Three-dimensional Configuration of Induced Magnetic Fields around Mars

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Abstract

Using over 6 years of magnetic field data (2014.10-2020.12) collected by the Mars Atmosphere and Volatile EvolutioN (MAVEN), we conduct a statistical study on the three-dimensional average magnetic field structure around Mars. We find that this magnetic field structure conforms to the pattern typical of an induced magnetosphere, that is, the interplanetary magnetic field (IMF) which is carried by the solar wind and which drapes, piles up, slips around the planet, and eventually forms a tail in the wake. The draped field lines from both hemispheres along the direction of the solar wind electric field (E) are directed towards the nightside magnetic equatorial plane, which looks like they are "sinking" toward the wake. These "sinking" field lines from the +E-hemisphere (E pointing away from the plane) are more flared and dominant in the tail, while the field lines from the –E-hemisphere (E pointing towards) are more stretched and "pinched" towards the plasma sheet. Such highly "pinched" field lines even form a loop over the pole of the –E-hemisphere. The tail current sheet also shows an E-asymmetry: the sheet is thicker with a stronger tailward J×B force at +E-flank, but much thinner and with a weaker J×B (even turns sunward) at –E-flank. Additionally, we find that IMF B_x can induce a kink-like field structure at the boundary layer; the field strength is globally enhanced and the field lines flare less during high dynamic pressure; however, the rotation of the planet, against expectations, modulate the configuration of the tail current sheet insignificantly.

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Key Points:

- The magnetic field structure has an evident hemispheric asymmetry along the direction of the solar wind electric field.
- The tail current sheet is thicker and has a stronger tailward J×B force near the flank of the +E-hemisphere.
- The effects of IMF Bx, the dynamic pressure of solar wind, and the rotation of the planet on the field structure are surveyed respectively.

Abstract

Using over 6 years of magnetic field data (2014.10-2020.12) collected by the Mars Atmosphere and Volatile EvolutioN (MAVEN), we conduct a statistical study on the three-dimensional average magnetic field structure around Mars. We find that this magnetic field structure conforms to the pattern typical of an induced magnetosphere, that is, the interplanetary magnetic field (IMF) which is carried by the solar wind and which drapes, piles up, slips around the planet, and eventually forms a tail in the wake. The draped field lines from both hemispheres along the direction of the solar wind electric field (**E**) are directed towards the nightside magnetic equatorial plane, which looks like they are "sinking" toward the wake. These "sinking" field lines from the +E-hemisphere (**E** pointing away from the plane) are more flared and dominant in the tail, while the field lines from the –E-hemisphere (**E** pointing towards) are more stretched and "pinched" towards the plasma sheet. Such highly "pinched" field lines even form a loop over the pole of the –E-hemisphere. The tail current sheet also shows an E-asymmetry: the sheet is thicker with a stronger tailward J×B force at +E-flank, but much thinner and with a weaker J×B (even turns sunward) at –E-flank. Additionally, we find that IMF B_x can induce a kink-like field structure at the boundary layer; the field strength is globally enhanced and the field lines flare less during high dynamic pressure; however, the rotation of the planet, against expectations, modulate the configuration of the tail current sheet insignificantly.

Plain Language Summary

To clarify the global magnetic field structure around Mars, we comprehensively study the three-dimensional (3D) magnetic field structure of the Martian magnetosphere based on measurements from MAVEN. Our study derives 3D distribution features of the magnetic field structure, quantitatively estimates the tail current sheet and also investigates possible effects brought by the IMF Bx, the dynamic pressure of solar wind, and planetary rotation on the magnetic field structure. This 3D magnetic field structure around Mars is essential to understanding the dynamic processes of the Martian magnetosphere.

1 Introduction

It is well known that both Venus and Mars lack a global dipole field and that the solar wind plasma flow along with the "frozen-in" interplanetary magnetic field (IMF) interacts with the atmosphere/ionosphere of the planet directly, resulting in an induced magnetosphere. On the dayside, IMF piles up to form a magnetic barrier and drapes around the planet. The draped IMF is stretched by the solar wind and slips into the wake to form an elongated induced magnetotail [e.g., Acuña et al., 1998; Luhmann al., 2004; Ma et al., 2002; McComas et al., 1986]. Researchers realize that most of the planetary ions escape to interplanetary space via the electromagnetic force, e.g. the solar wind electric fields (**E**), the hall electric fields, and the ambipolar electric fields [e.g., Barabash et al., 2007; Dubinin et al., 2011; Lundin, 2011; Dubinin & Fraenz, 2015; Fang et al., 2010; Futaana et al., 2017; Nilsson et al., 2021; Zhang et al., 2021]; therefore, knowledge of the magnetic field structure around the Mars is vital for understanding associated magnetospheric processes (e.g., the escape of planetary ions).

Venus is an ideal natural laboratory for studying an induced magnetosphere because the planet has no significant intrinsic field and only relies on its ionosphere as an obstacle to solar wind. Early studies based on the Pioneer Venus Orbiter have found a structure of draped field lines in the distant downstream tail (8-12 Venusian radii) and demonstrated that there is an asymmetrical tail field structure along the direction of the solar wind electric field (E-asymmetry) [Saunders and Russell, 1986; McComas et al., 1986]. Studies based on observations of the Venus Express, the ESA's first mission to Venus [Titov et al., 2006], demonstrated that E-asymmetry had already occurred in the terminator and the near-Venus tail, suggesting that magnetic field lines are likely wrapped more tightly around Venus in the –E-hemisphere (electric field points towards planet) [Zhang et al., 2010; Du et al., 2013]. Rong et al. [2014] reconstructed the three-dimensional (3-D) field structures of the near-Venus tail and found that its draped field lines would sink into the wake, while the magnetic field structure of the tail current sheet would become irregular in the –E-hemisphere. Chai et al. [2016] suggested that a global looping field around the tail might occur in addition to the draped field lines.

Unlike the induced magnetosphere of Venus, Mars has patches of localized intense remnant crustal fields, particularly in the southern hemisphere [e.g., Acuña et al., 1999; Connerney et al., 2005]. These crustal fields contribute to solar wind interactions, complicating the Martian space environment. Although many studies in the past several decades have been conducted based on the spacecraft missions such as Phobos-2, Mars Global Surveyor, and Mars Express [e.g., Yeroshenko et al., 1990; Halekas et al., 2006; Barabash et al., 2007; Fedorov et al., 2006], our knowledge about the magnetic field structure of Mars' magnetosphere is lacking due to limited orbit coverage and inadequate scientific equipment. However, NASA's recent mission on the Mars Atmosphere and Volatile EvolutioN (MAVEN) spacecraft carried both magnetometer and plasma instruments and provided global coverage of the Martian space environment within 3 R_m (R_m= 3390km, Mars radius), with an orbit period of about 4.5 hours [Jakosky et al. 2015], enabling us to study the global average magnetic field configuration around Mars.

Based on MAVEN observations, Harada et al. [2015] found that the tightly-wrapped field lines and the sunward flow of ionospheric plasma tend to occur in the –E-hemisphere. Inui et al. [2019] pointed out that Martian ions with high speeds form a plume in the +E-hemisphere, while dense and slow-speed ions form an ion trail in the –E-hemisphere. Both simulations and observations show that crustal fields can twist the Martian magnetotail [Luhmann et al., 2015; DiBraccio et al., 2018; Xu et al., 2020]. To lower the possible effects of these fields on magnetospheric field structure, Dubinin et al. [2019, 2021] focused solely on the northern hemisphere to study the field structure of Martian induced magnetosphere; they found that the draping fields wrap the planet in the +E-hemisphere and then propagate toward the –E-hemisphere. By studying the projected distribution of magnetic field in the plane perpendicular to the Sun–Mars line, Chai et al. [2019] argued that a looping magnetic field also rotates around the Martian magnetotail.

Although these studies have revealed some characteristics of the magnetic field configuration of the Martian magnetosphere, the 3-D configuration of the field structure and its variations remains unclear. Hence, our goal is (1) to draw the global 3-D magnetic morphology of the Martian magnetosphere based on the magnetic field data collected by MAVEN over a period of 6 years (2014.10-2020.12), and (2) to investigate the possible impacts brought about by the IMF, solar wind pressure, and planet rotation. Overall, such a study would benefit our understanding of solar wind interaction with Mars.

2 Coordinates and Data Set

In this paper, we adopt magnetic field data measured by the Magnetometer (MAG) [Connerney et al., 2015] from 1 October 2014 to 31 December 2020. MAG measures the magnetic field vectors at sample rates 32 Hz and 1 Hz. To minimize the noise and high-frequency fluctuations, we use the data of 1s resolution.

Two Cartesian coordinate systems are involved in this study. The first uses Mars-centered Solar Orbital (MSO) coordinates, where the X_{MSO} axis points from the center of Mars to the Sun, the Z_{MSO} axis points to the North Pole of Mars' orbital plane, and the Y_{MSO} axis completes the right-handed system. The second is the Mars Solar Electric coordinates (MSE), where X_{MSE} points antiparallel to the upstream solar wind flow, Y_{MSE} points along the cross-flow magnetic field component of the upstream IMF, and Z_{MSE} points along the direction of the convection electric field in the solar wind. Since the magnetic field configuration of the induced magnetosphere is guided by the IMF orientation, one has to study the 3-D magnetic field structure of the Martian magnetosphere in MSE.

To organize magnetic field data in MSE, we select orbits where pristine solar wind can be measured. Similar to procedures adopted by Liu et al. [2021], we first identify orbits with identifiable bow shock crossings according to the jump variation of their magnetic field strength, the ion energy spectrum of the Solar Wind Ion Analyzer (SWIA) [Halekas et al. 2013], and the electron energy spectrum of the Solar Wind Electron Analyzer (SWEA) [Mitchell et al. 2016]. Then, for each orbit, we took the average of upstream solar wind 30 minutes before (after) the inbound (outbound) bow shock crossing; the averaged solar wind velocity and IMF are denoted $\vec{V}_{sw1}$ and $\vec{B}_1$ ($\vec{V}_{sw2}$ and $\vec{B}_2$), respectively. Because the IMF is usually time-varied, we chose orbits during which the IMF was steady to construct MSE coordinates. This steady IMF is defined when the angle between $\vec{B}_1$ and $\vec{B}_2$ is less than 30°. Thus, for a steady IMF, we have $\vec{X}_{MSE}=-\frac{\vec{V}_{sw1}+\vec{V}_{sw2}}{|\vec{V}_{sw1}+\vec{V}_{sw2}|}$, $\vec{Y}_{MSE}=\frac{\vec{B}_{\perp 1}+\vec{B}_{\perp 2}}{|\vec{B}_{\perp 1}+\vec{B}_{\perp 2}|}$, and $\vec{Z}_{MSE}=\vec{X}_{MSE}\times\vec{Y}_{MSE}$. The subscript "$\perp$" represents the cross-flow component of the IMF, which can be calculated by subtracting the flow-aligned component, e.g., $\vec{B}_{\perp 1}=\vec{B}_1-(\vec{B}_1\cdot\vec{X}_{MSE})\vec{X}_{MSE}$. The direction of $\vec{Z}_{MSE}$ is also the same as that of the solar wind electric field (**E**). The Cartesian components of the magnetic field along the X-axis, Y-axis, and Z-axis in MSE are denoted as B_x, B_y, and B_z, respectively.

We found 4179 orbits in total that satisfy the conditions of a steady IMF; the measured magnetic field vectors in those orbits were transformed into MSE. To exclude the influence of crustal fields, we only kept magnetic field data points satisfying $|B_{obs}|\geq 10|B_{model}|$, where

$|B_{obs}|$ is the recorded magnetic field strength and $|B_{model}|$ is the magnetic field strength predicted by a state-of-the-art crustal fields model [Gao et al., 2021]. These data points constitute the data set we used in this study. For solar wind parameters corresponding to these orbits, we averaged those parameters outside the bow shock: for example, the average IMF of one given orbit is $IMF = \frac{\vec{B}_1 + \vec{B}_2}{2}$.

To avoid statistical bias, we checked the IMF distribution of our data set. Figures 1a–1c shows histograms of the upstream average IMF for each orbit. Here, the IMF strength is mostly smaller than 5 nT and peaks at ~2.5 nT (Figure 1a). The direction of IMF is characterized by its cone and clock angle. The cone angle—the angle between the IMF and $+X_{MSO}$—has a unimodal distribution and peaks at ~90° (Figure 1b). The clock angle—the angle between the projected IMF and $+Z_{MSO}$ in the YZ_{MSO} plane (and which increases rotationally from $+Z_{MSO}$ toward $+Y_{MSO}$)—exhibits a bimodal distribution with peaks reaching 90° and 270° (Figure 1c). The IMF distributions in our data set are consistent with typical ones regarding the upstream solar wind condition at Mars [Liu et al., 2021]. Thus, our data set is statistically significant enough to survey the average magnetic structure of the Martian induced magnetosphere.

As shown in Figures 1d–1f, the spatial region around Mars ($-2 < X_{MSE} < 3$ R_m, $-3 < Y_{MSE} < 3$ R_m, $-3 < Z_{MSE} < 3$ R_m) is adequately accounted for by our data set. In the following sections, we will study the magnetic field structure within this region (MSE coordinates are used unless otherwise stated.).

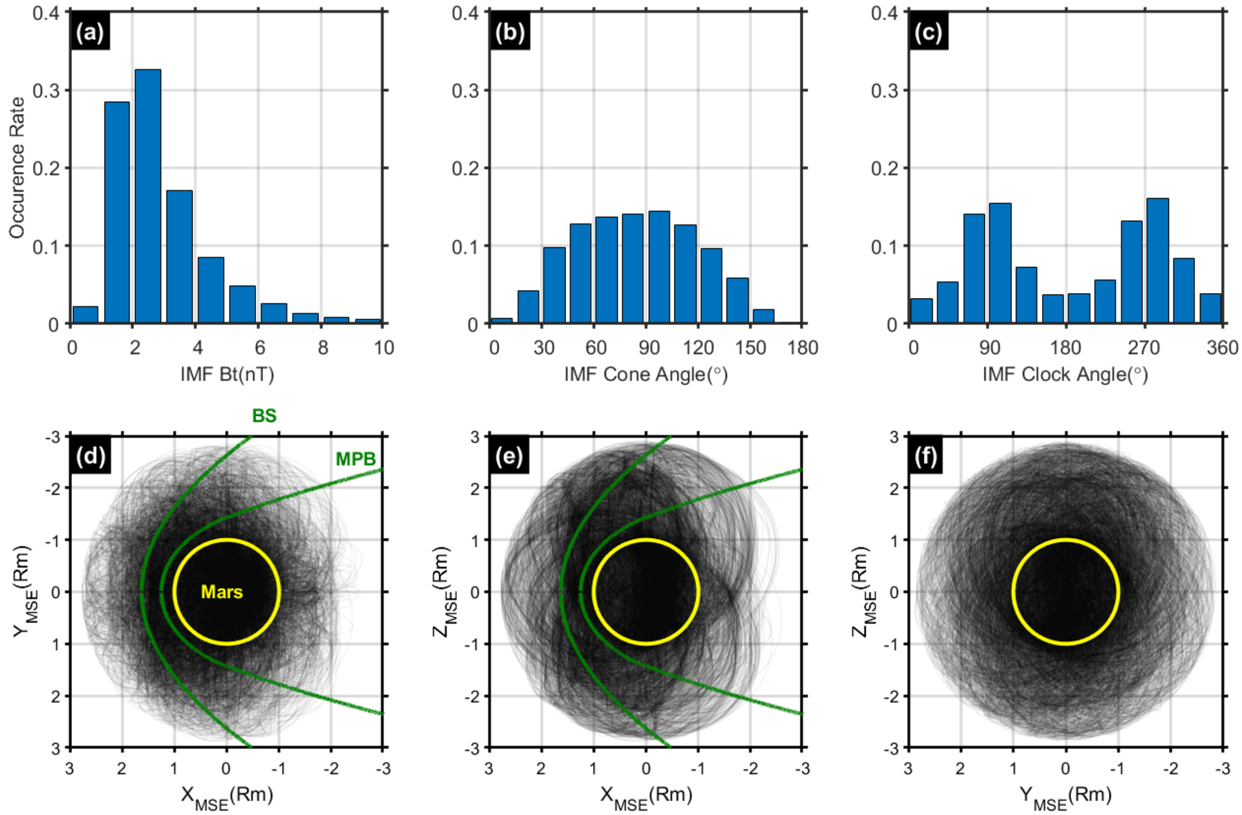

Figure 1. The upper panels show histograms of (a) the IMF strength, (b) the IMF clock angle, and (c) the IMF cone angle, respectively. The lower panels show orbit coverage of the data set, projected on the plane of (d) XY_{MSE}, (e) XZ_{MSE}, and (f) YZ_{MSE}, respectively. The yellow circles represent the body of Mars, while the green curves represent the nominal shape of the bow shock (BS) and the magnetic pile-up boundary (MPB) [Trotignon et al., 2006].

3 Statistical Results

To establish and draw the 3-D characteristics of the magnetic field configuration around Mars, we first check the average two-dimensional distributions of magnetic field vectors in the slices of the XZ_{MSE}, XY_{MSE}, and YZ_{MSE} planes, respectively, at different locations. Each slice is partitioned by a bin of 0.2×0.2 Rm, and the field vectors located in the slice are averaged for each bin. To ensure statistical significance, we ignore bins whose data points are fewer than ten.

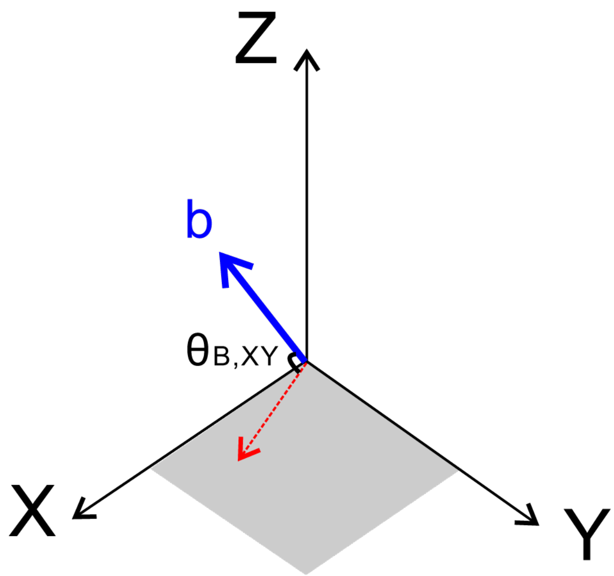

Figure 2. The sketched diagram to show the orientation of the unit magnetic field vector. The blue arrow represents the unit magnetic field vector ($\vec{b}$), the red arrow denotes the projection of $\vec{b}$ on XY_{MSE} plane. The $\theta_{B,XY}$ is the angle between $\vec{b}$ and XY_{MSE} plane.

To study the 3-D field structure, we also need to evaluate how much the average field vectors deviate from the slices above by calculating the angle between these vectors and the slices of XZ_{MSE}, XY_{MSE}, YZ_{MSE} planes, respectively:

$$\begin{cases} \theta_{B,XZ} = a\sin(b_y) \\ \theta_{B,XY} = a\sin(b_z) \\ \theta_{B,YZ} = a\sin(b_x) \end{cases} \tag{1}$$

where b_x, b_y, b_z represent the x, y, z component of the average unit magnetic field vector respectively in the bin. Taking $\theta_{B,XY}$ as an example (see Figure 2), the $\theta_{B,XY}$=90°(−90°) represents that the field lines are pointing along $+Z_{MSE}$ ($-Z_{MSE}$), while $\theta_{B,XY}$=0° represents the field lines are parallel to XY_{MSE} plane. Furthermore, a larger $\theta_{B,XY}$ indicates is the field lines are more perpendicular to the XY_{MSE} plane.

3.1 Magnetic Field Structure in XZ Plane

We first check the distribution of the magnetic field in different slices of XZ_{MSE} planes, with each slice having a thickness of 0.5 Rm within -2Rm < Y_{MSE} < 2Rm. Based on the average distribution of the B_x, B_y, and B_z components in the bin of each slice, we can plot the average projected magnetic field lines (MFLs) in the XZ_{MSE} plane, while calculating the $\theta_{B,XZ}$ according to Eq. (1).

In Figure 3, the upper panels show field distributions for slices in the +Y_{MSE}-hemisphere (Figures 3a–3d), while the lower panels do so for slices in the –Y_{MSE}-hemisphere (Figures 3e-3h). As we can see, the MFLs are directed tailward (sunward) in the +Y_{MSE} (-Y_{MSE}) –hemisphere, which means the IMF, pointing basically towards the +Y_{MSE} direction, begins draping near the planet. Meanwhile, we notice that, from both flanks along Y_{MSE} to the central meridian, the draping MFLs outside the magnetic pile-up boundary tilt towards the nightside magnetic equatorial plane (~ Z_{MSE}= 0); thus, the MFLs looks like they are "sinking" into the Martian wake. This pattern is reminiscent of the "sinking fields" observed in the Venusian magnetotail [Rong et al., 2014]. We also notice that the "sinking fields" from +Z_{MSE} –hemisphere can extend down to ~ Z_{MSE}= -1 Rm; thus, "sinking fields" are more significant in the +Z_{MSE}–hemisphere than in the -Z_{MSE}–hemisphere, which is consistent with the hemispheric asymmetry of "sinking fields" reported by Rong et al. [2014] in the Venusian tail. Recent studies by Dubinin et al. [2019, 2021] have likewise reported the E-asymmetry of draping field structure in Martian tail.

Meanwhile, outside both flanks (|Y_{MSE}|>1.5 Rm; see Figures 3a and 3e), the "sinking" field lines from both ±E-hemispheres are basically symmetrical respective to the plane of Z_{MSE}=0, indicating that the E-asymmetry is weaker there.

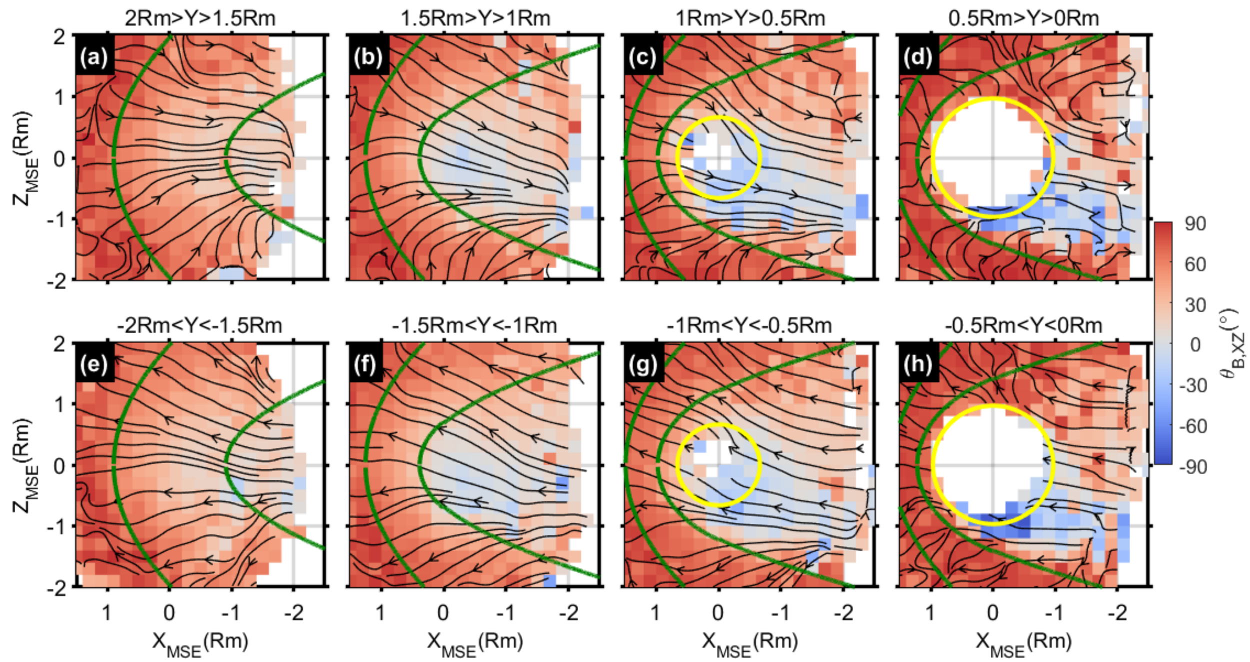

Figure 3. Average distributions of $\theta_{B,XZ}$ in the slices of the XZ$_{MSE}$ plane within different ranges of the Y$_{MSE}$ coordinate. Overplotted black lines with arrows denote the average MFLs. MFLs with red- (blue)-colored regions mean MFLs have a positive (negative) B_y component. In each panel or slice, the yellow circle represents the mean cut of Mars' body while the two green curves represent the mean cut of the nominal BS, MPB shape. Taking panel c as an example, the two green curves and the yellow circle are cuts of the BS, MPB shape and Mars' body, respectively, at Y$_{MSE}$=0.75 Rm.

Additionally, when approaching the central meridian from both flanks, the polarity of B_y component in some parts of the –E-hemisphere becomes negative (see negative $\theta_{B,XZ}$ in Figure 3); thus, corresponding MFLs seem stretched (Figures 3b–3c and Figures 3f–3g) and even "pinched" nearer the central meridian (Figures 3d-3h). Both "sinking" and "pinched" effects show that MFLs in the –E-hemisphere are tightly wrapped around the planet.

3.2 Magnetic Field Structure in XY Plane

Using the same procedures in subsection 3.1, we examine the magnetic field structure in slices of the XY$_{MSE}$ plane.

Figure 4 shows distributions of $\theta_{B,XY}$ and the average MFLs in slices of the XY_{MSE} plane with a thickness of 0.5 Rm from Z_{MSE} = 2Rm to Z_{MSE} = –2Rm.

Clearly, each panel of Figure 4 shows an IMF that basically points towards $+Y_{MSE}$ in the upstream and bends upon approaching the planet. The bent MFLs are draped around the planet, which results in a positive Bx in the $–Y_{MSE}$-hemisphere and a negative Bx in the $+Y_{MSE}$-hemisphere. From the flanks of both ±E-hemispheres to the equator region (Z_{MSE} = 0), the draped MFLs are more tightly wrapped around the planet on the dayside and the field lines more stretched in the down tail.

Interestingly, the field lines in the wake of the –E-hemisphere are highly stretched and are even "pinched" towards the central meridian or plasma sheet (Figures 4f – 4h). The "pinched" field lines in the –E-hemisphere correspond to the negative B_y component, as noted in Figure 3.

It is important to note from Figure 4 that $\theta_{B,XY}$ in the +E-hemisphere is positive (negative) when $Y_{MSE}<0$ ($Y_{MSE}>0$), a feature that extends even to the –E-hemisphere (Figures 4g – 4h). In contrast, the opposite distribution pattern of $\theta_{B,XY}$ only occurs near the flank of –E-hemisphere (Figures 4e – 4f). The distribution of $\theta_{B,XY}$ demonstrates that the draped MFLs with $Z_{MSE}> –1$ Rm "sinks" towards the –E-direction, while the draped MFLs with $Z_{MSE}< -1$ Rm "sinks" towards the +E-direction. The E-asymmetry of these "sinking" field lines, as demonstrated by Figure 4, is consistent with our findings in Figure 3.

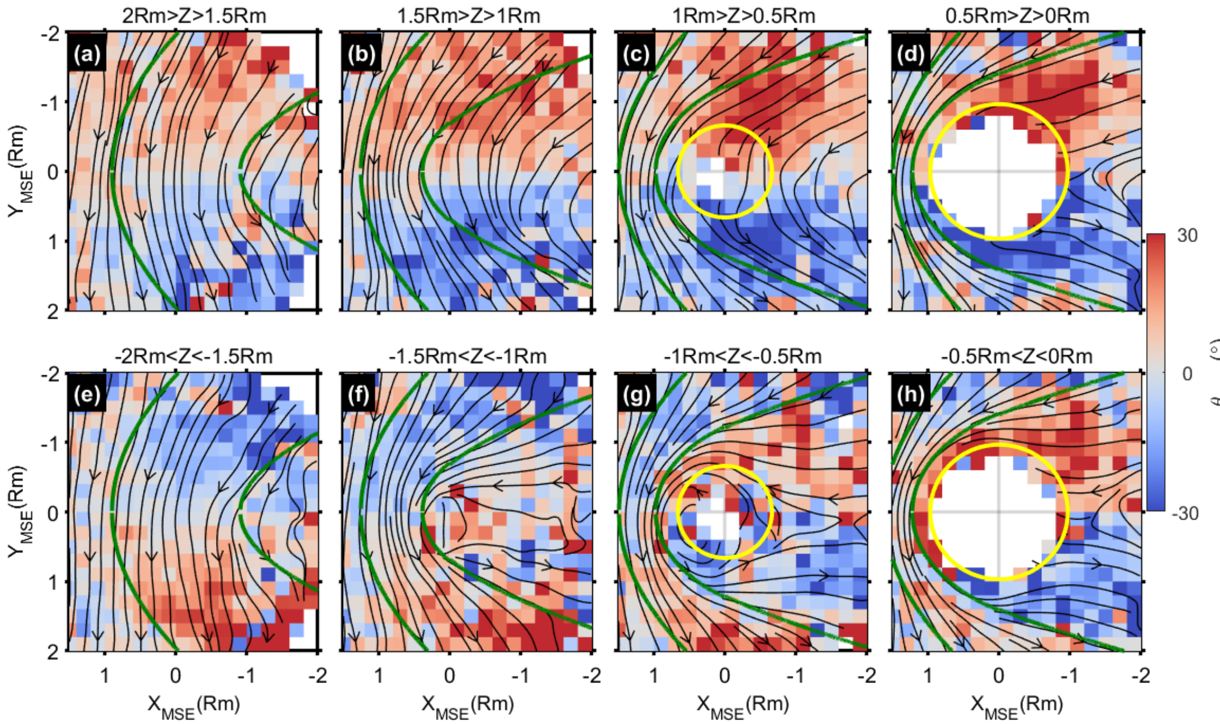

Figure 4. Average distributions of $\theta_{B,XY}$ in slices of the XY_{MSE} plane within different ranges of Z_{MSE} coordinates. Overplotted black lines with arrows denote the average MFLs. The format is the same as that of Figure 3.

3.3 Magnetic Field Structure in YZ Plane

Now we examine the magnetic field structure in slices of the YZ_{MSE} plane. Figure 5 shows distributions of $\theta_{B,YZ}$ and the average MFLs in slices of the YZ_{MSE} plane, with thickness 0.4 Rm, from dayside to nightside. Again, distributions of $\theta_{B,YZ}$ indicate that the magnetic field has a positive Bx component in the –Y_{MSE}-hemisphere and a negative Bx component in the +Y_{MSE}-hemisphere, which suggests that MFLs are bent with respect to Y_{MSE}=0 and are draped around the planet.

In the YZ_{MSE} plane, MFLs on the dayside point basically along +Y_{MSE} direction (Figures 5a–5b); nonetheless, as X_{MSE} moves downstream, the pattern of the MSLs becomes bulge-like when Z_{MSE} >–1 Rm and more concave-like when Z_{MSE} <–1 Rm (Figures 5c–5f). When we consider the reversed polarity of the Bx component with respect to the plane Y_{MSE}=0, these bulge-like or concave-like patterns correspond to "sinking field" projections on the YZ_{MSE} plane.

It is interesting to note that the dominance of bulge-like MFLs around the planet (Z_{MSE} >-1 Rm) results in the appearance of the "loop field" as presented by Chai et al. [2019].

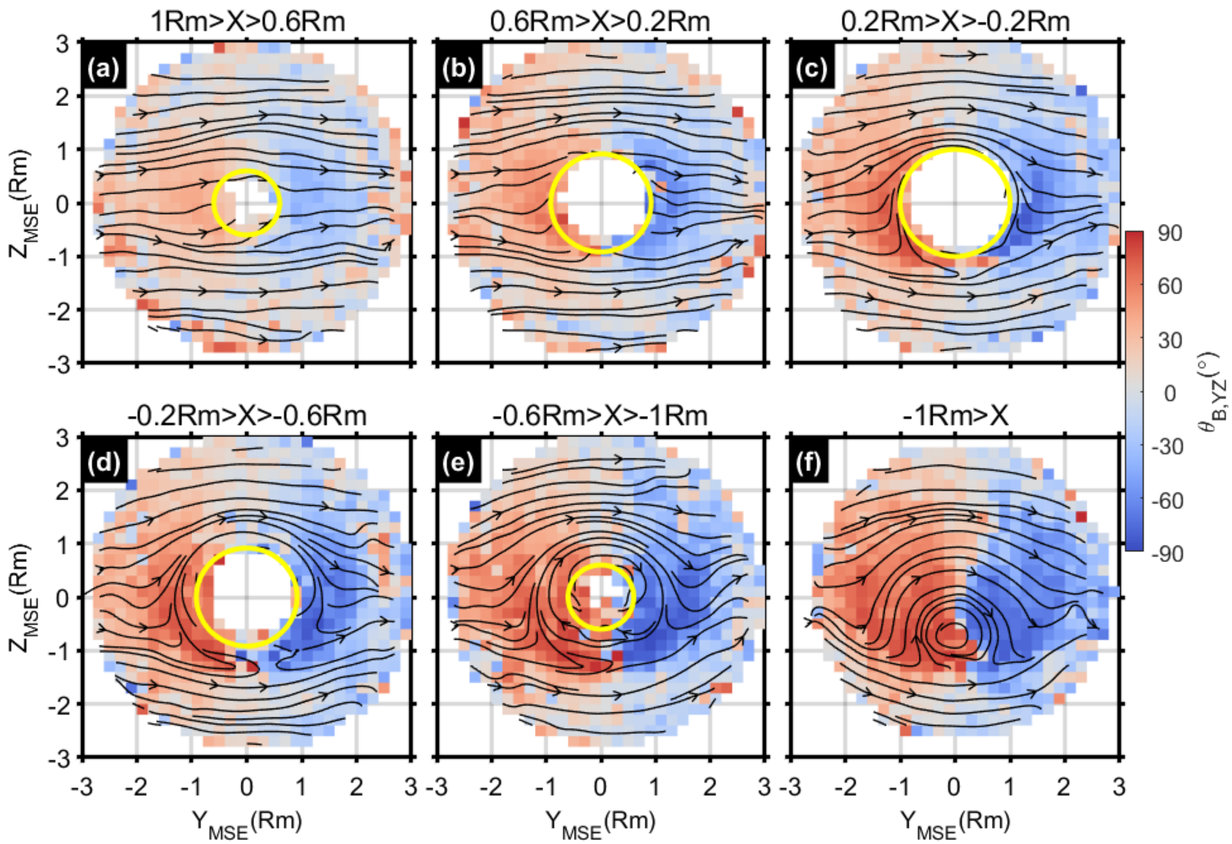

Figure 5. Average distributions of $\theta_{B,YZ}$ in slices of the YZ_{MSE} plane within different ranges of the X_{MSE} coordinate. Overplotted black lines with arrows denote average MFLs. The format is the same as that of Figure 3.

3.4 Visualization of 3-D MFLs

In the above subsections, we studied the projection of the magnetic field structure on different planes. Here, we draw the global 3-D magnetic field configuration directly by partitioning the spatial volume X_{MSE}(-3~3R_M)*Y_{MSE}(-3~3R_M)*Z_{MSE}(-3~3R_M) by a bin of 0.2Rm

×0.2Rm×0.2Rm and averaging the data points in each bin. Using these averaged data points, we plot the 3-D configuration of MFLs around Mars in Figure 6.

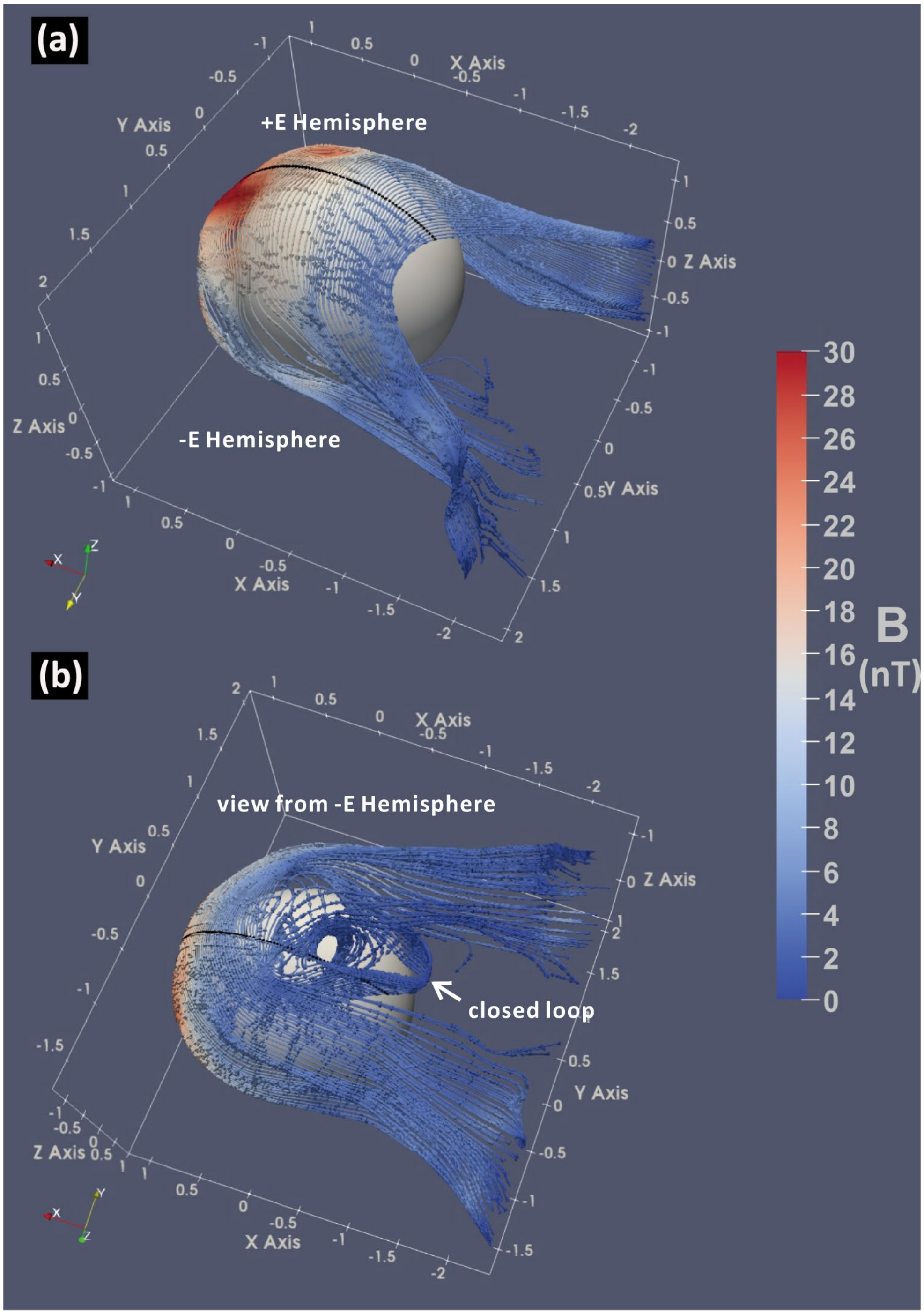

Figure 6. Average 3-D magnetic field lines in (a) the +E-hemisphere ($Z_{MSE}>0$) and (b) the E-hemisphere ($Z_{MSE}<0$). MFLs are colored according to field strength. The black dots in the XZ_{MSE} plane are the starting points for tracing the average MFLs, which are equally spaced within the solar zenith angle range of 0°~135° with constant altitude of 0.2 Rm.

As shown in Figure 6a, the configuration of MFLs in the +E-hemisphere is largely consistent with the classical draping pattern: that is, the MFLs flare with respect to the plane of Y_{MSE}=0, and these flaring field lines, after slipping over the terminator, tilt towards the magnetic equatorial plane as "sinking" fields. Nonetheless, the draped MFLs near the magnetic equatorial plane do not flare significantly but are "pinched" towards the central meridian in the wake. In contrast to Figure 6a, the draped MFLs in the E-hemisphere are generally "pinched" towards the central meridian in the wake (Figure 6b). We notice, in particular, that a closed magnetic loop could form over the pole of –E-hemisphere, which is consistent with the picture shown in Figure 4g. This magnetic loop was also noticed in previous studies [Dubinin et al., 2019; 2021].

4. Average Structure of the Magnetotail Current Sheet

As mentioned above, there is an evident E-asymmetry of the draped field lines in the Martian wake, which may imply a similar E-asymmetry in the structure of the induced magnetotail current sheet. In this section, we attempt to quantitatively diagnose the averaged properties of Martian current sheet, which will enable us to interpret the plasma dynamics of current sheet.

To consider the orbit coverage of MAVEN while avoiding the influence of the magnetosheath (see Figure 1), we confine the studied tail region to –1Rm<X_{MSE}<–2 Rm and |Y_{MSE}|<1.5Rm, and show the distribution of Bx component in Figure 7a. It is clear from Figure 7a that a tail current sheet separating two lobes with an opposite polarity of the Bx component is located at Y_{MSE}~0. To survey the possible variations of the current sheet structure along the Z_{MSE}-axis, we study four regions of the magnetic field structure within Z_{MSE}-axis ranges: that is, 0.5 Rm< Z_{MSE} <1Rm, 0<Z_{MSE}<0.5Rm, -0.5 Rm< Z_{MSE} <0, and -1Rm< Z_{MSE} <-0.5 Rm (see black dashed regions in Figure 7a). We project the location of MPB at X_{MSE}= –1Rm onto Figure 7a (see the green circle). Since the radius of MPB increases as it moves tailward, X_{MSE}=-1Rm is the lowest limit of MPB in our studied region. It is apparent that these four regions are inside the MPB.

To estimate the magnetic field structure over the current sheet in each region, we have to check the profiles of the magnetic field over the current sheet. Because the Bx component and the Bz component are correlated in Martian magnetotail (see Figure 3), minimum variance analysis (MVA) of the magnetic field in each region [Sonnerup & Scheible,1998] can help remove such correlations. MVA yields three eigen values ($\lambda_1 \geq \lambda_2 \geq \lambda_3 > 0$) and their corresponding eigenvectors $\{\vec{L}, \vec{M}, \vec{N}\}$. The three eigenvectors represent the directions of maximum, intermediate, and minimum variance of the magnetic field. They are orthogonal and constitute a local coordinate of the current sheet ($\vec{L} = \vec{M} \times \vec{N}$). $\vec{L}$ points along the magnetic field direction in the lobe, $\vec{M}$ is basically along $\vec{E}_{SW}$ and tangential to the current sheet plane, and $\vec{N}$ is the normal of current sheet and points basically along the Y_{MSE}-axis. The components of the average magnetic field along $\vec{L}$, $\vec{M}$, and $\vec{N}$ are labelled B_L, B_M, and B_N.

The average profiles of B_L (black lines), B_M (green lines), and B_N (blue lines) against Y_{MSE} for each region are shown in Figures 7b-7e. For all the regions, the B_M and B_N components are basically constant, while B_L varies significantly over the current sheet (Y_{MSE}~0 plane), which demonstrates that the field structure of the Martian tail current sheet is one-dimensional (1-D). Because the yielded $\vec{L}$ for each region is well distinguished from $\vec{M}$ and $\vec{N}$, as demonstrated by $\lambda_1 \gg \lambda_2, \lambda_3$, and the normal direction $\vec{N}$ is basically aligned with the Y_{MSE} axis (not shown here), we could fit the profiles of B_L to a typical 1-D Harris sheet model: e.g., $B_L = B_0 \tanh(\frac{Y_{MSE} - y_0}{L})$ [Harris, 1962], where B_0 is the lobe field strength, L is the typical scale of the sheet, and y_0 is the normal shift of the sheet center. Coefficients of the adjusted R-square (>0.9) indicate that the fitting results are satisfactory (see Table 1).

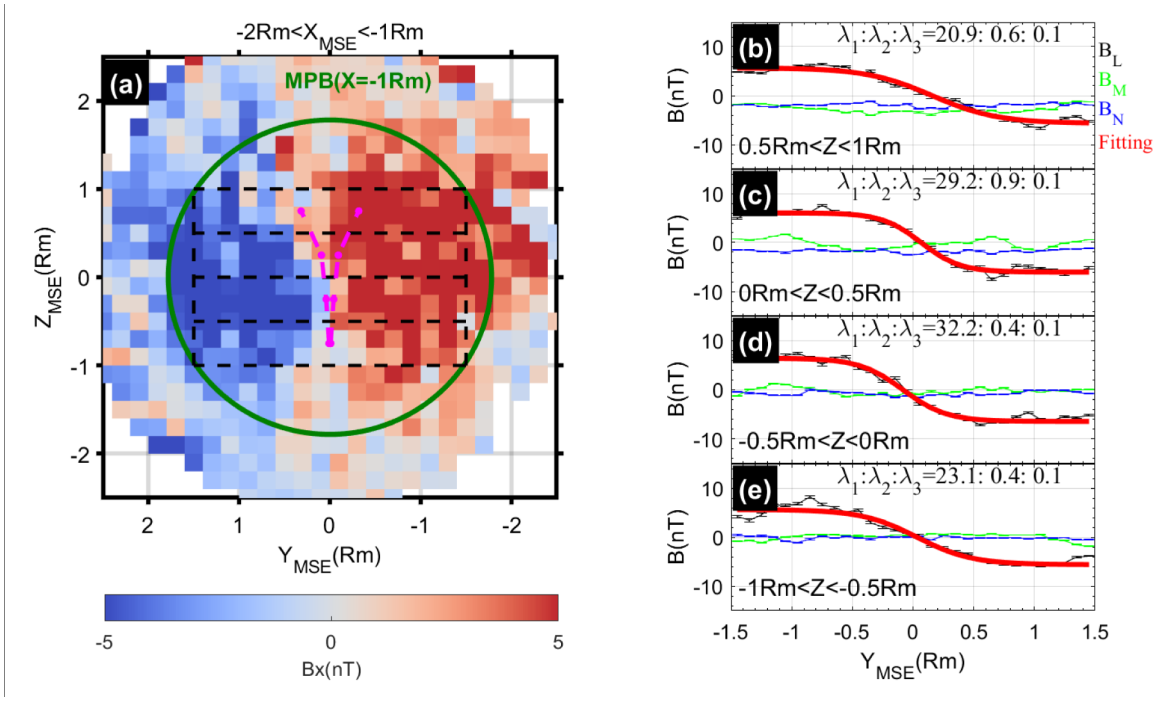

Figure 7. The left panel shows the distribution of Bx in the Martian magnetotail (–2Rm<X<-1Rm). The green cycle marks the nominal MPB shape when X=–1 Rm. The tail region is partitioned into four regions (rectangles marked by dashed lines, each with a width of 3Rm and a height of 0.5 Rm from Z_{MSE}=–1 Rm to Z_{MSE}=+1 Rm). The magenta dashed lines outline the thickness of the current sheet according to the curvature radius of the MFLs. The right panel shows the average profiles of B_L (black lines), B_M (green lines), and B_N (blue lines) against Y_{MSE} in each region. The lengths of the error bars are $2\times1.96\frac{\sigma}{\sqrt{n}}$, representing a 95% confidence interval, where $\frac{\sigma}{\sqrt{n}}$ is the standard error of the mean. The red dashed lines denote the fit curves of the Harris sheet model. The ratio of the three eigenvalues derived from MVA are labelled.

Based on the fitted parameters, the cross-tail current density at sheet center, which flows basically towards **E**, can be estimated as $J=\frac{B_0}{\mu_0 L}$, and the minimum curvature radius of MFLs reached at the sheet center can be estimated as $R_{c,\min}=\frac{<B_N>L}{B_0}$, if B_M is omitted, where $<B_N>$ is the average B_N component over the current sheet. $R_{c,\min}$ can be regarded to have half the thickness of the current sheet [e.g., Rong et al., 2014; Shen et al., 2007]. The resulting tailward Ampere force at the sheet center can be roughly estimated as $J\times B\sim J<B_N>$. Fitted parameters are listed in Table 1.

Table 1. Estimated Parameters of the Magnetotail Current Sheet in Different Regions

Region	B_0 (nT)	L (Rm)	R^2	<BN> (nT)	R_{c_min} (Rm)	J (nA/m^2)	$\vec{J}\times\vec{B}$ (nT*nA/m^2)
0.5Rm<Z<1 Rm	5.67	0.54	0.97	3.35	0.32	2.48	–8.31
0 <Z<0.5Rm	6.05	0.32	0.98	1.78	0.09	4.47	–7.96
-0.5Rm <Z<0	6.42	0.36	0.98	0.75	0.04	4.23	–3.17
–1Rm <Z<–0.5Rm	5.62	0.45	0.95	–0.12	0.009	2.93	0.35

[a]R^2 is the coefficient of the adjusted R square, which indicates fitting goodness (closer to one means a better fit).
[b]<B_N> is the averaged value of B_N over the range –1.5Rm<Y_{MSE}<1.5Rm.
[c]R_{c_min} is the estimated magnetic field curvature radius at the center of current sheet.
[d] J is the estimated current density at the center of current sheet.
[e] This is the estimated force of J×B at the center of current sheet. The +/– sign means the direction of J×B is sunward/tailward.

From Table 1, the Martian magnetotail has an evident E-asymmetry: the current sheet in the +E-hemisphere has a larger B_N component, is thicker, and has a stronger tailward Ampere force, but in the –E-hemisphere the sheet has a smaller B_N component, is thinner, and has a weaker Ampere force. The polarities of B_N and $\vec{J}\times\vec{B}$ are even reversed in the region of –1Rm <Z<–0.5Rm. The E-asymmetry of $\vec{J}\times\vec{B}$ demonstrates that ampere force (which plays out as magnetic tension force) can accelerate plasma sheet ions moving tailward, so that tailward velocity is greater near the flank of +E-hemisphere. Considering the number density of ionospheric plasma ions ~1cm^{-3} (~5cm^{-3}) in +E (–E)-hemisphere [Inui et al., 2019], and the average of $\vec{J}\times\vec{B}$ is –8.31 nT*nA/m^2 (–3.17 nT*nA/m^2) in +E (–E) hemisphere, these ions could be accelerated to ~180eV (~15eV) within a distance of 1Rm in the +E (–E) hemisphere by $\vec{J}\times\vec{B}$ (the accelerated energy equals the product of $\vec{J}\times\vec{B}$ and distance). Thus, the ions in the current sheet can be accelerated to a faster speed in the +E-hemisphere than that in the –E-hemisphere, which is consistent with previous observations [Dubinin et al., 2019; Inui et al., 2019]. Furthermore, the sunward $\vec{J}\times\vec{B}$ near the flank of the –E-hemisphere might explain, to some extent, sunward ions that tend to occur in the –E-hemisphere [Harada et al., 2015]. Further studies are necessary to address this issue.

In contrast to E-asymmetry, the lobe field B_0 is basically constant (5~6 nT) in the whole magnetotail. Current density at the current sheet center is relatively higher near the magnetic equator (–0.5 R_M<Z_{MSE} < 0.5 R_M) than the current density near both flanks (0.5 R_M<|Z_{MSE}|< 1

R_M), and the distribution pattern is consistent with a previous study (see Figure 3b of Ramstad et al. [2020]).

5. Influence of Solar Wind Conditions and Crustal Fields

5.1 Influence of IMF Bx

Previous studies on the induced magnetosphere of Venus have demonstrated that the polarity of IMF Bx could modulate the draping of IMF around the planet [e.g., McComas et al., 1986; Rong et al., 2016; Delva et al., 2017]. As sketched in Figures 8a–8b, under the presence of significant upstream IMF Bx component, a kink-like field structure named inverse polarity reversal layer (IPRL) (which a spacecraft would record when crossing it) [Romanelli et al., 2015] would appear at the boundary of an induced magnetosphere. This IPRL would disappear when IMF Bx ~0 (Figure 8c). However, IPRL on Mars has been seldom reported. Here, we use our data set to check the effect of IMF Bx on the induced magnetosphere of Mars.

Our data set, which we confined to $|Z_{MSE}|<1.5$Rm, is divided into three subdatasets or conditions: (1) IMF Bx<0 (cone angle<60°), (2) IMF Bx>0 (cone angle>120°), and (3) IMF Bx~0 (60°<cone angle<120°). We applied the procedure from Section 3 and plotted average MFLs for each subdatasets respectively in Figures 8d–8f. From the patterns of the average MFLs, one can clearly see that the IPRL is located at the magnetospheric boundary of $+Y_{MSE}$-hemisphere ($+Y_{MSE}$-hemisphere) under IMF +Bx (–Bx). In contrast, IPRL disappears when IMF Bx is negligible (Figure 7f). Simulation demonstrates that the density of oxygen ion is enhanced in IPRL [Jarvinen et al., 2010]. Given the kink-like structure of IPRL, we suggest that IPRL would induce sunward $\vec{J}\times\vec{B}$ or magnetic tension, which might counterbalance the tailward plasma flow to some extent and cause ion enhancement.

Previous studies suggest that IMF Bx could also shift the Venusian magnetotail current sheet and bring hemispheric asymmetry to the lobe magnetic flux [McComas et al., 1986], but this effect is questioned by Rong et al. [2016]. Based on a limited data point of MGS, Romanelli et al. [2015] argued that IMF Bx could shift the Martian magnetotail current sheet. The effect of IMF Bx on the Martian magnetotail lies will be addressed exclusively in another paper.

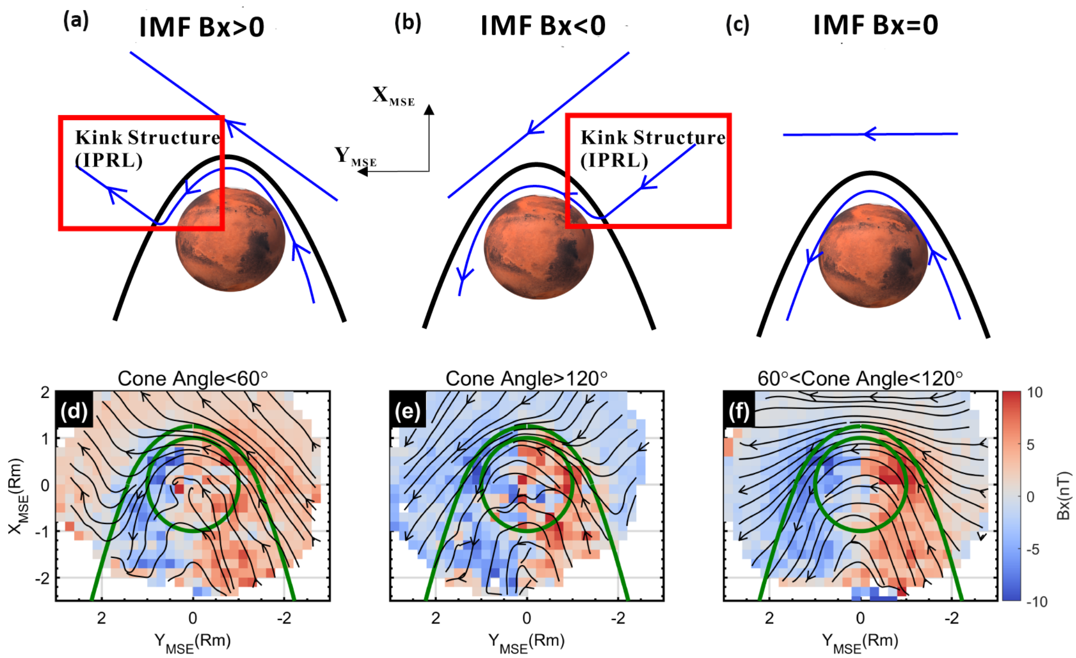

Figure 8. Draping configuration of magnetic field lines under (a) IMF +Bx, (b) IMF -Bx, and (c) IMF Bx~0. The distribution of Bx and MFLs under (d) IMF +Bx (cone angle<60°), (e) IMF -Bx (cone angle>120°), and (f) IMF Bx~0 (60°<cone angle<120°), respectively.

5.2 Influence of Solar Wind Dynamic Pressure

Solar wind dynamic pressure (Pdy) is believed to significantly impact the magnetic structure of an induced magnetosphere and ion escape [e.g. Ramstad et al., 2015; Dubinin et al., 2017; Nilsson et al., 2010, 2011; Zhang et al., 1994; Zhang et al., 2021]. Based on our dataset, we quantitatively evaluate how Pdy affects the magnetic field structure around Mars. To facilitate this, our dataset is dichotomized according to the median value of Pdy, i.e. 0.54 nPa. Data points with a Pdy higher than the median constitute a high Pdy subdataset, while those lower constitute a low Pdy subdataset. Comparing field distributions and configurations of these two subdatasets could highlight the effects of Pdy.

Distributions of magnetic field strength for the two subdatasets above demonstrate that magnetic fields around the planet, from the magnetosheath to the magnetic barrier as well as the whole magnetotail, are usually stronger during higher Pdy (Figures 9a–9b). This is plausible because draped MFLs are expected to be more compressed during higher Pdy.

In addition to the field strength, Pdy may also affect the flaring of the draped MFLs [Zhang et al., 1994]. Here, the flaring angle of MFLs, defined as $\theta_{B,X} = a\cos\left(\vec{b}\cdot\vec{x}\right)$, shows how much the magnetic field deviates from the x-axis. By surveying the response of $\theta_{B,X}$ to Pdy, we find that the magnetic field has a relatively smaller $\theta_{B,X}$ during higher Pdy than lower ones in the +E-hemisphere (Figure 9c). Thus, the draped MFLs in the +E-hemisphere generally stretch more or flare less during higher Pdy. The response of $\theta_{B,X}$ to Pdy in the –E-hemisphere, though less significant, is somewhat similar to that in the +E-hemisphere (Figure 9d). The reason seems obvious: MFLs with less flaring in the –E-hemisphere (see Figure 3) should be less sensitive to the impact of Pdy.

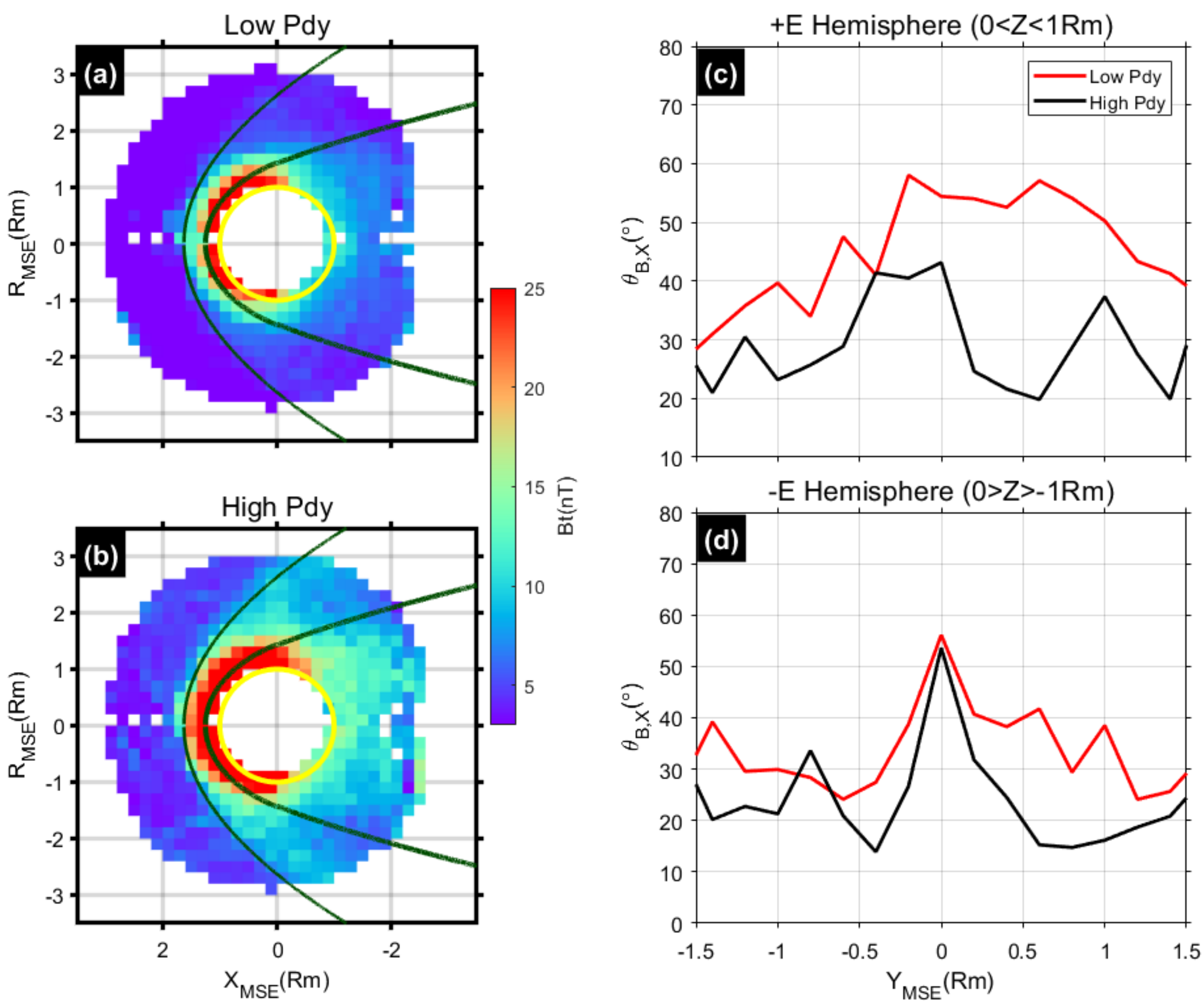

Figure 9. Response of the Martian induced magnetic field to dynamic pressure of solar wind. The left column shows the distributions of magnetic field strength during (a) lower Pdy and (b) higher Pdy. The Y coordinate is defined as $\mathrm{R_{MSE}} = \mathrm{sign}(\mathrm{Z_{MSE}}) * \sqrt{\mathrm{Y_{MSE}^2} + \mathrm{Z_{MSE}^2}}$. The right column shows variations of the flaring angle $\theta_{B,\mathrm{XZ}}$ against $\mathrm{Y_{MSE}}$ in (c) the +E-hemisphere and (d) the –E-hemisphere. Variation during during lower/higher Pdy is colored red/black.

5.3 Influence of Crustal Field Rotation

Previous studies suggested that the Martian magnetotail current sheet could be twisted by open field lines owing to the reconnection between the IMF and crustal fields [Luhmann et al., 2015; DiBraccio et al., 2018; Xu et al., 2020]; crustal fields may also influence the escape of Martian ions [e.g. Fang et al., 2010; Ramstad et al., 2016; Nilsson et al., 2011; Dubinin et al., 2020; Zhang et al., 2021]. Although the data points in our dataset are nearly unaffected by the crustal fields ($B_{model} < 0.1B_{obs}$), one cannot rule out their possible effects on the field structure of Martian magnetotail. Given Mars' rotation, the crustal field should diurnally modulate the tail field structure. Thus, in order to survey the effect of the crustal field, we check the response of the magnetic field distribution of Martian tail (–1Rm>X>–2Rm) to the planet's rotation.

To simplify the study, the dataset is divided into four subdatasets according to the local time (LT) when the strongest crustal fields are located at geo-longitude ~178° on the Martian surface (Figure 10a): (1) dawnside (3<LT<9), (2) dayside (9<LT<15), (3) duskside (15<LT<21), and (4) nightside (21<LT&LT<3). Because the IMF Bx component may shift the tail current sheet and bring about lobe asymmetry of magnetic flux [McComas et al.,1986], we only retain—to highlight possible effects brought about by planetary rotation—the data points with negligible IMF Bx (60°<cone angle<120°). Each of these data points has a corresponding LT of the strongest crustal fields, and the nearly uniform distribution of data points against these LTs rules out significant statistical bias among the four subdatasets (Figure 10b).

For these four subdatasets, we show distributions of Bx in the Martian tail when the strongest crustal field is located on the dawnside, the dayside, the duskside, and the nightside, respectively (Figures 10c–10f). Clearly, the distribution patterns of the subdatasets are similar;

all tail current sheets are roughly located at Y_{MSE} ~0. Thus, the rotation of crustal fields cannot significantly affect or modulate the configuration of the tail current sheet.

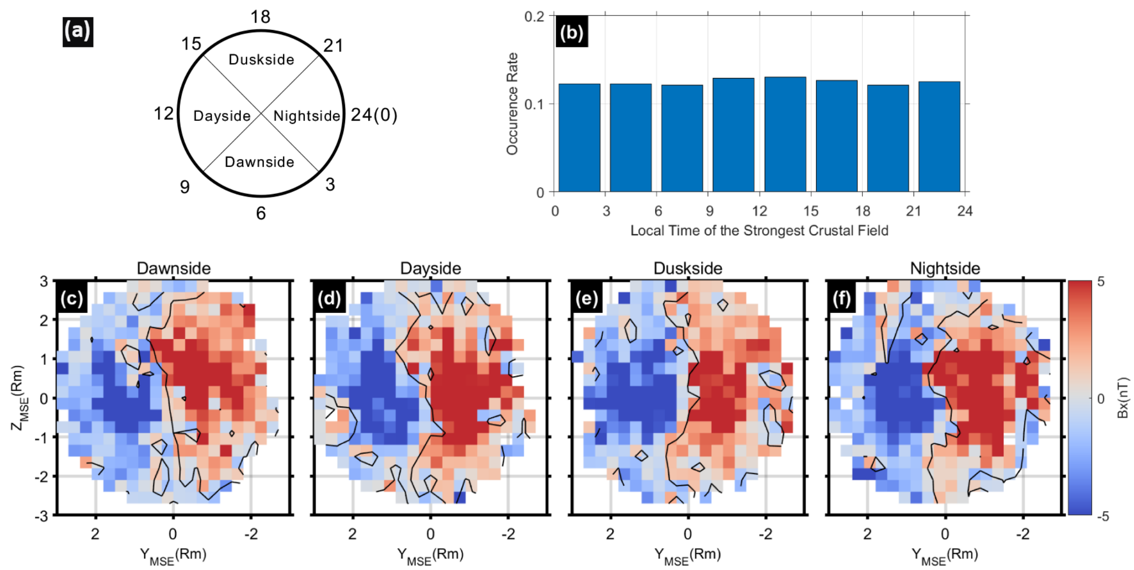

Figure 10. Effect of Martian rotation on tail field distribution. (a) Diagram of the four sectors chosen according to the local time of the strongest crustal field. (b) Distribution of data points against the local time of the strongest crustal field. The distribution of Bx in the YZ plane (-2<X<-1 Rm) when the strongest crustal field is on (c) the dawn side, (d) the day side, (e) the dusk side, and (f) the night side. Contours of Bx=0 are shown as black lines.

6 Discussion and Conclusion

In this study, which is based on a statistical survey of magnetometer measurements made by MAVEN from approximately 2014-10-01 to 2020-12-31, we derived the global 3-D magnetic field structure of the Martian induced magnetosphere. Our findings can be summarized as follows:

(1) The magnetic field structure around Mars is basically controlled by solar wind flow and IMF orientation, and the resulting morphology of the Martian magnetosphere conforms to the typical draping picture of an induced magnetosphere: a pair of tail lobes that is induced in the wake.

(2) The draped field lines from both flanks of the ±E-hemisphere are directed towards the magnetic equatorial plane, making the field lines look like they are "sinking" toward the wake. These "sinking" field lines could be driven by a downstream convergence of solar wind flow to the wake plasma cavity [Rong et al., 2014; Dubinin et al., 2019]. The field lines "sinking" from the +E-hemisphere are dominant in Martian tail because they can extend down to ~ Z_{MSE}= -1 Rm. The "sinking" field lines from the –E-hemisphere are more stretched and even "pinched" towards the central plasma sheet. The E-asymmetry of the "sinking fields" is consistent with previous studies on the field structure of Mars magnetotail [Dubinin et al., 2019, 2021] and also the Venusian magnetotail [Rong et al., 2014]. However, the E-asymmetry of "sinking fields" disappears outside the MPB, which indicates that asymmetry might arise due to the interaction of solar wind with the low-altitude atmosphere of Mars.

(3) The tail current sheet also shows an evident E-asymmetry corresponding to the E-asymmetry of draped field lines. The current sheet is thicker in the +E-hemisphere and thinner in the –E-hemisphere, and the tailward Ampere force $\vec{J}\times\vec{B}$ at the current sheet center, which is stronger near the flank of +E-hemisphere, is attenuated as it moves towards the –E-hemisphere. Thus, the tailward plasma flow can be accelerated to higher speeds by $\vec{J}\times\vec{B}$ near the flank of the +E-hemisphere. The much thinner current sheet and the sunward $\vec{J}\times\vec{B}$ at the flank of the –E-hemisphere may indicate that magnetic reconnection occurs preferentially there and explain the sunward ions observed there as well [Harada et al., 2015].

(4) Possible effects of IMF B_x, Pdy, and planetary rotation on the magnetic field structure are checked respectively. We find that a kink-like field structure appears at the boundary layer of the Martian magnetosphere under the presence of a significant IMF Bx component. While the global induced magnetic field around Mars is enhanced due to the compression of higher Pdy, the draped field lines in the tail flare less in such conditions. However, variations in the crustal field that are caused by planetary rotation do not seem to affect or modulate the configuration of tail current sheet significantly.

The E-asymmetry of the field structure has been observed in Venusian and Titan magnetotails [e. g. Saunders and Russell, 1986; Zhang et al., 2010; Du et al., 2013; Rong et al., 2014; Chai et al., 2016; Simon et al., 2006]; thus, it appears to be a ubiquitous phenomenon of induced magnetospheres. However, the physical mechanism responsible for E-asymmetry is still unclear. Previous studies on Venus demonstrated that E-asymmetry of the B_y component has appeared at low altitude around the terminator [Du et al., 2013] and can extend to the distant tail [Saunders and Russell, 1986]. This asymmetry can be reproduced in hybrid and multifluid magnetfigureohydrodynamic simulations but not in single-fluid ones [e.g., Zhang et al., 2010; Du et al., 2013, and references therein; Jarvinen et al., 2013]. Thus, it seems that E-asymmetry could be associated with particle kinetic effects. Similar to research on Venus, our study on Mars also demonstrates that the appearance of the –By component starts at a low-altitude around the terminator of the –E-hemisphere (see Figures 2d and 2h). Recent observations by MAVEN showed that there is a trail of O^+, extended from nightside ionosphere, in the –E-hemisphere [Dubinin et al., 2019]. Thus, the interaction of the O^+ trail with the draped IMF would seem to result in a kinetic effect that "drags" the draped field lines, making them more stretched out, as well as resulting in a weaker B_y and signature of $-B_y$ in the hemisphere. Dubinin et al. [2019, 2021] suggested that ionospheric plasma is extracted and accelerates toward the +E direction by the pick-up effect of solar wind, which in turn produces an –E-directing recoil effect to the ionosphere, forming an ion trail in the –E hemisphere. However, this recoil force is not well identified. Additionally, it is also unclear why the appearance of $-B_y$ starts at a low-altitude around the terminator of the –E-hemisphere instead of the +E-hemisphere. It might be that the draped IMF penetrates more easily into the ionosphere when in the –E-hemisphere (as opposed to the +E-hemisphere) under the motional solar wind electric field, so that the signature of $-B_y$ tends to appear under those conditions. A combination of future simulations may help unravel the real mechanism of this E-asymmetry.

An important feature of E-asymmetry is a loop field structure over the pole of –E-hemisphere (Figure 6), which has been interpreted as the product of magnetic reconnection [Dubinin et al., 2019, 2021]. Given the explosive process of magnetic reconnection with a transient timescale, however, it is hard to believe that an average-yielded loop field structure, seen as a temporally static structure, is the product of magnetic reconnection. We suggest instead that the loop structure is induced by the inhomogeneous distribution of current density, and there should be stronger current density flowing $+Z_{MSE}$ direction embedded in the loop. The pattern of the global Martian magnetospheric current derived by Ramstad et al. [2020] supports our interpretation.

Our study shows that the rotation of crustal field cannot affect the configuration of the tail current sheet significantly, which seems inconsistent with DiBraccio et al. [2018]. They argued that the current sheet could be twisted by open field lines owing to the reconnection between the IMF and crustal fields, a twist that could be more significant when the strongest crustal fields are on the noon. But the study by DiBraccio et al. was performed using MSO instead of MSE coordinates, which we favor here. We will address reasons for the discrepancy in a future study.

Finally, we also expect that future studies combining multipoint observations from China's TIANWEN-1 [Wan et al., 2020], MAVEN, and Mars Express [Barabash et al. 2006] might offer better opportunities to study the Martian magnetosphere and its response to solar wind variation and crustal field rotation.

Data Availability Statement

All MAVEN data used in this paper are available from NASA's Planetary Data System. MAG data can be found at https://pds-ppi.igpp.ucla.edu/mission/MAVEN/MAVEN/MAG. SWIA data can be found at https://pds-ppi.igpp.ucla.edu/mission/MAVEN/MAVEN/SWIA. SWEA data can be found at https://pds-ppi.igpp.ucla.edu/mission/MAVEN/MAVEN/SWEA.

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