The Dependence of the Venusian Induced Magnetosphere on the Interplanetary Magnetic Field: An MHD Study

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Abstract

The influences of the interplanetary magnetic field (IMF) on the induced magnetosphere of Venus are investigated using a global multispecies magnetohydrodynamics (MHD) model. The simulation results show that the induced magnetosphere is controlled by the IMF components perpendicular to the solar wind velocity (B_y and B_z in the Venus Solar Orbital Reference System), rather than the IMF magnitude (|B|). With the increase of (B_y^2 + B_z^2), the induced magnetosphere becomes stronger in field strength and thicker in spatial scale, and the bow shock locates farther from the planet. The parallel IMF component (B_x) has relatively small impacts on the magnetic barrier and the magnetotail, regardless of the various IMF magnitudes and orientations caused by different B_x. The responses of the Venusian induced magnetosphere to the change of upstream IMF are also studied. The time-dependent MHD calculations show that the dayside magnetosphere responds quickly with a timescale of 10–20 minutes, depending on the considered magnetospheric region. For comparison, the timescale required for the adjustment of magnetotail as driven by an IMF rotation is derived to be ~10–20 minutes.

Unified Astronomy Thesaurus concepts: Venus (1763); Interplanetary magnetic fields (824); Solar-planetary interactions (1472); Planetary magnetospheres (997)

1. Introduction

Lacking the protection of an intrinsic magnetosphere, Venus’s ionosphere interacts directly with the solar wind (Russell et al. 1979). The interplanetary magnetic field (IMF) piles up and drapes around the highly conducting ionosphere, forming a plasma region with an enhanced magnetic field (Phillips & McComas 1991; Bertucci et al. 2011). The region with predominant magnetic pressure, or the induced magnetosphere, can provide protection to the atmosphere from the solar wind (Zhang et al. 1991, 2007). The dayside induced magnetosphere, called the magnetic barrier, is separated from the ionosphere by the ionopause which is characterized by a sudden increase of ionospheric thermal pressure (Luhmann 1986), and the upper induced magnetosphere boundary (IMB) is determined by the pressure balance between the solar wind pressure and the magnetic pressure (Zhang et al. 1991). The thickness of the magnetic barrier increases with solar zenith angle (SZA), while the magnetic pressure is weaker with a higher SZA (Zhang et al. 1991). The induced magnetosphere on the nightside is named the magnetotail (McComas et al. 1986; Rong et al. 2014).

The induced magnetosphere is dependent on solar activities and solar wind. Specifically, the magnetic barrier is usually located above the ionosphere with strong solar radiation (Zhang et al. 1991), while the magnetic barrier is embedded with the ionosphere at solar minimum (Angsmann et al. 2011). The thickness of the magnetic barrier remains unchanged from solar maximum to solar minimum (Zhang et al. 2008). With the increase of solar activity, the magnetic field is stronger (Xiao & Zhang 2018) in the magnetic barrier but weaker in the magnetotail (Chang et al. 2018). When the solar wind dynamic pressure increases, the magnetic pressure in the magnetic barrier is enhanced (Ma et al. 2020), and the magnetic barrier shrinks (Zhang et al. 1991; Xu et al. 2021) and even sinks into the ionosphere (Phillips et al. 1985; Russell et al. 2006). With regard to a solar storm, variations in the induced magnetosphere would be complicated (Xu et al. 2019).

The induced magnetosphere is also modulated by the IMF orientation. The configuration of the induced magnetosphere is dependent on the direction of the IMF component orthogonal to both the solar wind velocity and motional electric field (Phillips et al. 1986; Zhang et al. 2010). The IMF cone angle, the angle between the IMF and solar wind flow, could influence the whole solar wind–Venus interaction system, involving the foreshock (Omid et al. 2020b), the bow shock (Russell et al. 1988), the magnetosheath (Du et al. 2009; Delva et al. 2017), the induced magnetosphere (Zhang et al. 2009; Xiao & Zhang 2018) and the ionosphere (Chang et al. 2020; Brecht & Ledvina 2021). Based on in situ observations, Masunaga et al. (2011) and Dubinin et al. (2013) reported the irregular configuration of the magnetic fields around Venus due to the flow-aligned IMF. The magnetic pressure in the induced magnetosphere is comparatively weak when the IMF cone...
angle is small (Chang et al. 2020; Xu et al. 2021). Xiao & Zhang (2018) examined the magnetic barrier for the cases of a large IMF cone angle ($60^\circ$–$90^\circ$) and a small IMF cone angle ($0^\circ$–$30^\circ$) and found that the peak magnetic field magnitude of the magnetic barrier is smaller when the IMF is quasi-parallel to solar wind velocity. Collinson et al. (2015) observed a weaker magnetic barrier during the nearly flow-aligned IMF as compared to the days before and after. Besides, numerous simulations have also been applied to studying the effects of the IMF on the Venusian induced magnetosphere. In view of an ideal magnetohydrodynamics (MHD) model, De Zeeuw et al. (1996) illustrated an atypical magnetic field morphology and the weak magnetic pressure in the inner magnetosheath under the flow-aligned IMF. Zhang et al. (2009) suggested that the induced magnetosphere disappears when the upstream IMF is strictly aligned with the solar wind flow. Hybrid models demonstrate the weakening magnetic pileup in front of Venus with a decreasing IMF cone angle (Johansson et al. 2010) and the asymmetry of the induced magnetosphere caused by the IMF cone angle (Jarvinen et al. 2013; Egan et al. 2019) or the flow-aligned IMF component ($B_z$; Kallio et al. 2006; Liu et al. 2009). These studies suggested that the formation and configuration of the Venusian induced magnetosphere are controlled by the IMF cone angle. The induced magnetosphere weakens with the decrease of the IMF cone angle and even disappears when the IMF cone angle is perfectly equal to $0^\circ$. Though the influences of IMF orientation were considered, the significance of the IMF magnitude was less discussed. Statistical studies from Venus Express data indicate that the coupling of IMF magnitude and orientation is important in the solar wind–Venus interaction (Chai et al. 2014; Rong et al. 2016). We could reasonably conclude that the effect of IMF orientation is not independent of the IMF magnitude.

However, the single-orbit observation is not capable of describing the global response of the Venusian induced magnetosphere, since the inconstant solar wind and the IMF cannot be determined when the obiter is downstream of the bow shock. In this study, we analyze the dependence of the Venusian induced magnetosphere on the IMF components using MHD simulations. The model results can advance our knowledge of the IMF effects on atmospheric bodies without intrinsic magnetic fields.

### 2. Simulation and Method

#### 2.1. Simulation Model

A three-dimensional global MHD model of Venus within the Block Adaptive Tree Solar Wind Roe-Type Upwind Scheme (BATS-R-US) code (Toth et al. 2012) is used in this study. This single-fluid multispecies MHD model developed by Ma et al. (2013) is analogous to the models for Mars (Ma et al. 2004; Ma & Nagy 2007) and Titan (Ma et al. 2006, 2007). The simulation is carried out in the Venus Solar Orbital (VSO) coordinates system, in which the $X$-axis is along the Venus–Sun line, the $Z$-axis points northward, the $Y$-axis completes the right-handed set and the origin is located at the center of Venus. The computational domain is limited to $-24 R_V < X < 8 R_V$, $-16 R_V < Y < 8 R_V$, and $-16 R_V < Z < 16 R_V$, where $R_V = 6052$ km is the radius of Venus. The spherical grid is adopted, with a resolution of $2.5^\circ$ in both longitude and latitude. The radial resolution is about 5 km at the inner boundary, which is set to be 100 km above the ground surface. An absorbing boundary is used for the inner boundary condition. The background neutral atmosphere and the ion production rates are described in Ma et al. (2013) for both solar cycle maximum and minimum conditions. In our work, the solar maximum condition is chosen to produce a clear ionopause as the lower boundary of the induced magnetosphere (Villrreal et al. 2015; Ma et al. 2020). Considering the source terms in the self-consistent atmosphere/ionosphere, a point implicit scheme is used in a limited region ($<2 R_V$). The neutral hydrogen is neglected in the chemical reactions and the resistivity is included in the MHD equation (Ma et al. 2013). The input solar wind parameters, including the solar wind number density of $17 \text{ cm}^{-3}$, the solar wind temperature of $2.5 \times 10^5 \text{ K}$, the solar wind velocity of $400 \text{ km s}^{-1}$ antiparallel to the +$X$ direction (Luhmann et al. 1993), and the IMF magnitude of 12.1 nT (Chang et al. 2018) represent the average solar maximum condition of Solar Cycle 22. To compare the effects of the IMF magnitude and orientation on the Venusian induced magnetosphere, 13 cases with different IMF components in Table 1 are simulated separately in the model. In each case, the upstream IMF vector is assumed to be in the ecliptic plane, thus the $B_z$ equals 0 nT and the motional electric field ($E = - V \times B$) is toward the $-Z$ direction in the VSO coordinates. We run the model with a local-time scheme to a quasi-steady state and then alter it to a time-dependent scheme for a 1 hour simulation. Furthermore, the responses of the Venusian induced magnetosphere to an IMF variability are studied using this time-dependent MHD model. Note that an MHD simulation cannot precisely reproduce the kinetic process of the solar wind–Venus interaction, but this model is adequate for our investigation because we focus on the pressure balance in the interaction system.

#### 2.2. The Scale of the Induced Magnetosphere

The scale of the magnetic barrier is determined by the altitudes of the ionopause and the IMB, of which the former is identified by the sudden increase of ionospheric thermal pressure, and the latter is considered as the location where the magnetic pressure balances the external solar wind pressure (Zhang et al. 1991). Theoretically, an equilibrium is achieved at the upper boundary (Chang et al. 2020): $P_i + P_b + P_c = (P_i + P_b)_{\text{IMB}}$, where $P_i$ is the thermal pressure, $P_b = B^2/2\mu_0$ is the magnetic pressure, $P_c = \rho v^2$ is the dynamic pressure and $\mu_0$ denotes the magnetic barrier. Different methods give different IMF standoff distances (Wang et al. 2021). Based on magnetic pressure, Zhang et al. (1991) defined the upper boundary as the position where the local magnetic pressure equals half of the upstream solar wind dynamic pressure adjusted for the normal angle of the barrier, $P_b = \frac{1}{2} \rho v_{sw}^2 \cos^2 \phi$, where $v_{sw}$ is the upstream solar wind velocity, and $\phi$ is the normal angle of the barrier, which equals to $0^\circ$ at the subsolar point. In similar single-fluid MHD simulations at Mars, Fang et al. (2015) used the flow...
speed gradient to define the IMB, and Ma et al. (2017) determined
the subsolar IMB based on the balance of magnetic pressure and
plasma thermal pressure, \( P_b = P_t \). Considering that the dynamic
pressure downstream of the bow shock could still play a role, the
distance of the boundary might be overestimated if the dynamic
pressure is ignored. In this study, the definition based on pressure
balance is adopted:

\[
P_b = P_t + P_d \cos^2 \phi.
\]  

(1)

We use the SZA as an approximation for \( \phi \). The temperature
anisotropy in the Venusian magnetosheath (Bader et al. 2019)
is ignored in this model. The thickness of the magnetic barrier
can be defined as the distance from the ionopause to the IMB.
Though the boundary of the magnetotail is not clear, the scale
of the magnetotail can be characterized by the region with an
enhanced magnetic field (Zhang et al. 2010).

3. Model Results

3.1. Control of the IMF on the Venusian Induced
Magnetosphere

Figures 1 and 2 show the contours of magnetic field strength
for Cases 1–4 in the equatorial (\( Z = 0 \)) plane and meridian
(\( Y = 0 \)) plane, respectively. The mean bow shock location at
solar maximum (Zhang et al. 1990) can be correctly matched by
the model result (Ma et al. 2013, 2020). Since the IMF has an
impact on the bow shock (Russell et al. 1988), the discrepancy in the bow shock location between our calculations and the statistical results of Zhang et al. (1990) is produced due to the fact that our input IMF here is not on an average condition. The bow shock of Case 3 shows an evident hemispheric asymmetry in the \( X-Y \) plane, in good agreement with Chai et al. (2014). Downstream from the bow shock, the magnetic field magnitude distributes more symmetrically in the
\( X-Y \) plane when the IMF cone angle is large, as shown in
Figures 1(a), (d). The magnetic dawn–dusk asymmetry of the magnetosheath in Figures 1(b), (c) is caused by the IMF cone angle or IMF \( B_x \) (Jarvinen et al. 2013). This dawn–dusk asymmetry also exists in the IMB location determined by Equation (1) as shown in Figure 1(c). The magnetic fields accumulate below the IMB, and a magnetic barrier is consequently built up, as displayed by the red color regions in Figures 1 and 2. For various IMF conditions, the magnetic barrier weakens gradually with the increase of SZA (Zhang et al. 1991) in the \( X-Y \) plane, as expected. However, from Figure 2, the strongest part of the magnetic barrier is formed at about \( SZA = 60^\circ \) and then vanishes quickly with increasing SZA. It seems the magnetic barrier in the \( X-Z \) plane cannot
cover the terminator region (\( SZA = 90^\circ \)). The magnetotail with two lobes is shown in the \( X-Y \) plane. The radius of magnetotail increases along the \( -X \)-axis direction. In Figures 2(a), (b), it is shown that a larger-scale magnetic barrier, which occupies a larger red area, is correlated with a larger IMF cone angle. The peak magnetic field of 106 nT in Figure 2(a) is stronger than the peak 89 nT in Figure 2(b). Furthermore, the enhancement of IMF strength can also lead to a larger-scale and stronger magnetic barrier as indicated by the darker red region in
Figure 2(a), compared to that in Figure 2(d). With a changed IMF \( B_x \) but fixed \( B_y \) and \( B_z \), the scale of magnetic barrier and magnetotail does not show any obvious variations as shown by Cases 1, 3 or 2, 4 in Figure 1, though the IMF cone angle and IMF strength vary substantially. However, the change in IMF \( B_y \) component can result in significant changes in the magnetic barrier (Cases 2, 3), and the same IMF \( B_y \) (Cases 1, 3 or Cases 2, 4) results in the same peak magnetic pressure in the magnetic barrier. For the cases with a large IMF \( B_y \), the tail has a larger
radius, though the magnetic field strength of the tail (\( \sim 20 \) nT) does not vary a lot.

To analyze the IMF effect on the magnetic barrier in detail, we compare the subsolar profiles of dynamic pressure, magnetic pressure, and thermal pressure in Figures 3(a)–(d), as functions of the distance away from Venus toward the Sun. At the bow shock, the solar wind dynamic pressure drops sharply and transforms into the magnetosheath plasma thermal pressure. The total pressure keeps conserved along the Sun–Venus line, with the dominant component altered from the dynamic pressure upstream of the bow shock to the magnetic pressure in the induced magnetosphere (Zhang et al. 1991; Terada et al. 2009; Ma et al. 2013). In each panel, the ionopause is denoted by the intersection of decreasing \( P_b \) and increasing ionospheric \( P_t \) while the IMF from Equation (1) is labeled by a vertical yellow line. The small proportion of dynamic pressure at the IMB demonstrates the plasma flow almost stagnates when encountering the magnetic barrier. The IMF and bow shock positions in Cases 1, 3 are farther than those in Cases 2, 4. Meanwhile, the IMF, the bow shock, and the peak magnetic pressure are similar in Cases 1, 3 (or in Cases 2, 4) which hold the same IMF \( B_y \) component. The thickness of the magnetic barrier, namely the length bounded by the ionopause and IMB, decreases from Cases 1, 3 to Cases 2, 4. For cases in which \( B_y = 11.7 \) nT, the magnetic pressure increases by 42% with respect to those where \( B_y = 3 \) nT. The subsolar ionopause location is comparatively stable in Figures 3(a)–(d), with only an unnoticeable decrease of \( \sim 0.005 R_V \) when \( B_y = 3 \) nT, which might be caused by the slight decrease of total pressure outside the ionosphere. Figures 3(c), (f) illustrate the modulations of IMF components on the subsolar induced magnetosphere and the subsolar plasma boundaries based on Cases 1–13. The variation in the bow shock location is consistent with previous studies (Chai et al. 2014; Wang et al. 2020). The IMF, the thickness, and field strength of the induced magnetosphere are not sensitive to the IMF \( B_x \) but increase with increasing \( B_y \). It is mentioned that Case 10 is close to the situation of disappearing induced magnetosphere proposed by Zhang et al. (2009). Therefore the depression of the magnetic barrier occurs and the magnetic pressure drops drastically at the left endpoint in Figure 3(f). If the lower density in the foreshock (Omidi et al. 2017; Collinson et al. 2020) was considered, the actual magnetic barrier might be further weakened (Ma et al. 2020) under parallel IMF. The induced magnetosphere thickness and plasma boundaries do not vary a lot when \( B_y \leq 3 \) nT. We suggested it is harder for the magnetic field to pile up above the ionopause when the IMF \( B_y \) is weak, which is consistent with a previous observation of the Venusian induced magnetosphere under the radial IMF (Collinson et al. 2015).

3.2. Responses of the Venusian Induced Magnetosphere to the
Change of the IMF

Since the induced magnetosphere is dependent on the magnitude and direction of the perpendicular IMF components, the responses of the Venusian induced magnetosphere to IMF variability are further investigated here. When the simulation of Case 1 (\( B_{IMF} = [3.1, -11.7, 0.0] \) nT) proceeds for 1 hour to
reach a quasi-stationary state, the upstream IMF is altered to $[11.7, 0.0, -3.1]$ nT. The IMF clock angle, defined as the angle between the $+Y$ direction and the projection of the IMF in the $Y-Z$ VSO plane here, rotates by $90^\circ$, and the magnitude of $B_Y^2 + B_Z^2$ decreases to 3.1 nT. This sudden field rotation will not form a current sheet (Vech et al. 2016) but is able to introduce some disturbances. The variations in the induced magnetosphere are analyzed along the subsolar line. Three slices ($X = 0, Y = 0, Z = 0$) in the VSO coordinate are used to demonstrate the magnetic field morphology throughout the magnetic barrier and the magnetotail. These three planes can characterize the structure of the induced magnetosphere in different dimensions. In the $Y-Z$ plane, we consider the local $B_X$ component, which could illuminate the draping of magnetic field lines. The ionopause is a thin layer (Russell et al. 2006), therefore we estimate the upper limit of the ionopause, or the ion composition boundary (ICB) at an altitude with an O$^+$ density of 100 cm$^{-3}$ (Ma et al. 2013), which characterizes the region dominated by planetary ions. Though the ionosphere is unmagnetized, this estimation can reveal the effects of the planetary ions in the following analysis. The time-dependent MHD results perform the temporal evolution of the Venusian induced magnetosphere under IMF rotation.

The subsolar initial responses are demonstrated by the variation of the local magnetic field clock angle in Figure 4(a). At 1:01:40, the rotated IMF arrives at Venus and the bow shock locates at $X = 1.45$ $R_V$. From 1:01:30 to 1:02:10, the IMF clock angle rotates from $-180^\circ$ to $-270^\circ$ and the strength of the IMF component in the $Y-Z$ plane decreases from 11.7 to 3.1 nT. Then the upstream IMF is constant at $[11.7, 0.0, -3.1]$ nT. As we can see, the bow shock and outer magnetosheath keep the clock angle synchronous with the IMF. The intersections of the red line at 1:01:30 and the other lines indicate the position that the perturbation propagates to. Clearly the perturbation moves slower while approaching Venus. The magnetic field orientation near the IMB ($X = 1.08$ $R_V$ shown in Figure 4(b)) reacts initially at 1:02:00, 20 s after the perturbation entering the bow shock, and then rotates to the $Z$ direction at 1:03:00, 50 s since the IMF is along the $Z$-axis. The whole subsolar magnetosheath, from the bow shock to the IMB, adapts to the IMF quickly less than 1 minute, which indicates the magnetosheath clock angle is trustworthy as a proxy for the upstream IMF clock angle (Fang et al. 2018; Dong et al. 2019). The O$^+$ density is shown by the black dash line at $X = 1.07$ $R_V$ (ICB). At 1:04:00, the original $B_Y$ outside the ICB is totally replaced by the new $B_Z$. In contrast, smoother and slower rotations occur in the inner magnetosphere inside the ICB. With the decrease in
altitude, the magnetic field is very weak in the region dominated by ionospheric thermal pressure \((X \leq 1.05 R_V)\) and responds slowly, with an associated timescale of \(\sim hr\) in the ionosphere as discussed by Ma et al. (2020). At 1:12:00, the transition of the clock angle from the inner magnetosphere \((-270^\circ)\) to the ionosphere \((-180^\circ)\) centers at \(X = 1.05 R_V\), and the region \(1.05 R_V \leq X \leq 1.07 R_V\) is regarded to be controlled mainly by the new arriving \(B_Z\). In fact, the \(B_Y\) component in the induced magnetosphere is negligible at 1:12:00 as shown by the peak magnetic pressure \(P_b\) in Figure 4(b). The time interval required for the adaptation of the inner magnetosphere to the IMF rotation is about 10 minutes.

In Figure 4(b), we show the subsolar bow shock, IMB together with the peak magnetic pressure as functions of time with temporal resolutions of 10 s before 1:03:00 and 60 s after 1:03:00. The vertical dash line denotes the arrival of the steady solar wind at 1:02:10. The subsolar bow shock location reacts within 10 s with the change of the IMF perpendicular component \((B_Z^2 + B_Y^2)\) (labeled in 4(a)) and solar wind dynamic pressure. The IMB also responds quickly. When the solar wind is unchanged since 1:02:10, the IMB still decreases sharply, implying a 20 s time decay. These rapid changes of the bow shock and IMB should be caused by the decrease of the IMF perpendicular component, as the amplitude of the dynamic pressure fluctuation is relatively small. The IMB continues varying and the bow shock is modulated by the dynamics of the induced magnetosphere, though a short-lived equilibrium of bow shock is reached at 1:02:10. A relatively steady state is achieved at 1:04:00, suggesting the necessary time for the bow shock and IMB to recover is 2 minutes. The pileup of the magnetic field is indicated by the peak magnetic pressure inside the induced magnetosphere. The peak \(P_b\) has a 10 s time delay when responding to solar wind \(P_d\) perturbation. Note that the \(P_d\) does not change from 1:01:50 to 1:02:00, but the \(P_b\) descends in the following 10 s, which should be caused by the variations in the IMF but not by the \(P_d\). The old field lines with dominating \(B_Y\) would slip away and the new \(B_Z\) will enter the magnetosphere. We use the peak values of \(B_Y^2 / 2 \mu_0\) and \(B_Z^2 / 2 \mu_0\) to show the relative importance of magnetic field components in the magnetosphere. The \(B_Y\) remains dominant until 1:05:00 and the new-entry \(B_Z\) needs 3 minutes to establish a new magnetic barrier. As mentioned above, the disturbance reaches the ICB at 1:03:00 and the original \(B_Y\) only exists inside the ICB at 1:04:00. Without supplements, the \(B_Y^2 / 2 \mu_0\) cannot be maintained and starts to drop at 1:03:00. The time interval for the \(B_Y\) to diffuse away is about 6 minutes since 1:04:00, as indicated by the quasi-linear slope of \(B_Y^2 / 2 \mu_0\).

Figures 4(c)–(k) are the snapshots of the magnetic field in the three \((X = 0, Y = 0, Z = 0)\) planes at different moments.
Figures 4(c)–(e) displays the draping of magnetic field lines using the $B_X$ component (color-coded) as a function of $Y$ and $Z$ coordinates. The reversal of $B_X$ is symmetric on the $Z$-axis at 1:04:00 and rotates gradually to the $Y$ axial symmetric state, with the original $B_Y$ replaced by the new-entry $B_Z$. This replacement proceeds from the outer magnetosphere toward the inner one. Of course the magnetosheath has already been stationary at 1:04:00. Figure 4(d) is an intermediate state where the draping is turning from the $X-Y$ plane to the $X-Z$ plane. At 1:12:00, the configuration is still not in equilibrium, as the symmetry of $B_X$ on the $\pm Y$ hemisphere can still be seen in the region close to the ionopause. Figures 4(f)–(h) exhibits the decay of the original magnetotail with the reduction of tail radius. At 1:12:00, the ambiguous two-lobe magnetotail in Figure 4(h) suggests the tail in the $X-Y$ plane is undermined, and a new tail is formed in the $X-Z$ plane (Figure 4(j)). As time
Figure 4. The temporal evolution of the Venusian induced magnetosphere under an IMF variation from \([3.1, -11.7, 0]\) nT to \([11.7, 0.0, -3.1]\) nT. (a) The clock angle along the subsolar line at different moments. The magnitude of the IMF component perpendicular to the X-axis is labeled. (b) The change of subsolar bow shock (BS), subsolar IMB, upstream solar wind dynamic pressure, the subsolar peak values of \(P_b (B^2/\mu_0)\), \(B_y^2/2\mu_0\) and \(B_z^2/2\mu_0\). (c)–(k) The snapshots of magnetic field distribution in the three \((X = 0, Y = 0, Z = 0)\) planes at different moments.
goes by, the new magnetotail develops gradually to a well-structured state as shown in Figure 4(k).

4. Discussions and Conclusions

In this work, the influences of IMF components on the Venusian induced magnetosphere are quantitatively studied based on a global MHD model, in order to improve our understanding of the responses of the Venusian induced magnetosphere to the variations in the IMF. Thirteen steady cases with various IMF inputs are compared. The simulation results show the induced magnetosphere increase systematically in the magnetic field strength and the spatial scale, with the increase of upstream IMF components perpendicular to solar wind flow. The bow shock distance, IMB distance, and the thickness of the induced magnetosphere are all correlated with the perpendicular IMF component \((B^2 + B^2 + B^2)\), while the parallel IMF component \(B_x\) has little effect on the Venusian induced magnetosphere and the subsolar bow shock location. The peak magnetic pressure in the magnetosphere and the scale of the magnetotail are also not sensitive to IMF \(B_y\). Similarly, the control of IMF magnitude \(|B|\) on the subsolar IMB at Mars (Ma et al. 2018) is possibly also due to the effect of the perpendicular IMF component. It seems that the IMF cone angle is not a factor modulating the induced magnetosphere but only the reason for the hemispheric asymmetry in the IMB location, the bow shock location, and the magnetic field strength of the magnetosheath. If the IMF cone angle played a role in controlling the Venusian induced magnetosphere (Johansson et al. 2010; Xiao & Zhang 2018), the increase of the IMF cone angle, as a result of the decrease of IMF \(B_x\), should be counterbalanced by the decrease of IMF magnitude. It is noted that the foreshock effect might result in lower density and magnetic field strength upstream of the bow shock, which could reduce upstream dynamic pressure. When the foreshock is more effective under a smaller IMF cone angle (Omidi et al. 2020a), the lower total pressure would lead to a weaker and expanded magnetosphere (Ma et al. 2020).

Since the IMF controls the induced magnetosphere, we use the time-dependent calculation to perform the time evolution of the induced magnetosphere under the change of the IMF. The dayside bow shock and magnetosheath could react instantly to the IMF rotation (1 s–1 minute), but the induced magnetosphere requires 1–10 minutes to regulate the magnetic field topology, depending on the considered region of the induced magnetosphere. Outside the ICB, the morphology of the induced magnetosphere adjusts to the IMF clock angle in 2 minutes, while the response inside the ICB ranges from 2 to at least 10 minutes. The bulk velocity of local plasma might be the main mechanism deciding the timescale outside the ICB, while the energy exchange and magnetic diffusion need to be considered inside the ICB since the planetary particles should play an important role. The recovery of the bow shock and the IMB takes 2 minutes to achieve a relative balance for the change of the IMF perpendicular component, and the magnetic barrier, as well as the IMB, continues, taking an extra 6 minutes to modify itself. At the terminator plane \((X = 0)\), the adaptation of the inner magnetosphere to the change of the IMF needs more than 10 minutes. The evolution of the magnetic structure implies the timescale for the decay of the magnetic field in the inner induced magnetosphere and the reformation of the magnetotail is in the order of 10 minutes or larger. The response of a Venusian induced magnetosphere to a pressure pulse event is quick, within 1 minute (Ma et al. 2020). For IMF variations, an MHD simulation demonstrates the induced magnetosphere reacts in a few minutes (Benna et al. 2009). The change of IMF orientation was observed to be transported into the magnetotail in 8.5 minutes (Slavin et al. 2009). From a hybrid model, the reaction of the Martian induced magnetosphere to IMF variability has a recovery timescale ranging between 8 s and 12 minutes (Romanelli et al. 2018, 2019). These previous studies show agreement with our results.

The MHD results revealed that the Venusian induced magnetosphere is constructed by the IMF component perpendicular to the solar wind velocity, with a timescale of 10 minutes. The enhancement of the perpendicular IMF component could enhance the magnetic pileup around the planet. The single-fluid MHD cannot reproduce the \(\pm E\) hemispheric asymmetry (Jarvinen et al. 2013) and the kinetic process in the foreshock region (Jarvinen et al. 2020; Omidi et al. 2020a). Multifluid models and hybrid models are expected to further describe the control of the IMF on the induced magnetosphere.

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References
Angsmann, A., Fränz, M., Dubinin, E., et al. 2011, P&SS, 59, 327
Bader, A., Stenbring Wieser, G., André, M., et al. 2019, JGRA, 124, 3312
Benna, M., Acuna, M. H., Anderson, B. J., et al. 2009, GeoRL, 36, L04109
Bertucci, C., Duru, F., Edberg, N., et al. 2011, SSRv, 162, 113
Brecht, S. H., & Ledvina, S. A. 2021, JGRA, 126, e27779
Chai, L., Fraenz, M., Wan, W., et al. 2014, JGRA, 119, 4964
Chang, Q., Xu, X., Xu, Q., et al. 2020, ApJ, 900, 9
Chang, Q., Xu, X., Zhang, T., et al. 2018, ApJ, 867, 129
Collinson, G., Sibeck, D., Omidi, N., et al. 2020, JGRA, 125, e28023
Collinson, G. A., Grebowsky, J., Sibeck, D. G., et al. 2015, JGRA, 120, 3489
De Zeeuw, D. L., Nagy, A. F., Gombosi, T. I., et al. 1996, JGRE, 101, 4547
Delva, M., Volwerk, M., Jarvinen, R., et al. 2017, JGRA, 122, 10396
Dong, Y., Fang, X., Brain, D. A., et al. 2019, JGRA, 124, 4295
Dong, T., Zhang, T. L., Wang, C., et al. 2009, GeoRL, 36, L09102
Dubinin, E., Fraenz, M., Woch, J., et al. 2013, P&SS, 87, 19
Egan, H., Jarvinen, R., & Brain, D. 2019, MNras, 486, 1283
