Spatially Highly Resolved Solar-wind-induced Magnetic Field on Venus

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The current work investigates the Venusian solar-wind-induced magnetosphere at a high spatial resolution using all Venus Express (VEX) magnetic observations through an unbiased statistical method. We first evaluate the predictability of the interplanetary magnetic field (IMF) during VEX’s Venus magnetospheric transits and then map the induced field in a cylindrical coordinate system under different IMF conditions. Our mapping resolves structures on various scales, ranging from the ionopause to the classical IMF draping. We also resolve two recently reported structures, a low-ionosphere magnetization over the terminator, and a global “looping” structure in the near magnetotail. In contrast to the reported IMF-independent cylindrical magnetic field of both structures, our results illustrate their IMF dependence. In both structures, the cylindrical magnetic component is more intense in the hemisphere with an upward solar wind electric field \(E^\text{SW} \) than in the opposite hemisphere. Under downward \(E^\text{SW} \), the looping structure even breaks, which is attributable to an additional draped magnetic field structure wrapping toward \(-E^\text{SW} \). In addition, our results suggest that these two structures are spatially separate. The low-ionosphere magnetization occurs in a very narrow region, at about 88°–95° solar zenith angle and 185–210 km altitude. A least-squares fit reveals that this structure is attributable to an antisunward line current with 191.1 A intensity at 179 ± 10 km altitude, developed potentially in a Cowling channel.

Abstract

1. Introduction

Some unmagnetized or weakly magnetized bodies in the solar system possess electrically conductive ionospheres, e.g., the planets Mars and Venus and the satellite Titan. These bodies interact with the solar wind (SW), inducing electric currents and shaping comet-tail-like magnetospheres (Bertucci et al. 2011). Among these bodies, Venus does not have Mars-like crustal fields, is relatively close to the Sun, is surrounded by dense SW, and has been observed using artificial orbiters. Therefore the Venusian magnetosphere is controlled sensitively by the SW, and relevant observations are relatively abundant, making the Venusian magnetosphere a natural laboratory for studying the interactions between the SW and unmagnetized bodies.

The interactions between the SW and the Venus plasma environment have been investigated observationally (e.g., Russell et al. 2006; Bertucci et al. 2011), and essential processes and structures have been reproduced in global hybrid simulations (e.g., Jarvinen et al. 2013; Jarvinen & Kallio 2014). Here, we briefly summarize the processes and structures, and for details, we refer to the relevant reviews (e.g., Brace & Kliore 1991; Russell et al. 2007; Baumjohann et al. 2010; Bertucci et al. 2011; Dubinin et al. 2020). The SW plasma surrounding Venus is supersonic and super-Alfvénic (the sound speed and Alfvén speed are significantly lower than the SW bulk velocity) with the frozen-in interplanetary magnetic field (IMF, \(B^\text{IMF} \)). When the SW plasma encounters Venus, the SW motional electric field \(E^\text{SW} \) drives electric currents in the highly conducting ionosphere and the surrounding plasma. The magnetic fields associated with the currents decelerate the SW flow, forming a bow shock, a magnetosheath, and a magnetic barrier or magnetic pileup region. At the bow shock, the SW plasma is decelerated to subsonic speeds. The deceleration thermalizes the plasma and excites intense waves and turbulence. The shocked SW plasma remains collisionless (collision frequencies much lower than gyrofrequencies), which populates the magnetosheath but cannot easily penetrate the magnetic barrier and is mostly deflected around the planet. The deflection gives rise to a wake with low-density plasma downstream, forming the magnetotail, where reconnection events and particle acceleration and loss occur. The boundary of the low-density plasma region is known as the induced magnetosphere boundary (IMB), sometimes also called the magnetopause. The induced currents are distributed most intensely in a thin layer, where the ionospheric thermal pressure holds off the magnetic barrier’s magnetic pressure. The layer is the bottom boundary of the magnetic barrier and is known as the ionopause. The ionopause currents are closed through currents in the magnetic barrier or at the IMB. According to, e.g., Russell et al. (2007) and Brace & Kliore (1991), the magnetic barrier is referred to as the innermost part of the magnetosheath, and both border the dayside ionosphere at the ionopause, whereas according to, e.g., Zhang et al. (2008a, 2008b) and Baumjohann et al. (2010), the magnetic barrier is defined as an independent region between the magnetosheath and the ionopause. The boundary between the...
magnetosheath and the magnetic barrier is characterized by a discontinuity of magnetic distortion and magnetosheath wave terminations, which is referred to as the dayside IMB or magnetopause (Zhang et al. 2008b). Referring to Zhang et al. (2008b), we sketch the structures involved in the current study in Figure 1.

The magnetic field configuration of the induced magnetosphere is characterized by a draping configuration that is elongated along the Sun–Venus axis (e.g., Luhmann 1986). In the plane normal to the Sun–Venus axis, the orientation of the induced magnetic field is mainly determined by $E_{SW}$ and the cross-flow IMF component, which is usually described in a coordinate system defined by referring to $E_{SW}$, which is known as the Venus-Sun electric field coordinate system (VSE for short, also called SW velocity and magnetic field coordinate system; e.g., Dubinin et al. 2014a; Du et al. 2013). The $x$-axis of the VSE coordinate system is antiparallel to the upstream SW velocity ($v_{SW}$), the $y$-axis is parallel to the IMF cross-flow component, and the $z$-axis is parallel to $E_{SW}$, therefore it is also called the $E_{SW}$ axis. In VSE coordinates, the classical induced magnetic field is overall antisymmetric between the $\pm y$ hemispheres and symmetric between the $\pm z$ hemispheres (namely $\pm E_{SW}$ hemisphere, e.g., Bertucci et al. 2011; He et al. 2016). The $\pm E_{SW}$ symmetry was reported broken in both the magnetic barrier and the magnetotail: the magnetic field is stronger in the $+E_{SW}$ hemisphere than the magnetic field in the $-E_{SW}$. These features were investigated in statistical studies (Du et al. 2013; Bertucci et al. 2003, 2005; Zhang et al. 1991, 2008b, 2010) and have been reproduced in simulations (Brecht 1990; Brecht & Ferrante 1991; Jarvinen et al. 2013), and are therefore well understood.

The above-mentioned magnetospheric structures are on planetary scales. Recently, two relatively small-scale magnetospheric structures were observed in the low-altitude ionosphere (below 300 km altitude; Zhang et al. 2012, 2015) and in the magnetotail (Chai et al. 2016), referred to as the $\pm E_{SW}$ asymmetrical low-ionospheric magnetization (e.g., Dubinin et al. 2014a) and “looping” magnetic field (Chai et al. 2016), as indicated by the red and pink symbols in Figure 1, respectively. The low-ionospheric asymmetry is characterized by a preference of the induced magnetic field pointing toward $+y$ in both $\pm E_{SW}$ hemispheres, namely parallel to the cross-flow IMF in the $+E_{SW}$ hemisphere, but antiparallel in the $-E_{SW}$ hemisphere, which was also described, alternatively, as a dawnward preference over the Venusian north pole (Zhang et al. 2015). Various mechanisms were proposed, including giant flux ropes formed in the magnetotail (Zhang et al. 2012), Hall currents induced regionally in the low ionosphere (Dubinin et al. 2014a), and antisunward transports of low-altitude magnetic belts built up on the dayside (Villarreal et al. 2015).

Figure 1. Venusian-induced magnetosphere in the planes (a) $y=0$ (b) and $x=0$ in the VSE coordinate system. The colored text boxes in the bottom left corner present references for the structures in corresponding colors, in which the white and black text denotes observational studies and simulations, respectively. Note that the definition of the dayside-induced magnetosphere boundary is denoted here as a dotted line because the relevant definitions are different in different studies. Read Section 1 for details.
The looping magnetic field is characterized by a planetary-scale cylindrical symmetry of the cylindrical magnetic field in the near-Venus magnetotail, which was explained in terms of a global-induced current system distributed in double cylindrical layers (Chai et al. 2016). Most studies of these two structures are observational, based on either manually selected cases (e.g., Dubinin et al. 2014; Zhang et al. 2015) or on observations without case selections (Chai et al. 2016). Studies with selected cases resolved the structures at relatively high spatial resolutions, but were potentially subject to prior knowledge in the selection, whereas unbiased studies, without any guiding selection, presented the structures at typically low spatial resolutions. Consequently, the spatial distributions of these structures are not determinedly resolved. For example, it is not known whether the low-ionospheric asymmetry overlaps the looping structure. To deal with this problem, we present unbiased statistical results of the near-Venus magnetic field at a high spatial resolution up to about 50 km. Our results suggest that as sketched in Figure 1, the low-ionosphere asymmetry was not covered by the recent relevant magnetohydrodynamic simulation in Villarreal et al. (2015), and the low-ionosphere asymmetry does not overlap the looping field. We further compare the spatially highly resolved depictions under different IMF conditions, demonstrating that the looping structure is not cylindrically symmetric and that it breaks under some IMF conditions.

Below, after explaining our data analysis in Section 2, we demonstrate the capability of our method in resolving small-scale magnetospheric structures in Section 3, and we investigate the looping field and low-ionospheric asymmetry in Section 4.

2. Data Analysis

Venus Express (VEX) operated in a polar orbit. The orbit had a periapsis at 170–350 km altitude at about 78°N latitude in the Venus Solar Orbital coordinate system (VSO), the x-axis points from Venus toward the Sun, the z-axis is normal to the Venus orbital plane, pointing northward, and the y-axis completes the right-handed set; e.g., Svedhem et al. 2007; Titov et al. 2006). Due to the high orbital eccentricity, VEX repeatedly encountered SW, magnetosheath, and magnetosphere. VEX was not accompanied by any independent spacecraft for monitoring the IMF condition in the VEX magnetospheric transit. Therefore the IMF has to be estimated. Here, after introducing and evaluating our IMF prediction in Section 2.1, we introduce a cylindrical coordinate system, our IMF binning, and a high spatial resolution mapping approach in Sections 2.2, 2.3, and 2.4, respectively. We use all available 4-second-averaged magnetic field observations from about 3000 orbits during the eight Venusian years of operation of VEX (Zhang et al. 2006). We refer to He et al. (2016) for the distribution of the orbits as functions of local time, solar zenith angle, and altitude.

2.1. IMF Predictability for the VEX Magnetospheric Transit

A popular IMF estimation approach compares the IMF conditions immediately before the inbound bow-shock crossing and after the outbound crossing (e.g., Zhang et al. 2015). However, the current study focuses on the magnetosphere over the northern polar cap, which is typically much closer to one bow-shock crossing, either inbound or outbound, than the other in any given orbit. This situation is similar to the situation illustrated by He et al. (2017), where the authors estimated the IMF for MESSENGER’s Mercurian magnetospheric transit using the actual IMF observation from the nearest SW encounter. Following the IMF estimation approach in He et al. (2017), we estimate the IMF conditions as the average of actual IMF observations in a remote 20-minute-wide interval of VEX’s nearest SW encounter at the closest bow-shock crossing, either inbound or outbound. The bow-shock crossings are identified manually and detailed in Rong et al. (2014). In each orbit, we first identify the VEX maximum latitude arriving as a reference point of the magnetospheric transit, and calculate the temporal separation between the reference point and the corresponding closest bow-shock crossing. The temporal separations of all orbits are distributed in Figure 2, which peaks at about 17 minutes with an average of 20.5 minutes. On average, the reference point is separated away from the center of the SW interval by \( \Delta t = \hat{t}/2 + 20.5 \text{ minutes} = 30.5 \text{ minutes} \), where \( \hat{t} = 20 \text{ minutes} \) is the sampling window width. Approximately, IMF is estimated as the actual IMF observations 30 minutes preceding or succeeding. Below, we evaluate the estimation using actual IMF observations through a correlation analysis.

For the correlation analysis, we first select the magnetic fields measured in the SW and average them within discrete 20-minute-wide intervals. We denote \( \mathbf{B}^{IMF}(t) \) as the average in the interval from \( t - 10 \text{ min} \) to \( t + 10 \text{ min} \). Then, \( \mathbf{B}^{IMF}(t \pm 30 \text{ min}) \) are “estimations” of \( \mathbf{B}^{IMF}(t) \). In total, the VEX SW observations enable about \( N_{\text{pair}} = 6.5 \times 10^5 \) independent pairs of \( [B_x, B_y, B_z] \), the three components of which are scatter-plotted in the three panels in Figure 3. The points are color-coded according to the IMF variability defined as \( \sigma_{total}^{20 \text{ min}} = \sigma_{B_x}^2 + \sigma_{B_y}^2 + \sigma_{B_z}^2 \). Here \( \sigma_{B_x}, \sigma_{B_y}, \text{ and } \sigma_{B_z} \) are the standard deviation of the three magnetic components within the 20-minute sampling window centered at \( t \pm 30 \text{ min} \). According to the ascending \( \sigma_{total}^{20 \text{ min}} \) and following He et al. (2017), we sort the \( N_{\text{pair}} = 6.5 \times 10^5 \) pairs into 10 groups evenly, and calculate the correlation coefficient \( r \) between \( B_x^{IMF}(t) \) and \( B_y^{IMF}(t \pm 30 \text{ min}) \) in each group, illustrating that \( r \) decreases with increasing \( \sigma_{total}^{20 \text{ min}} \) (not shown). For a robust analysis (following Section 2.5, He et al. 2017), we exclude the VEX orbits associated with

![Figure 2. Histogram of the temporal separation between the VEX maximum latitude passing and the corresponding closest crossing of the bow shock's outer edge. See Section 2.1 for details.](image-url)
disturbed IMF states, characterized by $\sigma_{20 \text{min}}^{\text{total}} > 3.7 \text{ nT}$, from the following analyses. In the end, we obtain $N_o = 2945$ orbits for which bow-shock crossings are identified when IMF states are not disturbed.

After removing the 15% most disturbed IMF pairs from the $N_{\text{pair}} = 6.5 \times 10^5$ pairs, we carry out a bootstrapping analysis as follows. First, we randomly select $N_o = 2945$ samples from the reduced set of $6.5 \times 10^5$ pairs with replacements to calculate the correlation coefficient $r$ and $p$-value. The sampling is repeated for $N_o = 5000$ times, yielding $N_o$ values of $r$ and $p$. Here, $N_o = 5000 > N_o$ is selected subjectively. The average and standard deviation of $r$ are present in each panel of Figure 3, indicating that the correlations are significant for all IMF components and demonstrating that the IMF estimation is reasonable. The correlation coefficients of the three components are close to each other, suggesting that their predictability is comparable. This is different from the IMF predictability at Mercury (He et al. 2017), where the predictability of the different components is significantly different.

2.2. A Cylindrical Coordinate System for Cataloging IMF Conditions

Venus does not have a significant intrinsic magnetic field, neither a global dipole field nor a regional crustal field, that is magnetically spherically symmetrical. The interaction between the SW and the Venusian ionosphere induces a global magnetic field $B^I$ and a magnetosphere. The interaction is largely magnetically rotationally symmetrical with respect to the axis along $v^\text{SW}$. Below, we describe the symmetry mathematically and use it to discuss the VSE system and introduce a new coordinate system.

2.2.1. The Rotational Symmetry in VSO

The large-scale topology of $B^V$ is characterized by a draped configuration, determined mainly by the upstream SW conditions, mainly its magnetic field $B^\text{IMF}$ (e.g., He et al. 2016). Mathematically,

$$B^V = B^V(r|B^\text{IMF})$$

(1)

Here, $B^\text{IMF}$ is assumed to be homogeneous on the planetary scale at Venus. Therefore it is not a function of $r$, but a function of time, $B^\text{IMF}(t)$.

Investigating the details of Equation (1) is sort of an essential task of SW and Venus interactions. The independent variables of Equation (1) are two vectors that can be denoted with six scale variables: the position vector $r := (r_x, r_y, r_z)$ and $B^\text{IMF} := (B^\text{IMF}_x, B^\text{IMF}_y, B^\text{IMF}_z)$. In VSO, the six scale variables could be reduced to five, or a three- and a two-dimensional vector, $r$ and $B^\text{IMF} := (0, B^\text{IMF}_y, B^\text{IMF}_z)$, if we neglect $B^\text{IMF}_x$ for simplicity. Although $B^\text{IMF}$ also plays an important role in shaping the magnetosphere (Zhang et al. 2009), it is less capable to explain the induced magnetic variance near Venus (as quantified in Figure 10 in He et al. 2016), and therefore is often neglected for a first-order approximation. Accordingly, Equation (1) is often simplified as

$$B^V = B^V(r|B^\text{IMF})$$

(2)

The response of $B^V$ to the IMF is characterized by rotational symmetry. Mathematically, for any angle $\omega$,

$$R(\omega)B^V(r|B^\text{IMF}) = B^V(R(\omega)r|R(\omega)B^\text{IMF})$$

(3)

Here, a product of a vector with the rotation matrix

$$R(\omega) := \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \omega & -\sin \omega \\ 0 & \sin \omega & \cos \omega \end{bmatrix}$$

represents a rotation of the vector with respect to the $x$-axis (i.e., $-v^\text{SW}$) by $\omega$.

2.2.2. In VSE

Specifically, we define the IMF clock angle $\theta^\text{IMF} := \arctan(B^\text{IMF}_y/B^\text{IMF}_z)$. Substituting $-\theta^\text{IMF}$ for $\omega$ in Equation (3) yields

$$R(-\theta^\text{IMF})B^V(r|B^\text{IMF}) = B^V(R(-\theta^\text{IMF})r|R(-\theta^\text{IMF})B^\text{IMF})$$

(4)

For an arbitrary vector $a$, its product with $R(-\theta^\text{IMF})$ defines a coordinate transformation from VSO to VSE: $a^\text{VSE} = R(-\theta^\text{IMF})a^\text{VSO}$ (see Figure 4(a)). Therefore Equation (4) writes $(B^V)^\text{VSE} = B^V(r^\text{VSE}|(B^\text{IMF}^\text{VSE}))$, which could be simplified as

$$(B^V)^\text{VSE} = B^V(r^\text{VSE}|\|B^\text{IMF}\|)$$

(5)

since $(B^\text{IMF}^\text{VSE}) \equiv (0, \|B^\text{IMF}\|, 0)$. Equation (5) has four independent scale variables, one less than in the VSO.
representation in Equation (2), which can therefore facilitate data processing, analysis, and interpretation. However, the VSE position vector $r^\text{VSE}$ is determined using the IMF estimation. Therefore the $r^\text{VSE}$ determination is subject to the error in the IMF estimation and $r^\text{VSE}$ cannot be determined at a singular point $\|B^\text{IMF}\| \approx 0$. To conquer these difficulties, we develop a cylindrical coordinate system in the following subsection.

2.2.3. A Cylindrical Coordinate System

The previous subsection uses the IMF clock angle $\theta^\text{IMF}$ to define the rotation matrix $R(-\theta^\text{IMF})$. We can also define $R(-\theta^\text{VEX})$ using the clock angle $\theta^\text{VEX} := \arctan(r^\text{VEX}_\rho, r^\text{VEX}_r)$, where $r^\text{VEX} := [r^\text{VEX}_\rho, r^\text{VEX}_\phi, r^\text{VEX}_\zeta]$ is the VEX position vector. Then, the product $R(-\theta^\text{VEX})a^\text{VSO}$ defines a coordinate transformation of the vector $a^\text{VSO}$ from VSO to a cylindrical coordinate system along the VSO x-axis. The three components of $R(-\theta^\text{VEX})a^\text{VSO}$ correspond, in order, to the axial, azimuth, and radial directions, which could be arranged into the conventional order ($\rho$, $\phi$, and $\zeta$) of cylindrical coordinate systems by multiplying with a permutation matrix

$$
U = \begin{bmatrix}
1 & 0 & 0 \\
0 & 0 & -1 \\
-1 & 0 & 0
\end{bmatrix}.
$$

As sketched in Figures 4(b) and 4(c), the $\zeta$-axis is the cylindrical axis pointing from the Sun to Venus, the $\rho$-axis is the radial direction parallel to the position vector $r^\text{VEX} := (0, r^\text{VEX}_\phi, r^\text{VEX}_\zeta)$, and the $\phi$-axis is the azimuth coordinate normal to the $\rho$-$\zeta$ plane. This coordinate system is called hereafter the solar-Venus-cylindrical (SVC) coordinate system. The product $a^\text{SVC} := UR(-\theta^\text{VEX})a^\text{VSO}$ transforms the vector $a^\text{VSO}$ from VSO to SVC. Specifically, the VEX position in SVC reads $[r^\text{VEX}_\rho, r^\text{VEX}_\phi, r^\text{VEX}_\zeta] := UR(-\theta^\text{VEX})r^\text{VEX}$. Substituting the definitions of $R$ and $U$ results in $r^\text{VEX}_\rho \equiv 0$. (Geometrically, $r^\text{VEX}_\rho \equiv 0$ denotes that VEX is on the plane determined by the Sun, Venus, and VEX). Therefore all VEX observations are distributed two-dimensionally on the $\rho$-$\zeta$ plane in the SVC system.

![Figure 4](image1.png)

Figure 4. (a) VSO (colored axis) and VSE (black axis) coordinate systems. (b) VSO (colored axis) and SVC (black axis) coordinate systems. Panel (c) is the same as panel (b), but viewed from the Sun. In each panel, the red axis points from the Venustian center to the Sun, while the green axis is normal to the Venus orbital plane and points north. See Section 2.2 for details.

![Figure 5](image2.png)

Figure 5. Estimates of the cross-flow IMF component for all the VEX magnetospheric transits in the SVC coordinate system. Each point corresponds to one 4-second-resolved magnetic vector collected by VEX under 4400 km altitude and within the solar zenith angle between 65° and 150°, while each arc corresponds to a transit of the targeting region of one orbit. The five colors represent five SW/IMF conditions, characterized by different polarities of $B^\text{IMF}$ and $E^\text{SW}$. See Section 2.3 for details.

We substitute $UR(-\theta^\text{VEX})$ for $R(\omega)$ in Equation (3), yielding $UR(-\theta^\text{VEX})B^V(r|B^\text{IMF}) = B^V(UR(-\theta^\text{VEX})rUR(-\theta^\text{VEX})B^\text{IMF})$, which can be denoted as

$$
(B^V)^\text{SVC} = B^V(r^\text{SVC}|B^\text{IMF})^\text{SVC} = B^V(r^\text{SVC}|B^\text{IMF})^\text{SVC} = B^V(r^\text{SVC}|B^\text{IMF} B^\text{IMF}).
$$

Distributing all on the $\rho$-$\zeta$ plane, the VEX observations allow only investigating the induced field $B^V$ in the $\rho$-$\zeta$ plane.
Accordingly, Equation (6) writes

\[ (B^V)^{\text{SVC}} = B^V(r_{\rho}, r_\zeta|B^\text{IMF}, B^\text{VEX}). \quad (7) \]

Similarly, to Equation (5) in VSE, Equation (7) also comprises four independent variables and describes the response of \( B^V \) to \( B^\text{IMF} \) and \( B^\text{VEX} \) in the \( \rho-\zeta \) plane. The SVC position vector is not subject to the IMF estimation and therefore is capable of handling the VSE singular point at \( |B^\text{IMF}| \approx 0 \). In the following subsections, we construct \( B^V(r_{\rho}, r_\zeta) \) under five different \( (B^\text{IMF}, B^\text{VEX}) \) conditions.

2.3. Five IMF Conditions

Figure 5 displays the IMF estimations for all VEX magnetospheric transits in the SVC \( \rho-\zeta \) plane. Each point corresponds to one vector of 4-second-resolved \( B^V \) observed below the altitude \( h < 4400 \text{ km} \) and within the range of solar zenith angle (SZA) between 65° and 150°, which is the targeting region of the current work. The arc-shaped traces reflect cylindrical rotations of VEX with respect to \( B^\text{IMF} \). One arc represents one targeting region transit. The portion colored in cyan corresponds to the 15% lowest magnitude \( |B^\text{IMF}| \), while the remaining portions, in magenta, blue, green, and red, denote four 60° wide ranges of the clock angle \( \theta^\text{IMF} \). The five colors approximately represent the five SW/IMF conditions, namely, \( B^\text{IMF} \approx 0 \), \( B^\text{IMF} > 0 \), \( B^\text{IMF} \approx 0 \), \( B^\text{IMF} < 0 \), \( B^\text{IMF} \approx 0 \), and \( B^\text{IMF} > 0 \). The last four conditions correspond to the transit of the polar caps of \( +B^\text{IMF}, -E^\text{SW}, -B^\text{IMF}, +E^\text{SW} \) hemispheres in the VSE coordinate system. Accordingly, these SW/IMF conditions are denoted hereafter as \( 0B^\text{IMF}, +B^\text{IMF}, -E^\text{SW}, -B^\text{IMF}, +E^\text{SW} \).

Under each of these conditions, we combine the VEX observations to construct \( B^V \) in \( \rho-\zeta \) depiction, using the method detailed in the following subsection.

2.4. A Nonuniform High Spatial Resolution Method for Mapping \( B^V(\rho, \zeta) \)

We distribute the \( B^V \) observations under the \( 0B^\text{IMF} \) condition, colored in cyan in Figure 5, equally into 14 altitude levels, then into 14 SZA bins at each altitude level, resulting in 14 \times 14 spatial bins with approximately identical sampling count, e.g., \( N_{\text{sample}} = 478-479 \) in all bins. In each bin, the median of the position vector \( (r_{\rho}, r_\zeta) \) of the 478–479 samples is shown as a point in the \( \rho-\zeta \) plane in Figure 6(a) and is color-coded with the median of the component \( B_\rho \). On each point, the black cross is the error bar that represents the upper and lower quartiles of \( (r_{\rho}, r_\zeta) \) of the 478–479 samples. Similarly, the \( B_\rho \) and \( B_\zeta \) components and the magnitude \( |B^V| \) are also constructed in Figures 6(b), (c), and (d), respectively. For the other four IMF conditions, \( (B^V(r_{\rho}, r_\zeta)) \) are also constructed and displayed in Figures 6(e)-(h), (i)-(l), (m)-(p), and (q)-(t). In addition, to check the details, we zoom and project \( B^\rho \) and \( |B^V| \), namely, Figures 6(b), (d), (f), (h), (j), (l), (n), (p), (r), and (t), into the SZA-altitude depiction in Figure 8.

The IMF dependence of the Venustian magnetospheric \( B^V \) distribution has been observationally investigated in both cases (e.g., Zhang et al. 2012) and statistical studies (e.g., Dubinin et al. 2014a; Zhang et al. 2015), which are mostly based on manually selected observations and therefore are subject to potential prior expectations. Some studies have also constructed unbiased statistical \( B^V \) under different SW/IMF conditions (Chai et al. 2016; Zhang et al. 2010), using data without any guiding selection. These unbiased studies focused mainly on large structures at planetary scales because they used a popular data-averaging approach. The approach divides the VEX samplings spatially uniformly into cubes and averages data in each cube separately (e.g., Du et al. 2013; Zhang et al. 2010). The resultant maps have uniform spatial resolutions but a nonuniform standard error of the mean (SEM) that is proportional to \( 1/\sqrt{N_{\text{sample}}} \). Here, \( N_{\text{sample}} \) counts observations in a bin that is highly spatially nonuniform (Figure 7(a); also see Du et al. 2013; Chai et al. 2016). In the current study, we map VEX magnetic observations with a uniform SEM by averaging the same number of samplings \( N_{\text{sample}} \) in each bin, which yields a uniform significance with a nonuniform spatial resolution, different from the uniformly spatially resolved works (e.g., Du et al. 2013).

Our resolution is about 1°–1.5° in SZA and up to about 50 km in altitude over 90° SZA at 200 km altitude, at least one order of magnitude higher than the typical resolution of results on the uniform spacing grid (e.g., about 600 \times 600 km in Du et al. 2013; Chai et al. 2016).

3. Classical IMF Draping Configuration at a High Spatial Resolution

The current section illustrates that our mapping approach can resolve structures at various spatial scales, including the planetary-scale IMF draping configuration and the thin ionopause. For convenience, hereafter, we denote the induced \( B^V \) on the in the \( \rho-\zeta \) plane as \( B^V(\bullet) = [B_\rho(\bullet), B_\zeta(\bullet)] \), where \( \bullet \in \{0B^\text{IMF}, \pm B^\text{IMF}, \pm E^\text{SW}\} \) denotes the IMF conditions.

3.1. Symmetries

In Figure 6, the most notable features in the three magnetic components are three antisymmetries, between \( B_\rho \) (e.g., \( B_\rho(0B^\text{IMF}) \) and \( B_\rho(\pm B^\text{IMF}) \), between \( B_\zeta \) (e.g., \( B_\zeta(0B^\text{IMF}) \) and \( B_\zeta(\pm B^\text{IMF}) \)), and between \( B^\rho \) (e.g., \( B^\rho(0B^\text{IMF}) \) and \( B^\rho(\pm E^\text{SW}) \)), illustrated in Panels (m, q), (i, j), and (o, s), respectively. The antisymmetries in \( B_\rho \) and \( B_\zeta \) reveal the draped IMF: the magnetic field is bending from the \( \pm \rho \) direction in the upstream SW to the \( \pm \zeta \) direction in the magnetosphere (for a three-dimensional schematic draping pattern, we refer to He et al. 2016).

Although above, the three magnetic components exhibit a dependence on SW/IMF conditions, \( |B^V| \) exhibits similarities under different SW/IMF conditions. The first similarity is the distinctive day-night difference: on the dayside, e.g., at \( \text{SZA} = 70^\circ \), \( |B^V| \) is stronger than that on the nightside at \( \text{SZA} > 90^\circ \), and it maximizes vertically at about 400–800 km altitude (see Figures 8(b), (d), (f), (h), and (j), which are zoomed versions of Figure 6(d), (h), (l), (p), and (t)), which corresponds to the magnetic barrier. For example, under \( +E^\text{SW} \) in Figures 6(h) and 8(d), \( |B^V| \) in the magnetic barrier is a few times stronger than the IMF magnitude: \( |B^\text{barrier}| > 40 \text{nT} \) versus \( (|B^\text{IMF}|) \approx 7.3 \text{nT} \). Because \( |B^V| \) in Figures 6 and 8 shares similarities between different IMF conditions, in Figure 9(a) we depict \( |B^V| \) as a function of \( h \) using all VEX observations at \( \text{SZA} = 70^\circ-75^\circ \) without considering IMF conditions.

In Figure 9, \( |B^V| \) maximizes at 30–35 nT at 400 and 900 km altitude. In this altitude range, the probability density of
Figure 6. Solar-wind-induced magnetic field $\mathbf{B}^{\text{IMF}}$ in the Sun–Venus-VEX plane (namely, the $\rho-\zeta$ plane in SVC) under the five SW/IMF conditions defined in Figure 5. One SW/IMF condition is arranged in the panels in one row, as specified in the colored boxes at the very left of each row. Below each box, \( \langle \mathbf{B}^{\text{IMF}} \rangle \) and \( \langle \| \mathbf{B}^{\text{IMF}} \| \rangle \) specify the average $\phi$-component and magnitude of the corresponding IMF (namely, the IMF samplings in the corresponding color in Figure 5), while \( N_{\text{sample}} \) counts the number of the samplings in one data bin denoted as one black cross in the row. From left to right, the columns display in order the three magnetic components and the magnitude, namely, $B_r^V$, $B_\phi^V$, $B_z^V$, and $\| \mathbf{B}^V \|$, respectively. The arrows in (e, i, m, q) represent the orientations of $\mathbf{B}^{\text{IMF}}$ and $\mathbf{E}^{\text{SW}}$. In each panel, the solid black lines display the solid surface of Venus and the terminator; one black cross represents one sampling bin, consisting of vertical and horizontal error bars. The tips and intersecting point of the error bars denote the quartiles of $r_\rho$ and $r_\zeta$ of the corresponding VEX samplings within the bin. On the intersecting point, the open circle is color-coded according to the median of the corresponding magnetic component within the bin. In the color-code bar on top of Panels (a)–(c), the arrows and circled-cross and -point symbols indicate the direction of the corresponding magnetic field with respect to the $\rho-\zeta$ plane. In Panels (h) and (l), the cyan line indicates the region covered by the simulation in Figure 7(b) by Villarreal et al. (2015), on top of which the dashed black line around the terminator represents the region that was excluded in the simulation. See Section 2.4 for details.
The \( \| \mathbf{B} \| \) exhibits two maxima, at 25–40 and 0–6 nT, as illustrated in Figure 9(d). The 25–40 nT maximum corresponds to the magnetic barrier, whereas the 0–6 nT maximum reveals the unmagnetized ionosphere that exists below the ionopause. We display the probability \( p \) of \( \| \mathbf{B} \| < 6 \) nT as a function of altitude in Figure 9(c) to use the weak \( \| \mathbf{B} \| \) as an indicator of the unmagnetized ionosphere. At 400–900 km, for about \( p < 10\% \), the ionosphere is unmagnetized. (Note that this indicator is imperfect. Otherwise, (1) \( p \) should maximize at 100% at a low altitude and decrease monotonously with \( h \), and (2) its vertical gradient should be proportional to the probability density of in situ occurrences of the ionopause. In Figure 9(a), below and above the 400–900 km region, \( \| \mathbf{B} \| \) decreases with decreasing and increasing \( h \), respectively. The vertical gradients are signatures of meridional currents flowing oppositely on the ionopause and IMB, as sketched in Figure 19 in Baumjohann et al. (2010), which is quantified in Figure 9(b). In Figure 9(b), the \( \| \mathbf{B} \| \) gradient maximizes at \( h = 320 \) km, with a full width at half maximum (FWHM) of about 90 km, extending from 280 to 370 km. Note that the gradient peak at \( h = 280–370 \) km describes the altitude of the maximum probability density of ionopause occurrences, rather than the complete occurring range or thickness of the ionopause. The ionopause at every instant is a thin layer without a vertical extension. The altitude \( h = 280–370 \) km is above the exobase (150–200 km; see Table 2 in Hodges 2000), suggesting that during VEX operation, the dayside (SZA < 70°–75°) bottom ionosphere is unmagnetized for most of the time. The low-ionosphere magnetization reported in VEX observations (e.g., Dubinin et al. 2014a; Zhang et al. 2012) occurs mostly around the terminator (as detailed below in Section 4.2) because most of the VEX low-ionosphere magnetic observations are distributed not far from the terminator due to the constraints of the VEX orbit, as displayed in Figure 7 and also pointed out by Dubinin et al. (2014a). At \( h < 200 \) km, 75.7% of the observations are distributed at \( 85° \leq \text{SZA} \leq 95° \) (Figure 7(b)).

The \( \| \mathbf{B} \| \) similarities in Figures 6(d), (h), (l), (p), and (t) are associated with different magnetic components under different SW/IMF conditions. Under \( \pm E_{SW} \) (in Figures 6(e)–(g) and (i)–(k)), the gradient is sharper in \( B_{E} \) than that in the other two components, whereas under \( \pm B_{IMF} \) (in Figures 6(m)–(o) and 6(q)–(s)), the gradient in \( B_{E} \) is sharpest. The gradients of these components suggest that the dominant components of the ionopause current in the \( \pm E_{SW} \) and \( \pm B_{IMF} \) hemispheres are in the directions of \( \pm \zeta \) and \( \pm \phi \)-axis, respectively, as displayed by the arrows, cross, and point in Figures 8(d), (f), (h), and (j). Figures 10(a) and 10(b) sketch the topology of the ionopause current in VSE coordinates in the plane \( r_s = R_v/4 \) and \( r_s = 0 \), respectively. In the current work, \( R_v = 6052 \) km denotes the radius of Venus. The currents exhibit symmetry between \( B_{E} \)-IMF hemispheres and antisymmetry between the \( \pm E_{SW} \) hemispheres. On the dayside, \( \pm j_o \) in the \( \pm B_{IMF} \) hemispheres closes \( +j_c \) in the \( +E_{SW} \) hemispheres with \( -j_c \) in the \( -E_{SW} \) hemisphere. Over the poles of the \( \pm E_{SW} \) hemispheres, \( \pm j_c \) flows across the terminator and then closes through the SW or through currents on the IMB or in the magnetic barrier. Furthermore, the vertical \( B_{E} \) gradient in, e.g., Figures 6(f) and 8(c) allows estimating the ionopause current density: the drop by more than 20 nT from the magnetic barrier maximum to low altitude is associated with a current with an intensity higher than 15 A km\(^{-1} \) under the assumption of a sheet-like current distribution.

### 3.2. \( \pm E_{SW} \) Asymmetries

Although Section 3.1 illustrates the similarity of \( \| \mathbf{B} \| \) between the \( \pm E_{SW} \) hemispheres, the \( \| \mathbf{B} \| \) intensity is stronger in the \( +E_{SW} \) hemisphere than in the other hemisphere. Referring to \( \| \mathbf{B} \| = 25 \) nT as a boundary, the magnetic barrier extends to about \( 85° \) SZA under the \( +E_{SW} \) condition (Figure 8(d)), but about \( 75° \) SZA under the \( -E_{SW} \) (Figure 8(f)). To quantify the \( \pm E_{SW} \) difference, in Figure 11(a) we display \( \| \mathbf{B} {+E_{SW}} \| - \| \mathbf{B} {-E_{SW}} \| \), namely, the difference between
The main contributing component to the asymmetric $\|B\|$ is $B_{fo}$, which exhibits an $\pm E^{SW}$ antisymmetric polarity (Figures 6(h) and (l)), as discussed in Section 3.1. To quantify the break of the antisymmetry between Figure 6(h) and 6(l), we display $B_{fo}(+E^{SW}) + B_{fo}(-E^{SW})$ in Figure 11(b). The $\pm E^{SW}$ difference reflects the asymmetry of the IMF wrapping between the $\pm E^{SW}$ poles, as reported in Zhang et al. (2010).

In Figure 11(a), the $\|B\|$ difference exhibits three peaks, on the dayside in the magnetic barrier, on the nightside in the very near magnetotail, and exactly over the terminator at low altitude (in the ionosphere; see the contour line of 13 nT). The barrier and terminator $\|B\|$ peaks are associated with peaks in the $B_{fo}$ difference in Figure 11(b) (above 13 nT; see the contour lines). The barrier and magnetotail peaks extend into global scales, whereas the terminator peak is restricted quite regionally. The global-scale asymmetries are known as the magnetic $\pm E^{SW}$ asymmetry (investigated in both observations and simulations; Saunders & Russell 1986; Zhang et al. 1991; Jarvinen et al. 2013), which also exists at Mars (Vennerstrom et al. 2003). The underlying mechanism is still under debate. Finite Larmor radii effects of pickup ions were suggested to account for the asymmetry (Phillips et al. 1987), but hybrid simulations (Brecht 1990) could reproduce the phenomenon without planetary ions, and indicated that the Hall effect contributes significantly to the asymmetry. In addition, global magnetohydrodynamics (MHD) simulations with multifluid
treatment at Mars (Najib et al. 2011) reproduced the $\pm E_{SW}$ asymmetry, suggesting that the decoupling of separate ion fluids could serve as an alternative explanation.

Compared with the global-scale asymmetries, the regional asymmetry over the terminator is relatively less well understood and is discussed below in Section 4.2.

4. New Lights on the Induced Field

The previous section demonstrates the capability of our mapping approach to resolve small-scale strictures. In the current section, we investigate two structures that have not been depicted in the classical draping configuration.
4.1. The Looping Magnetic Field

A cylindrical symmetrical preference of positive $B_\phi$ was reported on a cylinder in the magnetotail, which was called the induced global magnetic field looping (Chai et al. 2016). The looping structure is denoted by the pink region in Figures 1 and 12(a). For a comparison with Chai et al. (2016), in Figure 11(c) we average $B_\phi$ under the SW/IMF conditions $\pm B_{\text{IMF}}$ and $\pm E_{\text{SW}}$ (Figures 6(f), (j), (n), and (r)). As a reference, the black box in Figure 11(c) sketches the distribution of the $B_\phi$ symmetry according to Chai et al. (2016). In Figure 11(c), the tail-like $B_\phi$ maximum on the nightside is largely consistent with the black box and wrapping slightly toward low latitude.

The tail-like $B_\phi$ maximum exhibits a quantitative difference between the different IMF conditions (in Figures 6(f), (j), (n), and (r)). The $B_\phi$ maximum is strongest under $+E_{\text{SW}}$ (Figure 6(f)) and weaker under $\pm B_{\text{IMF}}$ (Figures 6(n) and 6(r)). Under $-E_{\text{SW}}$ (in the black rectangle in Figure 6(j)), $B_\phi$ even partially reverses to negative. This IMF dependence suggests a cylindrical asymmetry, as sketched in Figure 12(b). Chai et al. (2016) explained the symmetry of $+B_\phi$ preference in terms of currents on two cylinders with the identical longitudinal axis pointing toward $\zeta$ and $-\zeta$ (as sketched in Figure 4(b) in Chai et al. 2016, and here in Figure 12(a) by the red symbols). The breaking of the symmetry of the $+B_\phi$ preference under the $-E_{\text{SW}}$ condition reported here suggests that the current system is not cylindrically complete in the near tail. A correction of the looping structure and two-cylinder currents is sketched in Figure 12(b).

This corrected looping structure could be explained as the superposition of the classical magnetic draping structure with an additional draping configuration. This superposition theory was proposed to explain a similar structure on Mars (Dubinin et al. 2019). Similar to Venus, Mars does not have an internal dipole magnetic field either, and its interaction with SWs

**Figure 11.** Panel (a): The difference between Figures 6(h) and (l). Panel (b): The sum of Figures 6(f) and (j). Panel (c): The average of Figures 6(f), (j), (n), and (r). The green contour lines in Panels (a) and (b) highlight the most intense peaks in these panels. The black arrowed lines in Panel (c) sketch the current proposed in Chai et al. (2016).
produces a similar looping structure (Chai et al. 2019). Dubinin et al. (2019) attributed this looping structure to an asymmetrical pileup of IMF and an associated additional draping configuration in which magnetic fields bend toward the $-E^{\text{SW}}$ direction in the planes normal to the SW velocity. The authors also reproduced this structure in hybrid simulations. The additional draping can produce closed loops over the $-E^{\text{SW}}$ hemisphere and weaken the magnetic field and potentially also magnetic reconnection (also see Rong et al. 2014; Ramstad et al. 2020).

Another morphological character of this looping in Figure 11(c) is that it does not overlap with but is isolated from the low-ionospheric preference of $B_\phi$ over the terminator, as detailed in the following subsection.

### 4.2. Ionospheric $\pm E^{\text{SW}}$ Asymmetry Over the Terminator

Section 3.2 mentioned the $\pm E^{\text{SW}}$ asymmetry over the terminator (highlighted in the black circle in Figure 11(b)). In this small region, the polarity of the induced magnetic component $B_\phi$ is unresponsive to the upstream $B_\phi^{\text{IMF}}$ polarity and prefers to be positive (see the circle in Figure 6(j) and the green isoline in Figure 8(e)). Otherwise, in all other regions, the $B_\phi$ polarity is consistent with the IMF polarity of $B_\phi^{\text{IMF}}$. The asymmetry has been investigated using selected cases (e.g., Dubinin et al. 2014a; Zhang et al. 2015) and was called the $\pm E^{\text{SW}}$ asymmetrical response of low-ionospheric magnetization to the $B_\phi^{\text{IMF}}$ polarity (e.g., Dubinin et al. 2014a). Here, Figures 11(b) and 8(c) and (e) present the unbiased statistic at high spatial resolution.

Not surprisingly, our unbiased statistical results are significantly different from those based on selected cases. For example, the maximum $B_\phi$ is about 13 nT at $+E^{\text{SW}}$ in Figure 8(c) and about 4 nT at $-E^{\text{SW}}$ in Figure 8(e), which are significantly lower than the averaged magnetic intensity, 45 nT, of the 77 selected events in Zhang et al. (2015). This significant difference between $+E^{\text{SW}}$ and $-E^{\text{SW}}$ is also inconsistent with the conclusion in Zhang et al. (2015) that the asymmetry does not show a preference for any particular IMF orientation. Furthermore, our results illustrate that the asymmetry occurs in a very narrow region, at about solar zenith angle $85^\circ < \text{SZA} < 95^\circ$ and altitude $h < 230$ km, referring to $B_\phi > 4$ nT in Figure 8(e). To specify further the extensions in $h$ and SZA, we construct the one-dimensional distribution of $B_\phi$ as a function of $h$ and SZA in Figure 13 under $\pm E^{\text{SW}}$ conditions. The vertical dashed line in each panel displays the half-maximum of $B_\phi$, referring to which, $B_\phi$ peaks at about $h = 185-210$ km, $h = 185-250$ km, SZA $= 88^\circ-95^\circ$, and SZA $= 88^\circ-93^\circ$ in Figures 13(a), (b), (c), and (d), respectively. (Note that $B_\phi$ maxima will be smeared out if using broader $h$ or SZA windows. Therefore the estimation of the $B_\phi$ peak width is subject to the sampling window widths.) Of the identifications of these four peaks, the peak identification in Figure 13(b) is most vulnerable to disturbances of the half-maximum of $B_\phi$. For example, if the half-maximum of $B_\phi$ in Figure 13(b) increases by 2 nT, the peak width will shrink from $h = 185-250$ km to 200–230 km. We therefore describe below the altitude variations, referring mainly to Figure 13(a). The regional distribution implicates that simulations to reproduce the structure entail a high spatial resolution, at about $1^\circ$ in SZA and 10 km in altitude. Note that this SZA range was not included in the simulation in Figure 7(b) by Villarreal et al. (2015), where the simulation presents the magnetic distribution in the VSO $x$-$y$ plane at $z = 1$ Rv, as sketched by the yellow line in Figure 1 and by the cyan line in Figure 6(h) and Figure 11(a).

### 4.3. The Cowling Channel at Venus

Several efforts were made to interpret the asymmetry detailed in Section 4.2, e.g., in terms of the giant flux rope, magnetic belt, intrinsic field, or induced field, and antisunward transports of low-altitude magnetic belts (Zhang et al. 2012; Dubinin et al. 2014a; Villarreal et al. 2015). The potential interpretations were discussed qualitatively in Dubinin et al. (2014a) and Dubinin et al. (2014b), which suggested that the most promising explanation is a Cowling current. As sketched in Figure A1 and detailed in Appendix, a Cowling channel
entails a particular electromagnetic configuration, including a narrow band of high Hall conductivity $\sigma_H$, elongated perpendicular to an ambient magnetic field $B_\phi$, and a primary electric field $E_0$, perpendicular both to the gradient of the $\sigma_H$ band and to $B_\phi$. A Cowling channel might occur over the poles of $\pm E^{SW}$ hemispheres with an orientation as sketched in Figure 14. In the daytime Venusian ionosphere, the Hall conductivity $\sigma_H$ maximizes vertically nearby the maximum vertical peak of the ionospheric electron density (V2 layer; see Dubinin et al. 2014a; Pätzold et al. 2007). The peak is thin vertically and extends broadly in horizontal directions, which is typically under the ionopause and therefore is unmagnetized. However, as suggested by Figures 6 and 8, the ionopause does not cross the terminator, but is below about 85° SZA at 200–400 km altitude. Therefore the SW magnetic field $B^{IMF}_{\phi}$ might penetrate the ionosphere over the $\pm E^{SW}$ poles (Dubinin et al. 2014a). Over the poles, the V2 layer is normal to the $\rho$-axis and $\sigma_H$ gradient, while the $B^{IMF}_{\phi}$ is parallel to the $\phi$-axis and might serve as $B_\phi$. Under this configuration, an antisunward primary electric field $E_0$ might induce a Cowling current along the $\zeta$-axis, $j_C = j_P + j_H$. The magnetic field associated with $j_C$ might account for the low-ionosphere $\pm E^{SW}$ asymmetry. However, a few issues about the Cowling current are still open. Here we discuss the specific distribution of the current and the primary field $E_0$.

4.3.1. The Distribution of the Cowling Current

Dubinin et al. (2014a) have not specified how the Cowling current $j_C$ is distributed. The simplest distribution model is an infinite straight line current with a constant intensity. A line

Figure 13. Panel (a): The induced magnetic field $B_\phi$ as a function of altitude at $88^\circ < \text{SZA} < 93^\circ$ under the $+E^{SW}$ condition. For this plot, the $B_\phi$ observations are first sampled between the vertical white lines in Figure 8(c) and divided into altitude bins; each of which comprises an equal number of samples. In each bin, the quantiles of the altitude and $B_\phi$ of the samplings are presented by a black cross comprising a vertical and horizontal error bar. Panel (b): Same plot as Panel (a), but for the $-E^{SW}$ condition sampled from Figure 8(e). Panels (c) and (d): Similar plots as Panels (a) and (b), but for $B_\phi$ as a function of SZA at $180 < h < 230$ km altitude (sampled between the horizontal dashed white lines in Figure 8(c) and (e), respectively). In each panel, one colored cross denotes one VEX sample; the samplings are evenly divided into bins of $h$ or SZA; in each bin, the quartiles of the samplings are denoted as the black bars, and the vertical dashed magenta line denotes the half-maximum (e.g., it occurs at 8.5 nT in Panel (a) because the median of $B_\phi$ maximizes at 17 nT around $h = 190$ km).

Figure 14. A sketch of the Cowling channel and Cowling current over the poles of $\pm E^{SW}$ hemispheres. The symbols are explained in Figure A1(a) and Appendix.
current would induce a magnetic field inversely proportional to the distance to the line, and therefore the induced magnetic intensity would monotonically decrease with increasing distance. The associated cylindrical component \( B_\phi \) would also decrease monotonically with increasing altitude above the current, as illustrated by the magenta line in Figure 15(a). Inconsistent with this monotonic altitude dependence in the current model, the \( B_\phi \) component of the VEX observation (Figures 13(a)–(b)) maximizes at about 200 km. To address this inconsistency, we propose a minor correction to the infinite line current model.
We assume that the line current does not occur at a fixed position, but at a random position, e.g., \( r_j \sim N_2(\mu_0, \sigma^2) \), a two-dimensional Gaussian random variable with a mean of \( \mu_0 \) and variance of \( \sigma^2 \). The probability density function of \( r_j \) for the particular case of \( \mu_0 := [r_{0x}, r_{0y}] = [0, 0] \) is displayed in Figure 15(c). A line current with constant intensity \( j_c \) at \( r_j \) will induce a distribution of magnetic \( B_\phi \), as depicted in Figure 15(b). Above the current, \( B_\phi \) exhibits a peak, similar to that in Figure 13(a). Furthermore, we use values at the black points in Figure 13(a) for a least-squares fit to the \( B_\phi \) along the magnetola line in Figure 15(b), resulting in \( j_c = 191 \, \text{A}, \quad d = 10 \, \text{km}, \quad \text{and} \quad r_{0\phi} = 1Rv + 179 \, \text{km}. \) The fitted results, as displayed in Figure 15(d), suggest that a current located at altitude \( 179 \pm 10 \, \text{km} \) with an intensity of \( 191 \, \text{A} \) could account for the \( B_\phi \) variation in the VEX observation (Figure 13(a)).

4.3.2. The Primary Electric Field

Dubinin et al. (2014a) conjectured that the primary electric field \( E_{0C} \) might arise from downward-drifting electrons. In the Cowling channel, electrons are supposed to be decoupled from ions due to their different ratios of the gyrofrequency over the collision frequency (\( \kappa_i < 1 \) but \( \kappa_e > 1 \); see Appendix A.1). The downward electron drift is supposed to be on the order of magnitude of 100 m/s and is being driven by the SW motional electric field \( E_{SW} \) mapping along SW magnetic field lines. However, this mechanism is still lacking details. For example, the downward electron drift is associated with an upward Pedersen current \( j_{Ped} \), accumulating potentially polarization charges on the upper and lower ionospheric boundaries. The polarization charges and the induced polarization electric field would be superimposed on \( E_{SW} \), resist the downward electron drift, and terminate \( E_{0C} \). Another detail is that the electron drift mechanism cannot explain why the asymmetry occurs in a very narrow SZA range over exactly the terminator because the Cowling channel and electron drift might occur in a broader SZA range. An alternative explanation of \( E_{0C} \) is a horizontal polarization electric field. Over the terminator, it maximizes the solar radiation gradient in the \( \zeta \) direction, and therefore maximizes the gradients of the ionospheric density \( \nabla \sigma_n \) and conductivity \( \nabla \sigma_T \). It is also over the terminator in the \( \pm E_{SW} \) hemisphere where the ionopause current merges with the cross-tail current. By preventing a divergence of currents, polarization charges and electric field \( E_\zeta \) might be created and serve as the primary electric field \( E_{0C} \) in the Cowling channel. Note that the polarization mechanism might be equivalent to the electron drift mechanism, but it might describe the asymmetry from a different perspective. Evaluating mechanisms and quantitatively explaining the asymmetry entails simulations at a spatial resolution higher than an order of magnitude of 10 km due to the narrow vertical extension.

5. Summary

The current work uses all VEX magnetic observations to map the near-Venus-induced magnetic field under different IMF conditions at a high spatial resolution through an unbiased statistical method. Using VEX SW observations, we predict the IMF for the VEX magnetospheric transit and evaluate the prediction. For the mapping, we define the SVC coordinate system. Similar to the VSE system, SVC also makes use of the cylindrically symmetrical response of the induced magnetic field to the IMF, but is superior to VSE because the determination of SVC axes is not subject to the error of the IMF estimation, and SVC can deal with the near-zero IMF condition. Our mapping resolution is spatially not uniform, maximizing in the ionosphere where VEX collects most observations. The high resolution enables depicting the small-scale structures, such as the ionopause, as well as the planetary-scale structures, such as the classical draping configuration and the magnetic pileup region. At 70°–75° solar zenith angle (SZA), the ionopause occurs with the highest probability density between 280 and 370 km altitude, above the expected exobase (150–200 km), suggesting that the bottom ionosphere at SZA < 75° is unmagnetized for most of the time during the VEX operation. Our mapping reveals that the magnetic pileup region extends to about 85° SZA over the +E_{SW} pole, but about 75° SZA over the –E_{SW} pole. In addition, our mapping resolves the ±E_{SW} asymmetry in the low-ionospheric magnetization and the planetary-scale looping magnetic field. The looping structure is cylindrically asymmetrical: much stronger under +E_{SW} than under –E_{SW}. Under –E_{SW}, the looping breaks, which can be attributed to the presence of an additional IMF draping configuration that occurs in the planes perpendicular to the SW velocity. The looping occurs in the magnetotail, separated from the low-ionospheric ±E_{SW} asymmetry that occurs in the narrow region, at about 88°–95° SZA and 185–220 km altitude. Our least-squares fit of VEX observations to a line current model at a Gaussian random position suggests that the altitude variation of the low-ionospheric asymmetry is attributable to an antisunward line current with an intensity of 191.1 A at 179±10 km altitude. We explain this line current in terms of a Cowling channel.

Our results also implicate that to reproduce the Venustian low-ionospheric magnetization through simulations entails an altitude resolution of about 10 km. As artificial satellites orbit extraterrestrial planets mostly with high orbital eccentricities, their observations are typically highly spatially unevenly distributed. Our mapping method exploits these unevenly distributed data sets to resolve structures on various scales, with higher resolutions in regions with denser observations. Further works could implement the method on observations at Mars and Titan, where similar low-ionospheric magnetization and the planetary-scale looping structures are expected or observed.

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Appendix

Cowling Channel

A.1. Atmospheric Electrical Conductivity and Its Altitude Dependence

In magnetized plasma, the Lorentz force drives charged particles drifting gyratorily and periodically perpendicular to the ambient magnetic field \( B_\phi \). As a result, the particles are bound to magnetic field lines. The gyrotary drift might be interrupted by collisions with other particles, either charged or neutral. In an extreme collisional case, the gyrotary is relatively negligible, and particles are freed from the magnetic field and move freely at the bulk velocity of the ambient particles. A measure of the relative importance between the gyrotary drift and collision is the ratio of the gyrofrequency to collision...
frequency $\kappa = \frac{\Omega}{\nu}$. The ratio $\kappa$ quantifies the expectation of the number of gyratory drifting circles that one particle could achieve in between two collisions with other particles. The collision frequency is proportional to the particle densities. In planetary atmospheres, the collision frequency therefore decreases exponentially with increasing altitude as the neutral density decreases, whereas the gyrofrequency is relatively less dependent on altitude. Accordingly, $\kappa$ overall increases with altitude. At low altitude, collisions are superior to gyratory drifts ($\kappa \ll 1$), whereas at high altitude, the collisions are rare and gyratory drifts are more important ($\kappa \gg 1$). In between the low and high altitudes, there is a transitional altitude $h_{t\kappa=1}$, where $\kappa \approx 1$. However, the vertical increasing rate $\frac{dh_{t\kappa=1}}{dh}$ is different for different species, steeper for electrons than for ions $\frac{dh_{t\kappa=1}}{dh} > \frac{dh_{e\kappa=1}}{dh}$, yielding higher transitional altitudes for ions than for electrons $h_{i\kappa=1} > h_{e\kappa=1}$. Here, $i$ and $e$ in the subscripts denote ions and electrons, respectively.

As a result, the atmospheric electrical conductivity and its isotropy are altitude dependent. Above $h_{i\kappa=1}$ when plasma is collisionless ($\kappa_i \gg 1$, $\kappa_e \gg 1$), in response to an applied electric field $E_0$, both ions and electrons drift toward the direction of $E_0 \times B_0$ on the macroscopic scale, and no net current is generated. Under $h_{e\kappa=1}$ in the collisional case ($\kappa_i \ll 1$, $\kappa_e \ll 1$), the applied field $E_0$ drives ions and electrons flowing along $E_0$ oppositely, generating a current $j_p = \sigma_p E_0$ parallel to $E_0$, independent of $B_0$. The current $j_p$ is known as Pedersen current, and the coefficient $\sigma_p$ is known as Pedersen conductivity. Between $h_{i\kappa=1}$ and $h_{e\kappa=1}$ in the intermediate case ($\kappa_i \ll 1$, $\kappa_e \gg 1$), electrons are already bound to $B_0$, whereas ions could still essentially move with ambient winds. The applied field $E_0$ decouples electrons from ions: electrons drift in the direction $E_0 \times B_0$, whereas the ions prefer following toward $E_0$. The caused current comprises a component $j_p$ following along $E_0$ and a component $|j|_H = \sigma_H |E_0|$ parallel to $E_0 \times B_0$. The current $j_H$ is known as the Hall current and the coefficient $\sigma_H$ is known as Hall conductivity.

For references, the range $(h_{i\kappa=1}, h_{e\kappa=1})$ approximately corresponds to (90 km, 150 km) in the terrestrial equatorial ionosphere (see Figure 2.5 in Kelley 2009) and (130 km, 270 km) at Venus (see Dubinin et al. 2014a).

A.2. Cowling Channel: A Model and Two Instances at Earth

In a particular configuration of conductivity and magnetic field, the electric current in the direction of $E_0$ might be much intenser than $j_p$ due to a superposition of $j_H$. The geometry of the configuration is characterized by a band of $\sigma_p$ that is elongated infinitely in one dimension, but is restricted in the perpendicular direction. Figure A1(a) sketches the configuration and the causative relations of the superposition through three steps. In the first step, a primary electric field $E_0$, parallel to the elongated direction and within the ambient magnetic field $B_0$ that is normal to the plane spanned by $\nabla \sigma_p$ and $E_0$ generates the Hall and Pedersen current $j_H$ and $j_p$. Second, on the boundary where $|\nabla \sigma_p| > 0$, polarization charges and electric field $E'$ are created by preventing a divergence of $j_H$. In the last step, the secondary field $E'$ further generates secondary Hall and Pedersen currents $j'_H$ and $j'_p$. $j'_H$ flows along $j_H$ and therefore the total current parallel to $E_0$ equals $j_C = j_p + j'_H$, which is more intense than $j_p$. The reinforcement of the current in the $E_0$ direction is called Cowling effect (e.g., Yoshikawa et al. 2013), the reinforced current $j_C$ is known as Cowling current (e.g., Tang et al. 2011). $\sigma_C := |j_C|/E_0$ is the Cowling conductivity, and the whole current system is called the Cowling channel. Note that the horizontal separations of elements shown in Figure A1(a) represent only the causative relations in the explanation, but not the spatial distribution. In space, the elements coexist under an electrodynamic equilibrium, as sketched in Figure A1(b). The three steps illustrated in Figure A1(a) are not a unique explanation for the equilibrium. In the end, only the equilibrium matters.

For detailed discussions, we refer to the literature in the context of two instances of Cowling channels in Earth’s ionospheric E-layer, over the equator and auroral zone, respectively (e.g., Kelley 2009; Fuji et al. 2011, and references therein). The corresponding Cowling currents in these two instances are well known as the equatorial electrojet (EEJ; Forbes 1981, and references thereafter) and auroral electrojet (AEJ; Bostrom 1964, and references thereafter). The orientation of these two Cowling channels is sketched in Figures A1(c) and (d). In both cases, the Cowling channels are zonally elongated and the geomagnetic field serves as $B_0$. In the case of EEJ, $B_0$ is northward, the gradient $\nabla \sigma_p$ is vertical, and the eastward component of the electric field induced by the tidal wind serves as the primary electric field $E_0$. For the boreal westward AEJ, $B_0$ is downward, $\nabla \sigma_p$ is in the magnetic meridional direction, and the zonal electric field mapped from the magnetosphere serves as $E_0$.

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![Figure A1](https://example.com/figureA1.png)

(a) causative relations $j_C = j_p + j'_H$ [\(\sigma_H\)]

(b) spatial relations

(c) EEJ

(d) boreal westward AEJ

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**Figure A1.** Panel (a): An explanation of a Cowling channel. Note that in Panel (a), the symbols from left to right represent the causative relations rather than the spatial distribution, which is sketched in Panel (b). Panels (c) and (d): Orientations of the Cowling channel in the equatorial electrojet and in the boreal westward auroral electrojet.
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