A Case Study of the Induced Magnetosphere Boundary at the Martian Subsolar Region

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Abstract
One Martian induced magnetosphere boundary (IMB) crossing at the subsolar region is analyzed here with multiple instruments on board MAVEN. Properties of the magnetic field and particles around the IMB are evaluated. We find different trends of variation in magnetic field components at the two sides of an interface coincident with the previously defined ion composition boundary. This case shows the IMB at the Martian dayside could be divided into three parts: two regions (denoted as R1 and R2), with different field and plasma properties, and an interface between them. Currents found in R1 and R2 are flowing in antiparallel, and the current density in R2 (at lower altitude) is significantly larger than that in R1 (at higher altitude). Results indicate the interaction between Mars and the solar wind could induce strong currents in the IMB, which are with antiparallel current directions and separated by an interface where the ion composition changes. This could be a typical feature that occurred during the interaction between the solar wind and the nonmagnetized planets.

Unified Astronomy Thesaurus concepts: Mars (1007); Planetary boundary layers (1245)

1. Introduction
The space environment around Mars has been explored so far by measurements from exploratory missions for decades, such as Mars 2, 3, and 5, Phobos 2, Mars Global Surveyor (MGS), Mars Express (MEX), Mars Atmosphere and Volatile EvolutioN (MAVEN), and now the Tianwen-1 Mars Orbiter. Mars has no global intrinsic magnetic field, but a significant remnant crustal magnetic field in the southern hemisphere (Acuña et al. 1998). Thus the solar wind can interact with the Martian ionosphere/upper atmosphere. This interaction then forms the bow shock, magnetosheath, and induced magnetosphere, which are well defined with magnetic field and plasma characteristics.

A boundary region exists between the magnetosheath and the lower induced magnetosphere/ionosphere, which has been extensively investigated by the spacecrafts that visited Mars and assumed as the obstacle to the solar wind (Bertucci et al. 2011; Dubinin et al. 1996; Holmberg et al. 2019). Different terms have been proposed to describe this boundary region (Espley 2018) based on specified instruments on board different missions. Most of the terms are listed in Table 1 and briefly reviewed below.

At early time, the interaction between Mars and the solar wind was measured by Mars 2 and 3, when Bogdanov & Vaisberg (1975) proposed the ion cushion to describe the boundary characterized by intense cold ions with low convective velocity, while Michel (1971) had used induced magnetopause (a magnetic barrier) in their discussion.

In the Phobos 2 era, Rosenbauer et al. (1989) named the boundary region magnetopause, with plasma composition observed by TAUS. Riedler et al. (1989) called this the planetopause, with magnetic field measured by MAGMA and FGMM (also by Grard et al. 1989, with measurements from plasma wave system), while Lundin et al. (1990) found a mass-loading boundary (MLB) out of the magnetopause with plasma measurements by ASPERA. Breus et al. (1991) argued this as ion composition boundary (ICB) with MAGMA and ASPERA observations, which was denoted as protonopause by Sauer et al. (1994), while Dubinin et al. (1996) suggested this could be named boundary layer with combined measurements from Phobos 2.

By observations from MGS MAG/ER, Acuña et al. (1998) used the magnetic pile-up boundary (MPB) to describe the boundary and denoted the lower region as the magnetic pile-up region or dayside magnetic barrier, which was extensively used and studied (Bertucci et al. 2003, 2005; Crider et al. 2000), while Lundin et al. (2004) proposed the induced magnetosphere boundary (IMB) for that boundary with measurements from MEX ASPERA-3. Later, Bertucci et al. (2011) reviewed the boundary region, named as IMB, and concluded several characteristics for it as below: (1) increase in magnetic field magnitude; (2) decrease in magnetic field fluctuation; (3) enhancement of magnetic field draping; (4) decrease in electron temperature; (5) increase in total electron density; (6) decrease in solar wind ion density.

Pressure balance was widely used in studies of Venus when they defined the ionopause and the position of the magnetic barrier (Zhang et al. 1991). Recently, Xu et al. (2016) also proposed a pressure boundary where the magnetic pressure equals the sum of plasma thermal and dynamic pressure in their simulation. The evaluation of the pressure balance near Mars measured by MAVEN has shown that this boundary is not strictly coincident with IMB or ICB (Matsunaga et al. 2017; Holmberg et al. 2019).

To avoid confusion among those terminologies, we hereafter name this boundary region between the magnetosheath and the lower induced magnetosphere at Mars as the Mars-Solar Wind...
| Terminology                        | Authors Mission Instrument | Data Resolution                      | Definition/Description                                                                 | Other Authors                                                                 |
|-----------------------------------|-----------------------------|--------------------------------------|----------------------------------------------------------------------------------------|-------------------------------------------------------------------------------|
| magnetopause                      | Rosenbauer et al. (1989) Phobos 2 TAUS | ions composition 4 minutes           | solar wind proton fluxes decrease; heavy ion fluxes increase                           | Verigin et al. (1991), Vaisberg et al. (2018)                                  |
| planetopause                      | Riedler et al. (1989) Phobos 2 MAGMA, FGMM | magnetic field 1.5, 2.5, 45 or 600 s  | the magnetic field rotates and enhances; magnetic field turbulence ceases              | Grard et al. (1989), Grard et al. (1991)                                        |
| mass-loading boundary (MLB) ion composition boundary (ICB) | Lundin et al. (1990) Phobos 2 ASPERA | plasma composition 8 minutes (3D), 13 s to 2 minutes (2D) | planetary ions modify the solar wind inside                                             | Dubinin et al. (1996)                                                         |
| magnetic pile-up boundary (MPB)   | Breus et al. (1991) Phobos 2 ASPERA, MAGMA | ...                                  | solar wind protons disappear; planetary ions increase; magnetic field smoothly rotates; magnetic fluctuation sharply drops | Sauer et al. (1994), Matsunaga et al. (2017), Halekas et al. (2018)               |
| induced magnetosphere boundary (IMB) | Acu’a et al. (1998) MGS MAG/ER | magnetic field 2 to 16 Hz electron spectrum | the magnetic field rotates and its mean magnitude increases; magnetic fluctuation ceases; high energy electron fluxes decrease | Crider et al. (2000), Vignes et al. (2000), Bertucci et al. (2003), Boscoboinik et al. (2020) |
|                                   | Lundin et al. (2004) MEX ASPERA-3 | plasma composition 3 minutes         | solar wind plasma stops; planetary plasma dominates after it                          | Dubinin et al. (2006), Dubinin et al. (2008), Matsunaga et al. (2017), Holmberg et al. (2019), Lentz et al. (2021) |
Interface at Dayside (MSWID). The abundant and simultaneous observations by multiple instruments on board MAVEN, also with relatively higher temporal resolution than previous missions, provide us a great chance to investigate the properties and the relations of different physical parameters within the MSWID. This study aims to analyze the characteristics of the MSWID, confirming the properties reported and denoted by previous various terms and checking whether they were describing the same region or not. Additionally, the signature of the current near the MSWID is of significance. Ramstad et al. (2020) recently statistically obtained the global scale current systems at Mars; however, the fine structure of the currents near the boundary could not be known due to the grid constraint (Boscoboinik et al. 2020). Below we present the overall appearance of the magnetic field and plasma for one selected case and evaluate the current flowing in there, which could help us unambiguously determine the characteristics of the MSWID and understand the interaction process between Mars and the solar wind. The thickness of the MSWID is variable and here is about 200 km (Holmberg et al. 2019).

2. Observation and Analysis

MAVEN has provided abundant particle and field measurements since 2014 September. It orbits Mars at an elliptic orbit with an initial perigee of 150 km and an apogee of 6200 km, an inclination of 75°, and a period of ~4.5 hr (Jakosky et al. 2015). Comprehensive data, including magnetic field and plasma, could be obtained from multiple instruments on board MAVEN. The Magnetometer (MAG; Connerney et al. 2015), consisting of two triaxial fluxgate magnetometer sensors, is able to measure the magnetic field up to 32 Hz in a dynamic range from 0.1 to 60,000 nT. The Solar Wind Electron Analyzer (SWEA; Mitchell et al. 2016) measures the electron distribution with energy within 3 ~ 4600 eV, while the Solar Wind Ion Analyzer (SWIA; Halekas et al. 2015) measures the ion distribution with an angular resolution of 22.5° and an energy range of 5 eV ~ 25 keV. The SWIA onboard moment dataset is used to obtain the proton number density, bulk velocity, and temperature, which then are validated with the coarse dataset (Halekas et al. 2017). The Suprathermal and Thermal Ion Composition analyzer (STATIC; McFadden et al. 2015) measures the ion mass compositions in the energy and angular distributions. The energy range for ions is from 0.1 eV to 30 keV. Many different data products are provided by STATIC, and we use the C6 dataset to obtain the energy fluxes for H+ and heavy ions (e.g., O+ and O2+) and then their number densities calculated with the energy flux in the corresponding mass channel. Here we investigated the MSWID with those simultaneous and higher temporal measurements, which enable the unambiguous determination of the plasma environments around Mars and were not achieved by previous missions.

The MSWID formed during the interaction between Mars and the solar wind could be more stable near the subsolar region (Bertucci et al. 2005; Vaisberg et al. 2018; Holmberg et al. 2019), thus we select one crossing at a solar zenith angle (SZA) of 17°/8 on 2015 September 30. This crossing is presented in Figure 1, which shows the spacecraft flew from the solar wind into the Martian induced magnetosphere. Figures 1(a) and (b) present the spacecraft trajectory in the x–y and x–z planes in MSO (Mars Solar Orbital coordinate, with x directing to the Sun from the Martian center, z being normal to the Mars orbital plane, and y completing the right-hand system), during the time interval of 15:20 to 16:20. The trajectory is colored to illustrate the spacecraft position at the corresponding time indicated by the color bar. Figures 1(c)–(f) show the magnitude (|B|) and three components (Bx, By, Bz) of the 1 Hz magnetic field. The solar wind velocity is (~310.48, 18.13, 55.29) km s−1 in the MSO coordinates. The interplanetary magnetic field is (~−0.03, 5.04, −2.73) nT before 15:30. Later when the spacecraft backs into the solar wind, the interplanetary magnetic field is (~−0.95, 2.18, −4.68) nT, rotated about 38°, which is generally stable. Clearly, we can observe jumps of |B| around 15:32 and 15:36, and sufficient magnetic fluctuations appear just behind these jumps, also with an increase in ion number density and temperature (not shown), which are signatures of the bow shock crossings. A broad region is recognized as the magnetosheath characterized by magnetic fluctuations lasting from 15:37 to about 16:10, with |B| increasing at about 16:00. During 16:10 to 16:14, such magnetic fluctuations are obviously ceased together with abruptly increased |B|. From about 16:14, |B| is decreasing, and field components experience significant direction change, which may indicate the entrance into the lower induced magnetosphere/ionsphere region. The MSWID is indicated by the blue and yellow shaded regions, in which the magnetic fluctuation ceases and magnetic field components vary.

Detailed information of the plasma environment around the MSWID is presented in Figure 2 from 16:05 to 16:20. Figures 2(a) and (b) show the magnetic field magnitude and three components in 1 Hz from MAG, respectively; Figure 2(c) shows the power spectrum of magnetic fluctuations below 1 Hz obtained by the wavelet analysis method; Figure 2(d) shows the energy flux spectrum of electrons from SWEA; Figure 2(e) shows the energy flux spectrum of ions from SWIA; Figure 2(f) shows the energy flux spectrum of different ion components from STATIC; Figure 2(g) presents the number density of the solar wind protons from SWIA; Figure 2(h) presents the number density of H+ (blue) and heavy ions (O+ (green) and O2+ (red)) calculated from energy flux measured by STATIC; Figure 2(i) shows the bulk velocity of protons from SWIA; Figure 2(j) presents the magnetic pressure (blue), plasma dynamic pressure (green), and plasma thermal pressure (red); Figure 2(k) then shows the ratio of the three pressure terms, i.e., beta*, with the black dashed line indicating 1.0. According to Xu et al. (2016) and Holmberg et al. (2019), here the magnetic pressure is defined as \( P_\mu = B^2/2\mu_0 \) with magnetic field strength B from MAG; the plasma dynamic pressure is defined as \( P_{\text{dyn}} = m_p n_i v_i^2 \) with proton number density \( n_i \) and bulk velocity \( v_i \) from SWIA, and \( m_p \) is the proton mass; the thermal pressure the in magnetosheath is assumed to be dominated by ions and defined as \( P_{\text{the}} = n_i k_BT_i \) with proton number density \( n_i \) and temperature \( T_i \) from SWIA, and \( k_B \) is the Boltzmann constant. Then beta* = \( (P_{\text{dyn}} + P_{\text{the}})/P_\mu \). Since the region of interest is generally above the ionsphere, we here have not used the measurements from LPW to estimate the plasma thermal pressure inside the ionsphere (Holmberg et al. 2019). Three vertical dashed lines are obtained: (1st line at 16:12:20) generally decreased magnetic fluctuations together with an increased field magnitude, decreased flux of high energy electrons, and decreased solar wind proton density (Figures 2(a)–(e)); (2nd line at 16:14:10) density ratio of heavy ions to protons is equal to 1.0, and solar wind protons stop there (Figures 2(g)–(h)); (3rd line at 16:16:00) direction change...
Figure 1. Subsolar region crossing on Mars by MAVEN from 15:20 to 16:20 on 2015 September 30. (a, b) MAVEN orbit projection on $x$–$y$ and $x$–$z$ planes in MSO, with the colored trajectory illustrating the position of the spacecraft at the corresponding time indicated by the color bar. Black dashed lines indicate bow shock and MPB in Trotignon et al. (2006). (c–f) Magnetic field magnitude ($|B|$) and three components ($B_x$, $B_y$, $B_z$). Lower notes denote the position, altitude, and corresponding SZA. The blue and yellow regions indicate the Mars-Solar Wind Interface at Dayside (MSWID) investigated.
Figure 2. Plasma environment around the boundary region between the Martian magnetosheath and lower induced magnetosphere. (a, b) Magnetic field magnitude and components. (c) Power spectrum of the magnetic field from wavelet analysis. (d, e) Electron and ion energy flux spectrum. (f) Energy flux spectrum for different ion mass. (g) Proton number density from SWIA. (h) H\(^+\) (blue), O\(^+\) (green), O\(_2^+\) (red) number density from STATIC. (i) Proton velocity components in MSO from SWIA. (j) Plasma dynamic pressure (green), plasma thermal pressure (red), and magnetic field pressure (blue). (k) Pressure ratio (beta \(\ast\)). Three vertical dashed lines indicate edges of the Mars-Solar Wind Interface at Dayside (MSWID), with the blue and yellow shaded region representing the R1 and R2 parts.
the three magnetic components start from 16:14 generally stop here (Figure 2(b)).

Generally, properties relevant to the previously defined terminologies could be found during this crossing: (1) interval from the 1st to the 2nd line may coincide to the magnetopause, planetopause, MPB, or IMB, where the magnetic field increases and rotates, the solar wind particles stop, and the planetary ion densities increase. (2) the wide region that starts before the 1st line (at ~16:00) to the 2nd line may coincide with the MLB, where the magnetic field strength generally increases and the solar wind velocity (Figure 2(i)) decreases, representing the solar wind is modified by Mars. (3) the 2nd line may coincide with the magnetopause, planetopause, or ICB, where the plasma composition becomes dominated by Martian heavy ions. This case no doubt shows the advantage of MAVEN measurements in investigating the MSWID since we can measure different plasma parameters simultaneously (Holmberg et al. 2019). Wang et al. (2020) used the name plasma depletion region for a region similar to before the 2nd line, and tangential discontinuity for a region similar to after the 2nd line (Figure 2). The pressure boundary indicated by $\beta = 1.0$ is around 16:05:28 (Figure 2(j)), which is generally coincident with the starting point where the magnetic field increases. However, magnetic fluctuation is still obvious after this pressure boundary. Holmberg et al. (2019) evaluated the pressure terms at Martian dayside and showed that the upper pressure-balanced region is far higher than the IMB.

In summary, we find that the MSWID at the Martian subsolar region might consist of three parts, two regions (denoted as R1 and R2, illustrated by the blue and yellow shaded region in Figure 2 respectively, and also shown in Figures 1 and 3) and one interface between them coincident with the previously defined ICB (Matsunaga et al. 2017): (1) R1, bounded by the 1st and 2nd lines, which is generally coincident to the previously defined MPB; (2) R2, bounded by the 2nd and 3rd lines which may coincide to previously named magnetopause, or may be the ICB if assuming the ICB has a wide varying transition region (Vaisberg et al. 2018); (3) the interface between R1 and R2 (denoted as ICB below), indicated by the 2nd line where the heavy ions start dominating. Above the MSWID is the magnetosheath, while below the MSWID are properties of the induced magnetosphere/ionosphere. The thicknesses of R1 and R2 in altitude are both about 110–120 km.

Although the 2nd line (corresponding to ICB) is found where the density ratio equals 1, we have found that this time point is associated with a trend change of variation in the magnetic components, i.e., before this time (in R1), a pure pile-up exists in both $B_x$ and $B_y$ which increase in the same direction in the magnetosheath; after this time (in R2), $B_z$ abruptly changes its direction from $\sim -40$ nT to $32$ nT, and not soon, $B_x$ and $B_y$ also experience such change. The trends of variation in the magnetic field are different in R1 and R2 which is not mentioned dedicatedly in previous studies. However, such correlation could be important to understand the formation of the MSWID. The magnetic variations found in the MSWID reveal the existence of current layers which will be evaluated below. Bertucci et al. (2005) and recently Boscoboinik et al. (2020) had analyzed the current density in MPB (corresponding to R1 here). They showed that the normal direction of the current sheet is generally aligned to the normal of the fitted model of MPB which is close to a sphere in geometry at Martian dayside (Trotignon et al. 2006). The current density is about 81 nA m$^{-2}$ in Bertucci et al. (2005) at SZA = 63°. Cases in Boscoboinik et al. (2020) showed the current densities could vary from 92 to 403 nA m$^{-2}$ under different upper solar wind dynamic pressure, though the relation between them is not clear. A global profile of the current at Mars was statistically investigated in Ramstad et al. (2020), which showed that the current flowing within the IMB (or MPB) is antidirected to the one flowing within the ionosphere, with a current density of $\sim 20$ nA m$^{-2}$. However, their grid is too large to resolve the

**Figure 3.** Altitude profiles for magnetic field and current density in MSO coordinate from 16:05 to 16:20 on 2015 September 30. (a) Components of the magnetic field. (b) Magnitude of the field. (c) Components of current density. (d) Magnitude of current density. SZA corresponding to altitude is denoted on the right. The blue and yellow shaded regions indicate the R1 and R2 parts as in Figure 2.
MSWID, at least for this case, and thus may underestimate the current density and omit the detailed structure of the current. To our knowledge, this is the first time that the current in R1 and R2 are both evaluated. Current densities \( \mathbf{J} \) can be calculated from Ampere's law, i.e., \( \nabla \times \mathbf{B} = \mu_0 (\mathbf{J} + \epsilon_0 \frac{\partial \mathbf{E}}{\partial t}) \), where \( \mathbf{B} \) is the magnetic field, \( \mu_0 \) is the permeability of free space, \( \epsilon_0 \) is the permittivity of free space, and \( \mathbf{E} \) is the electric field. The MSWID studied here could be assumed a quasi-time-steady structure, thus the time-varying displacement electric field is ignored. Therefore we can obtain the current density from the curl of the magnetic field \( \mathbf{J} = \frac{1}{\mu_0} \nabla \times \mathbf{B} \).

If the currents are assumed as sheet structures embedded within the R1 and R2, variations of \( \mathbf{B} \) in the normal direction of the current sheet are then negligible, thus the curl of \( \mathbf{B} \) can be resolved with one satellite’s observation in the LMN coordinate, where the N is the normal direction of the current sheet, and L and M define the plane where the currents flow and the magnetic field components vary significantly. The LMN coordinate could be obtained by applying the minimum variance analysis (MVA; Sonnerup & Scheible 1998) to the magnetic field, as done in Bertucci et al. (2005) and Boscoboinik et al. (2020). In MVA the eigenvalue \( \lambda_1, \lambda_2, \) and \( \lambda_3 \), corresponding to the maximum, intermediate, and minimum direction respectively, can be used as indicators of reliability. The minimum direction is regarded as the normal direction (i.e., N in LMN coordinate).

For R1, the normal direction of the current sheet \( n_1 = (-0.953, -0.141, 0.268) \), and the eigenvalue ratio of intermediate-to-minimum \( \lambda_2/\lambda_3 = 11.6 \). For R2, the normal direction \( n_2 = (-0.855, -0.491, 0.166) \), and \( \lambda_2/\lambda_3 = 637.7 \). The angle between \( n_1 \) and \( n_2 \) is about 21°. Meanwhile, the MAVEN position around the interface between R1 and R2 in MSO is [1.13, -0.16, 0.33]RM (Mars radius, \( R_M = 3397.0 \) km), thus the unit vector of the spacecraft position at this time \( n_r = (0.952, -0.131, -0.277) \), so the angle between \( n_1 \) and \( n_r \) is 164°36' (15°64'), and between \( n_2 \) and \( n_r \) is 142°72' (37°28').

Considering the uncertainty in the MVA method and the angles estimated above are close, we assume that the unit vector of the MAVEN position could be an appropriate proxy for the normal direction of the current sheet within the MSWID (Bertucci et al. 2005; Trotignon et al. 2006; Boscoboinik et al. 2020), which would be convenient for estimating the current density profile in altitude. Thus the original magnetic field smoothed among 60 s is transferred into a local orthogonal coordinate with \( n_r \) as its z direction (\( z_{\text{loc}} \)), \( n_r \times z_{\text{MSO}} \) as its x direction (\( x_{\text{loc}} \)), and y completes the right-hand coordinate (\( y_{\text{loc}} \)). Under this assumption, the current is flowing in \( x_{\text{loc}} - y_{\text{loc}} \) plane, thus the current density in this coordinate \( J_{\text{loc}} \) could be obtained with:

\[
J_{\text{loc}} = \frac{1}{\mu_0} \begin{pmatrix}
-\Delta B_{\text{loc}} \\
\Delta B_{\text{loc}} \\
0
\end{pmatrix} \begin{pmatrix}
x_{\text{loc}} \\
y_{\text{loc}} \\
z_{\text{loc}}
\end{pmatrix}
\]

(1)

After the \( J_{\text{loc}} \) in the local orthogonal coordinate is obtained, the current density in MSO coordinate \( J_{\text{MSO}} \) can be derived from \( J_{\text{loc}} \) according to the transformation matrix determined by \( x_{\text{loc}}, y_{\text{loc}}, \) and \( z_{\text{loc}} \).

We then calculated the current density in the R1 and R2 in two ways. (1) According to the method in Bertucci et al. (2005) and Boscoboinik et al. (2020), i.e., getting the magnetic field at the edges of R1 and R2 and utilizing Equation (1), we obtain the current density in R1 \( J_{\text{MSO}} = [1-21.89, -79.21, -37.66] \) nA m⁻², with a magnitude of \( \sim 90.4 \) nA m⁻², and that in R2 \( J_{\text{MSO}} = \left[73.33, 379.9, 71.98\right] \) nA m⁻², with a magnitude of \( \sim 393.4 \) nA m⁻². (2) Another method is taken to calculate the current density to investigate the altitude profile of the current flowing within the MSWID. That is, at each time \( T_0 \) from the 1st to the 2nd and 3rd line, we obtain the differences of the magnetic field and position before and after \( T_0 \), i.e., \( T_1 \) and \( T_2 \) \( (T_0 - 60s < T_1 < T_0 - 15s; T_0 + 15s < T_2 < T_0 + 60s) \). Multiple current densities around \( T_0 \) could be obtained with those measurements at different \( T_1 \) and \( T_2 \), and the largest one is picked as the current density at \( T_0 \). Then we obtain the current densities at different \( T_0 \), which thus provide the altitude profile of the current density around the MSWID. This profile is illustrated in Figure 3. Figures 3(c) and (d) show the altitude profile of magnetic field components and magnitude; Figures 3(c) and (d) show the altitude profile of the current density in MSO and its magnitude. R1 and R2 are indicated by the blue and yellow shaded regions. It is obvious that the currents have a different direction in R1 and R2, and the current density in R2 at lower altitudes is sufficiently larger. Also, the maximum current density exceeds 500 nA m⁻², which is much larger than the current density calculated from the method in Bertucci et al. (2005) and Boscoboinik et al. (2020), indicating previous works may underestimate the current densities in MSWID. Different SZA crossings and solar wind conditions have effects on MSWID position (Bertucci et al. 2011), though cases in Boscoboinik et al. (2020) showed varying current densities under varying solar wind dynamic pressure, whether they have effects on the current density and how they affect it needs further investigation.

3. Discussion

Detailed analysis for an MSWID crossing at the Martian subsolar region with comprehensive measurements by MAVEN is presented in this study. A signature of two current layers is reported in the MSWID. Properties of the MSWID are estimated, some of which had been shown by observations before MAVEN. For example, magnetic fluctuations turn weak or disappear and the plasma composition changes from the solar wind to the planetary origin. However, the MAVEN measurements provide a tremendous opportunity to unambiguously determine the variations of relative parameters, such as the magnetic field, protons, and heavy ions, and to investigate their correlations.

According to analyses in Holmberg et al. (2019), Vaisberg et al. (2018), etc., the MSWID between the magnetosheath and the lower induced magnetosphere/ionosphere is complicated and variable under different solar wind conditions and at different SZAs. Our case is observed at the subsolar region with SZA \( \approx 17°8' \) and appears as a well-defined MSWID resulting from the interaction between Mars and the solar wind, which could be mainly divided into three parts: R1, R2, and one interface between them similar to ICB where the number density of heavy ions and protons are comparable.

R1 (1st to 2nd line): the magnetic fluctuation seen in the magnetosheath generally stops here; the field magnitude strengthens and so do the field components, which exhibit a signature of pure field pile-up: the flux of high energy electrons decreases, and the solar wind protons number density decrease.
too; the magnetic pressure is generally larger than the plasma pressure and the pressure-balanced point is far above this region, consistent with conclusions in Holmberg et al. (2019). The current here is found flowing dawnward and southward with a magnitude exceeding 90 nA m$^{-2}$. This region is similar to predefined MPB.

The interface (ICB) (2nd line): the solar wind protons stop here, while the heavy ions, O$^+$ and O$_2^+$, start dominating; the cold electrons appear, which may refer to the ionization process (Cridel et al. 2000; Dubinin et al. 2008); a new feature not mentioned before is that an abrupt trend change of variation in magnetic components is corresponding to where the number density of heavy ions equals that of protons. The signature of ICB is common in this MSWID, regardless of its position and solar wind condition; however, the ICB here is rather thin and it could have a larger thickness at other SZAs (Halekas et al. 2018; Vaisbergy et al. 2018; Holmberg et al. 2019).

R2 (2nd to 3rd line): the magnetic pressure is large and the plasma composition shows planetary origin; the magnetic field experiences a significant direction change within the region, which indicates a strong current there. The current magnitude exceeds 393 nA m$^{-2}$ and is flowing antiparallel to the current in R1. This region could be the upper boundary of the induced magnetosphere or the magnetized ionosphere, a typical signature of the unmagnetized planet (Zhang et al. 1991). Holmberg et al. (2019) showed that the pressure-balanced point between the magnetic pressure and the ionosphere thermal pressure is far below this region.

Investigation of the magnetic field, plasma, and other related parameters here show the properties of magnetic structure and current in the MSWID, which is between the magnetosheath and the lower induced magnetosphere/ionosphere. A new feature reported here is the abrupt trend change of variation in magnetic components corresponding to when the number density of heavy ions exceeds that of protons, i.e., the ICB. And at the two sides of the ICB, the currents are antiparallel and asymmetric. The interplanetary magnetic field near this orbit is about (0.46, 3.61, −3.71) nT and the solar wind velocity is about (−308.5, 34.2, 62.9) km s$^{-1}$, therefore the solar wind convection electric field ($\mathbf{E} = - \mathbf{V} \times \mathbf{B}$) is about (0.35, 1.17, 1.10) mV m$^{-1}$, in MSO coordinates. As seen from the $J_x$ and $J_y$ in Figure 3(d), the currents in R1 and R2 flow antiparallel and parallel to the convection electric field, respectively, exhibiting a signature similar to the global scale current flowing in the IMB and ionosphere (Ramstad et al. 2020). However, the currents evaluated in R1 and R2 are rather close in space.

However, this case is at the Martian sub-solar region. Whether the features reported here are common for all SZAs or different solar wind conditions should be investigated further, since other studies had proposed a complicated situation for this MSWID at large SZAs, where the current signatures may be weak or disappear, and the interface coincident with ICB may occupy a larger spatial region (e.g., Halekas et al. 2018; Vaisbergy et al. 2018). Whether or not an overlap of the three separated parts could occur and cause such complications needs future work to evaluate.

4. Conclusions

This study analyzes one MAVEN crossing of the dayside interface of Mars and the solar wind, i.e., MSWID, with multiple instruments. A signature of two current layers is reported in the MSWID and properties of MSWID are evaluated, such as the increase of the magnetic field, decrease of the magnetic fluctuation, and the variation of the ion components. The MSWID could be divided into three parts: R1, R2, and one interface between them, similar to the predefined ICB where the heavy planetary ions are dominant over the protons. Two current layers are found in R1 and R2. And the current in R1 (at higher altitude) is generally antiparallel to the solar wind convection electric field, while the current in R2 (at lower altitude) is parallel to the electric field.

The MSWID investigated here is preferred to represented by the term IMB, whose definition, however, is thus different from that in the literature. This idea was mentioned but not further discussed in Holmberg et al. (2019). Above the IMB, it is characterized by magnetosheath properties, such as the magnetic fluctuation and heated ions and electrons, and below the IMB, it is characterized by planetary ions and large magnetic pressure. Within the IMB, it could be separated into R1, R2, and one interface between them based on the above analysis, mainly the signature of the two antidirected and asymmetric current layers flow in R1 and R2. The currents in R2 are larger and could be the induced current resulting from the interaction between Mars and the solar wind, which might thus cause the induced magnetosphere/magnetized ionosphere. The concept of ICB, where the number density of heavy ions equals that of protons, could be a common feature to find the IMB; the upper edge of the IMB might be found where the magnetic fluctuation ceases and/or the solar wind particles start to decrease; the lower edge of the IMB might be found where the strong current decreases or disappears.

The case presented here shows that the magnetic structures and plasma variations in the IMB resulted from the interaction of Mars and the solar wind. The study illustrates that a rather strong current may be induced within the IMB where the interplanetary magnetic field draping is enhanced and the solar wind particles decrease or disappear, and then result in the induced magnetosphere. Further statistical studies may need to accomplish a more general understanding of IMB.

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References

Acuña, M. H., Connerney, J. E. P., Wasilewski, P., et al. 1998, Sci, 279, 1676
Bertucci, C., Mazzelle, C., Acuña, M. H., Russell, C. T., & Slavin, J. A. 2005, JGRA, 110, A01209
Bertucci, C., Mazzelle, C., Cridel, D. H., et al. 2003, GeoRL, 30, 1099
Bertucci, C., Duru, F., Edberg, N., et al. 2011, SSRv, 162, 113
Bogdanov, A. V., & Vaisberg, O. L. 1975, JGR, 80, 487
Boscoboinik, G., Bertucci, C., Gomez, D., et al. 2020, GeoRL, 47, e92230
Breus, T. K., Krymskii, A. M., Lundin, R., et al. 1991, JGR, 96, 11165
Connorney, J. E. P., Espley, J., Lawton, P., et al. 2015, SSRv, 195, 257
Criders, D., Cloutier, P., Law, C., et al. 2000, GeoRL, 27, 45
Dubinin, E., Modolo, R., Frenz, M., et al. 2008, GeoRL, 35, L11103
Dubinin, E., Sauer, K., Lundin, R., et al. 1996, JGR, 101, 27061
Dubinin, E., Winningham, D., & Fränz, M. 2006, Icarus, 182, 343
Espley, J. R. 2018, JGRA, 123, 4521
Grard, R., Nairn, C., & Pedersen, A. 1991, P&SS, 39, 89
Grard, R., Pedersen, A., Klimov, S., et al. 1989, Natur, 341, 607
Halekas, J. S., McFadden, J. P., Brain, D. A., et al. 2018, JGRA, 123, 8439
Halekas, J. S., Ruhunusiri, S., Harada, Y., et al. 2017, JGRA, 122, 547
Halekas, J. S., Taylor, E. R., Dalton, G., et al. 2015, SSRv, 195, 125
Holmberg, M. K. G., André, N., Garnier, P., et al. 2019, JGRA, 124, 8564
Jakosky, B. M., Lin, R. P., Grebowsky, J. M., et al. 2015, SSRv, 195, 3
Lentz, C. L., Baker, D. N., Andersson, L., et al. 2021, JGRA, 126, e28105
Lundin, R., Zakharov, A., Pellinen, R., et al. 1990, GeoRL, 17, 877
Lundin, R., Barabash, S., Andersson, H., et al. 2004, Sci, 305, 1933
Matsunaga, K., Seki, K., Brain, D. A., et al. 2017, JGRA, 122, 9723
McFadden, J. P., Kortmann, O., Curtis, D., et al. 2015, SSRv, 195, 199
Michel, F. C. 1971, RVGeo, 9, 427
Mitchell, D. L., Mazelle, C., Sauvaud, J.-A., et al. 2016, SSRv, 200, 495
Ramstad, R., Brain, D. A., Dong, Y., et al. 2020, NatAs, 4, 979
Riedler, W., Möhlmann, D., Oremsky, V. N., et al. 1989, Natur, 341, 604
Rosenbauer, H., Shutte, N., Apáthy, I., et al. 1989, Natur, 341, 612
Sauer, K., Bogdanov, A., & Baumgärtel, K. 1994, GeoRL, 21, 2255
Sonnerup, B. U. Ö, & Scheible, M. 1998, ISSIR, 1, 185
Trotignon, J. G., Mazelle, C., Bertucci, C., & Acuña, M. H. 2006, P&SS, 54, 357
Vaisberg, O. L., Ermakov, V. N., Shuvalov, S. D., et al. 2018, JGRA, 123, 2679
Verigin, M., Shutte, N. M., Galeev, A. A., et al. 1991, P&SS, 39, 131
Vignes, D., Mazelle, C., Rme, H., et al. 2000, GeoRL, 27, 49
Wang, J., Lee, L. C., Xu, X., et al. 2020, A&A, 642, A34
Xu, S., Liemohn, M. W., Dong, C., et al. 2016, JGRA, 121, 6417
Zhang, T. L., Luhmann, J. G., & Russell, C. T. 1991, JGR, 96, 11145