, the atmospheric matter is slowly dragged off in the nightside as depicted in successive frames (Figures 9(b)–(f)) with increasing time. The asymmetry in the loss locations is due to the dipole tilt angle of 11°.

Figure 10 shows the temporal evolution of mass-loss rates as obtained from the simulation. A cube of dimension 6.6 \( R_\oplus \) (extending from \(-3.3 R_\oplus\) to \(+3.3 R_\oplus\) in all three directions) with its center coinciding with the center of the planet is considered. The box encompasses the planet and its atmosphere. Mass-loss...
rates are calculated at all six faces of the cube as given in Figures 10(a), (b), and (c). The total loss is plotted in Figure 10(d). It is found that the mass-loss rates increase first, reach a peak value, and then decrease steadily. The loss at the nightside is found to be greater than at the dayside as expected (Figure 10(a)). Because there is no asymmetry in the magnetospheric configuration in the \( y \)-direction, the loss rates are equal at both faces (Figure 10(b)). In the \( z \)-direction, the asymmetry is introduced by the dipole tilt (Figure 10(c)). The atmospheric mass-loss rate for hot Jupiter (which has a much larger radius and therefore, a larger surface area holding the atmosphere) was found by Penz et al. (2008) to be about \( 3.5 \times 10^{10} \, \text{g s}^{-1} \). In our case (Earth-like), the peak value of the mass-loss rate reaches about \( 2.3 \times 10^{7} \, \text{g s}^{-1} \). It is important to mention here that the energy measurements in Figure 3 are carried out in the entire computational domain while for evaluating planetary mass-loss rate, local measurements are considered in a small cube containing the planet (as given in Figure 10). Figure 11 shows the mass-loss rates from a cube with edge \( 6.6R_{\text{E}} \) (blue curve with circles), \( 24R_{\text{E}} \) (red curve with squares) and \( 44R_{\text{E}} \) (green curve with triangles). The center of the box coincides with that of the planet. For a small box \( (6.6R_{\text{E}}) \), the mass-loss rate peaks at a higher value initially relative to the boxes with edges of \( 24R_{\text{E}} \) and \( 44R_{\text{E}} \), but subsequently, all tend to converge. This is because for a larger box, it takes a longer time for the lost mass to reach the box faces, but as we approach steady state, the value of the mass-loss rate becomes independent of box size. The information within the computational domain propagates at the velocity of the stellar wind. Considering the distance between the center of the planet to the right end of the domain \( (225R_{\text{E}}) \) and the assumed stellar wind velocity \( (\sim 1200 \, \text{km s}^{-1}) \), the timescale in which the wind sweeps the entire domain comes out to be about 20 minutes. The curves in Figure 11 have not converged within the simulation time; however, they are tending toward a (dynamical) steady state in mass-loss rate. We therefore make the assumption that the simulations have reached an approximate steady-state scenario within our simulation timescale, i.e., 90 minutes (four and a half times the flow timescale).

Another notable effect of SPI is magnetospheric radio emission (Bastian et al. 2000), which mainly occurs due to electron cyclotron maser instability (Weber et al. 2017; Daley-Yates & Stevens 2018). Highly energetic electrons carried by the incoming stellar wind plasma get trapped in the auroral regions of the planet and radiate at the gyrofrequency of the planetary magnetic field lines. The only condition for such a phenomenon to occur is that the local plasma frequency must be lower than the gyrofrequency (Stevens 2005), as is the case for the Sun–Earth system. The radio emission usually occurs in a hollow cone at the polar regions and varies in nature depending on planetary properties (Farrell et al. 1999; Quinennec & Zarka 2001). The intensity of the magnetospheric radio emission can also be estimated, which is proportional to the radio power given by

\[
P_r = \delta \frac{M_* v_{\text{sw}}^2 R_{\text{eff}}^2}{4a^2}
\]

as used by Stevens (2005) and Daley-Yates & Stevens (2018). Here, \( \delta \) is the efficiency parameter, \( M_* \) is the stellar mass-loss rate, \( R_{\text{eff}} \) is the effective radius of the planetary magnetosphere as seen by the stellar wind, and \( a \) is the orbital radius. Here, \( \delta \sim 7 \times 10^{-6}, M_* \) for a Sun-like star is \( M_* \approx 1.268 \times 10^{12} \, \text{g s}^{-1} \), \( R_{\text{eff}} \) is the magnetopause standoff distance which is roughly \( 5R_{\text{E}}, a = 1 \, \text{au} \), and \( v_{\text{sw}} \) is from Table 1. The \( P_r \) value is
given by

$$P_{\text{r}} = 1.4 \times 10^{15} \, \text{erg s}^{-1} \left( \frac{\delta}{7 \times 10^{-6}} \right) \left( \frac{M_{\oplus}}{M_{\odot}} \right)$$

$$\times \left( \frac{v_{\text{sw}}}{11.8 \times 10^7 \, \text{cm s}^{-1}} \right)^2 \left( \frac{R_{\text{eff}}}{5R_{\oplus}} \right)^2 \left( \frac{a}{1 \, \text{au}} \right)^{-2}.$$ (14)

The above estimate for the radio power is for our reference simulation in which a stellar wind velocity of about three times the value of the typical slow solar wind velocity at 1 au is chosen. Also, the magnetopause standoff distance is half the typical value for our Sun–Earth system. Therefore, considering that the host star in our reference simulation has the same mass-loss rate as the Sun, the above radio power estimate of $1.4 \times 10^{15} \, \text{erg s}^{-1}$ will be about two times higher than that expected for the Sun–Earth system at 1 au. For the case of a hot Jupiter, Daley-Yates & Stevens (2018) estimated the radio power to be $1.42 \times 10^{19} \, \text{erg s}^{-1}$.

We assume that the considered exoplanet system is at a distance of 10 pc from our solar system and try to estimate whether the exoplanet may be observable at Earth, due to its radio emission as calculated above. Using the distance $D = 10 \, \text{pc} = 3.09 \times 10^{19} \, \text{cm}$, the emission power reaching Earth would be $P_{\text{r}}/D^2 = 1.47 \times 10^{-24} \, \text{erg cm}^{-2} \, \text{s}^{-1}$. Suppose the observations are made at a frequency of 1 MHz, the brightness of the exoplanet radio emission at Earth would be $1.47 \times 10^{-3} \, \text{erg Hz}^{-1} \, \text{cm}^{-2} \, \text{s}^{-1} = 147 \, \text{nJy}$. The brightness so obtained is below the sensitivity of most current instruments available. For instance, the Square Kilometre Array (SKA) (www.skatelescope.org) operates at a frequency range of 50 MHz–15.3 GHz (www.skatelescope.org/technical/info-sheets/). The telescope sensitivities are $1.2 \, \mu\text{Jy}$ at 12.5 GHz, $2 \, \mu\text{Jy}$ at 1.4 GHz, and so on. The sensitivity decreases as the operating frequency is lowered. Now, the frequency of the radio emission is equal to 2.8 times the planetary dipole moment, which is taken to be $0.31 \, \text{G}$. Therefore, the maximum possible frequency at which the radio emission from the above exoplanet system may occur is about $0.87 \, \text{MHz}$, which is much below the operating frequency range of SKA. Thus, we infer that SKA, with its present specifications, will not be able to detect the simulated exoplanet.

Figure 12(a) shows the plot of the stellar wind passive scalar density in the $xz$ plane at $y = 0$ for the S-IMF case after about 76 minutes of interaction. The red contour lines are used to denote $v_x = 0$. So, the contours encompass the regions of negative velocity in the $x$-direction, i.e., the inflow toward the planet through the magnetotail. This basically means that if any nonzero stellar wind passive scalar density portion lies within the contoured regions, there is a chance of stellar wind plasma getting injected into the planetary atmosphere as evident from the figure. This plasma can then be trapped in the closed field lines of the planet. The plasma particles can thereafter exhibit the phenomenon of magnetic mirroring (Kulsrud 2005), which results in its bouncing back and forth between the two poles of the planet. This continues as long as the particle trajectory satisfies an angle smaller than the pitch angle. In the instance where the angle between the particle’s trajectory with the local magnetic field exceeds the pitch angle, these particles can escape into the surrounding medium (which, near the poles, is the planetary atmosphere). Thus, particles reaching $10R_{\oplus}$ or less could potentially get trapped in the closed field lines and exhibit mirroring, and a certain fraction could be lost to the planetary or exoplanetary atmosphere. It is to be noted here that the asymmetry induced due to the introduction of the tilt facilitates greater inflow through the magnetotail and polar.
regions. The curve in Figure 12(b) shows the temporal evolution of the stellar plasma influx rate through the magnetotail in units of g s$^{-1}$. To estimate this, a square plane of dimension 10$R_E$ is placed at a distance of 10$R_E$ from the center of the planet in the nightside, and the mass influx rate through that plane toward the planet due to the stellar wind passive scalar is calculated. It is found that, after initial transients, the mass influx rate reaches a steady value of about 12.5 g s$^{-1}$.

3.3. Magnetospheres with Extreme Tilt Angles: Steady-state Reconnections

Most planets in our solar system have a moderately tilted dipolar axis which is comparable to that of Earth. Nevertheless, we also find planets where the dipole axis is extremely tilted, e.g., Uranus and Neptune (Russell & Dougherty 2010). Such planets hosting an intrinsic dipolar magnetosphere have a convective core (Glatzmaier et al. 1999), and the resulting geodynamo causes polarity reversals in the polarity of this dipole over geological timescales. The signatures of these polarity reversals are captured, for example, in magnetized rocks on the sea floor. However, such reversal incidents have not been directly observed. In this subsection, we present the steady-state configurations of the interactions between stellar wind and magnetospheres with no tilt and with extreme tilt angles (45° and 90°), and explore the reconnection configurations for both S-IMF and N-IMF cases. Thus, our simulations encompass the scenarios of (a) planets with a highly tilted intrinsic magnetosphere, and (b) phases during field reversals modeled by a simple dipole whose inclination increases with time. We explore the tilt angles up to 90°. This is because the relative orientation between the stellar field and the dipolar axis, for inclinations ranging from 90° to 180°, are the same as the orientations 0°–90° with the opposite $B_z$ in the IMF. Thus, we effectively capture a full reversal of the planetary dipole under the assumption that it remains dipolar during the reversal.

For each tilted dipolar magnetosphere, we impose the stellar wind and allow the simulations to reach a steady state. By steady state, we mean here the dynamical equilibrium configuration of the system at which the magnetic energy, kinetic energy, and thermal energy become nearly invariant with time. Figure 13 shows the steady-state magnetospheric configurations for the above-mentioned cases. The colormaps are identified by the magnitude of the current density. The reconnection regions show higher current density. The magnetic field streamlines are plotted in 3D. If the streamlines are plotted on a 2D slice, we are actually restricting the streamline integration to occur only within the slice of actually 3D data (magnetic field), which may give rise to unwanted artifacts.

Figure 13(a) shows the steady-state magnetosphere for no tilt and the S-IMF case as a standard for comparison. The dayside dipolar lobe is heavily compressed with a reconnection zone at the substellar point, due to which we observe high current density in this region. A slight enhancement in the current density, with respect to the background current, outlines the magnetospheric envelope, due to the curvature of magnetic
field in these regions. At the nightside, the pinching of planetary field lines leads to the formation of a magnetotail and purely stellar field lines at the right end of the box. The pinched region where reconnection occurs again shows higher current density. Thus, from our plots, we can associate the regions with high current density either with magnetic reconnection events or regions with highly curved magnetic field lines. In Figure 13(b), the N-IMF case for a no-tilt magnetosphere is shown. This depicts a magnetosphere that is more complicated relative to the case of S-IMF. The highly compressed dayside lobe is indicated by the high current density. The reconnection zones, unlike the S-IMF case, is located on the northern and southern lobes on the nightside magnetosphere. Mixed field lines either originate from the upper pole of the planet and leave through the lower boundary, or they originate from the lower pole and leave through the upper boundary of the box. Purely stellar field lines enter through the lower boundary, curl around the extended magnetosphere, and leave through the upper boundary.

In Figure 13(c), a tilt of 45° is introduced for the S-IMF case. Compared to the no-tilt cases, this case shows a highly complex structure based on the trajectory of the magnetic field streamlines. The asymmetry in the dayside current density map is clearly visible in the form of a dark blue region bordering the tilted dipolar lobe. The substellar reconnection zone is also shifted below the equatorial plane. The magnetotail is shifted above the equatorial plane along with the nightside reconnection zone. Purely stellar field lines form as a result of pinching of the planetary field lines and are found at the right end of the box (nightside). In the 45° N-IMF case (Figure 13(d)), very high current density is found in the north polar region. The magnetotail becomes very constricted due to the tilt. The reconnected field lines in this highly inclined dipole causes the open field lines to reach into the lower latitudes. This causes the reconnection events to induce plasma flow into lower latitudes.

In Figure 13(e), the magnetic north pole faces an incoming S-IMF wind. The reconnections occur on the upper lobe, leading to the formation of mixed field lines that leave the lower boundary on the dayside. Mixed lines originating from the magnetic south pole on the nightside leave through the right end of the box. A high current sheet region is found just below the equatorial plane where the pinching of planetary field lines takes place to give rise to purely stellar lines. The effect of an N-IMF wind on the 90° magnetosphere would just be a mirror image of the whole configuration about the horizontal.

4. Conclusions

In this paper, we have created an SPI module using the 3D compressible MHD code PLUTO and studied the effects of the impact of stellar wind on a planetary magnetosphere for a “far-out” star–planet system. The stellar wind is assumed to be a magnetized shock. We have considered the wind magnetic field to be either parallel (N-IMF) or antiparallel (S-IMF) to the planetary dipolar axis. The magnetopause standoff distance is matched with the expected value for various stellar wind velocities, which serves the purpose of benchmarking our code.

A planetary magnetosphere with an Earth-like tilt is first considered to provide a point of comparison for increasingly complex configurations. The temporal evolution of the interaction reveals numerous features about the magnetic reconnections that take place on the route to a dynamical equilibrium. For S-IMF, the steady-state magnetospheric configuration is not so complex. Reconnections occur at the
dayside while a magnetotail is formed at the nightside, due to the pinching of planetary field lines, and plasma blobs are sequentially ejected. On the other hand, for N-IMF, reconnections are mostly found at the polar regions, and highly twisted field lines form at the nightside. Deviations from the original dipolar profile are found primarily at the nightside, due to a large number of reconnection events in this region. The magnetic energy density with respect to that of the isolated dipolar magnetic field is found to be higher at the nightside, due to the clustering of field lines. The interesting features of the magnetotail dynamics demand a greater emphasis of spacecraft observations in this region to help us better understand the nightside interaction.

The injection of stellar and interplanetary plasma material into the planetary atmosphere may lead to the evolution of the planetary atmosphere with consequences for the habitability of the planet. We find the possibility of such inflow from the nightside magnetosphere. Our simulations show that inflow of stellar plasma into the inner magnetosphere is possible to within $x \approx 10R_E$ through the magnetotail at the nightside with a mass influx rate of $12.5 \, \text{g s}^{-1}$. This plasma can then be trapped in the closed field lines of the planet and get sucked.
into the atmosphere as a consequence of the phenomenon of magnetic mirroring (Kulsrud 2005). It is to be noted here that in order to study magnetospheric injection, we have only considered large-scale plasma flows and not particle dynamics (i.e., at the kinetic level). Such injection is known to lead to phenomena such as auroras and radio emission—which may be used to detect and characterize planetary or exoplanetary magnetospheres. We have also investigated atmospheric mass loss that occurs as a result of the interaction and have provided a quantitative estimate of mass-loss rates in different directions relative to the star–planet axis. It is found that the loss is much higher in the nightside than the dayside, as expected.

We have also considered magnetospheres with extreme tilt angles, which is relevant for planets such as Neptune and Uranus in our solar system. This configuration can also mimic stages in planetary field reversals assuming that the profile remains dipolar during such polarity excursions. The interactions show that the magnetic reconnection regions are usually associated with large current density although high currents may also be found in regions of highly curved magnetic fields or clustered field lines due to wind impact. Global asymmetry in the magnetospheric structure is induced for such high tilts. The nature of reconnections are quite different for the S-IMF and N-IMF cases. The implications are low-latitude auroral formation and altered cosmic-ray influx profiles. Reconnection-powered radiation (Uzdensky 2016) serves as an important tool for identifying or detecting magnetospheric configurations in exoplanets. As deduced from our results, such radiation zones are expected to be found at higher or lower latitudes depending on the magnetospheric tilt. Therefore, confronting such simulations with observations—whenever they become possible, would allow us to constrain the nature of exoplanetary magnetic dynamos and magnetospheres.
The results of our numerical simulations pave the way for understanding how stellar winds shape planetary magnetospheres for different structural configurations and the role that magnetic reconnection plays in this process.

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