Role of IMF $B_x$ in the solar wind-magnetosphere-ionosphere coupling

Z. Peng, C. Wang, and Y. Q. Hu

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[1] As far as the role of the interplanetary magnetic field (IMF) in the solar wind-magnetosphere-ionosphere (SMI) coupling is concerned, the role of the IMF $B_x$ has more or less been ignored. Recent studies have shown that the IMF $B_x$ plays an important role in the geometry of the bow shock under low Alfvén Mach numbers. Using global MHD simulations, this paper presents a further examination of the effects of the IMF $B_x$ on the geometry of the magnetopause, the ionospheric transpolar potential, and the magnetopause reconnection rate, which quantify the SMI coupling process, under low Alfvén Mach numbers. The role of the IMF $B_x$ manifests itself in three aspects: (1) the magnetopause shifts toward either north or south, depending on whether the $B_x \cdot B_z$ is negative or positive, whereas the bow shock expands in the opposite direction; (2) during southward IMF, the magnetic merging line shifts northward (southward) on the day side and southward (northward) on the night side for $B_x > 0$ ($B_x < 0$); (3) both the ionospheric transpolar potential and the magnetopause reconnection rate decrease with increasing $B_x$, and the relative reduction may reach as high as 20% under extreme cases. The physical mechanism for this reduction is attributed to the change in the width of the magnetosheath, which is sensitive to the variation of $B_x$ under low Alfvén Mach numbers.


1. Introduction

[2] It is generally believed that magnetic reconnection serves as the main means of the energy coupling in the solar wind-magnetosphere-ionosphere (SMI) system, and the magnitude and orientation of the interplanetary magnetic field (IMF) plays a crucial role in it [Dungey, 1961]. Various empirical functions have been proposed to characterize the SMI coupling [Newell et al., 2007]. Most of these coupling functions involve the IMF $B_x$, $B_y = \sqrt{B^2_y + B^2_z}$, and the IMF clock angle $\theta_{IMF} = \arccos(B_y/B_z)$ without reference to the IMF $B_z$, whereas the “oldest” coupling parameter, the Akasofu epsilon, contains the magnitude of the magnetic field including also the radial component [Perreault and Akasofu, 1978].

[3] Recently, Chapman et al. [2004] investigated the effect of the IMF $B_x$ on the shape of the bow shock in terms of global MHD simulations, in which the magnetopause is fixed to be an ellipsoid given by Farris et al. [1991] and the IMF is set to be generic northward ($B_x > 0$). Their simulations demonstrated that due to the presence of $B_x$, the bow shock becomes asymmetric in the $x$-$z$ plane, where the IMF lies. The asymmetry comes from the anisotropy of fast magnetosonic waves in the magnetosheath: a larger wave speed leads to a wider magnetosheath and thus a more distant bow shock. However, such asymmetry becomes significant only for a solar wind with low Alfvén Mach numbers.

[4] In addition to the geometry of the bow shock, one would expect that the IMF $B_x$ should affect the shape of the magnetopause, the state of the magnetosphere and ionosphere, and their dynamic coupling with the solar wind especially under generic southward IMF cases ($B_x < 0$). This paper presents a further investigation of the IMF $B_x$ effect on the SMI system using global MHD simulations. We limit ourselves to generic southward IMF cases ($B_x < 0$), in which the SMI coupling is strong and sensitive to the magnitude and orientation of the IMF. It is assumed for simplicity that the IMF $B_z$ is southward ($B_z < 0$) and the IMF $B_x$ is sunward ($B_x > 0$). Our analysis is not limited to the shape of the bow shock. It extends to the shape of the magnetopause and the magnetic merging line, where magnetic reconnection between the earth’s closed magnetic field and the IMF takes place, generating the magnetic merging and the ionospheric transpolar potentials, which characterize the strength of the SMI coupling.

2. Simulation and Diagnosis Methods

[5] The PPMLR-MHD code developed by Hu et al. [2005, 2007] is used to conduct global MHD simulations...
of the SMI system. The solution domain is taken to be $-300 \leq x \leq 30$ and $-150 \leq y, z \leq 150$ in units of $R_E$ (the Earth’s radius) in GSE coordinate. It is discretized into $160 \times 162 \times 162$ grid points: a uniform mesh is laid out in the near Earth domain of $-10 \leq x \leq 10$ and $-10 \leq y, z \leq 10$, 0.4 in spacing, and the grid spacing outside increases according to a geometrical series of common ratio 1.05 along each axis. An inner boundary of radius 3 is set for the magnetosphere in order to avoid the complexity associated with the plasmasphere and strong magnetic field. The reader is referred to the paper by Hu et al. [2007] for more details of the numerical method.

[6] All numerical runs are made under the following simplifying assumptions: (1) the solar wind is along the Sun-Earth line, (2) the solar wind number density and thermal pressure are fixed to be $n_{sw} = 5 \text{ cm}^{-3}$ and $p_{sw} = 0.0126 \text{ nPa}$, respectively, (3) the IMF is generic southward with $B_z = -10 \text{ nT}$, superposed by a positive $B_x$ that is adjustable, and (4) the ionosphere is assumed uniform with a fixed Pedersen conductance of $\Sigma_P = 5 \text{ S}$ and a zero Hall conductance. Each run continues for more than 5 hours in physical time until a quasi-steady state is reached for the SMI system.

[7] A quasi-steady state of the SMI system with a finite IMF $B_0$ is obtained with the use of the following technique. Suppose that we want to obtain a quasi-steady state with an IMF equal to $B_i = (10, 0, -10) \text{ nT}$. To this end, a simulation is carried out first to find the quasi-steady solution for due southward case with the same IMF strength, namely, $B_0 = (0, 0, -14.14) \text{ nT}$. Taking this solution as the initial state, we then introduce a discontinuity that is perpendicular to the plane spanned by $B_0$ and $B_i$ and parallel to the vector of $B_i - B_0$. The unit normal of this discontinuity, $n$ with a negative x-component, satisfies the following conditions:

$$n \cdot (B_0 \times B_i) = 0, \quad n \cdot (B_i - B_0) = 0, \quad |n| = 1.$$

It is easy to show that the solution of $n$ is unique, $n = (-0.383, 0, 0.924)$ for the present case. Meanwhile, when the IMF changes from $B_0$ to $B_i$ across the discontinuity, the normal component keeps continuous ($= -13.07 \text{ nT}$), whereas the tangential component equals in magnitude ($= 5.41 \text{ nT}$) but changes in direction. The initial discontinuity is assumed to intersect the inflow boundary of the simulation domain at $x = 30$. Finally, the introduced discontinuity moves with the solar wind and interacts with the magnetosphere, resulting in a new quasi-steady solution that is associated with the required IMF $B_1$ with a finite $B_x$.

[8] The value of $B_x$ is taken to be 0, 10, and 20 nT, resulting in an angle of the IMF to the x-axis, $\theta_x = \arccos (B_x / \sqrt{B_z^2 + B_x^2})$, to be 90°, 45°, and 26.6°, respectively. All runs are repeated for two separate values of $v_{sw}$: 400 and 800 $\text{km s}^{-1}$. The solar wind and IMF parameters mentioned above are listed in Table 1 along with the corresponding Alfvén Mach number ($M_A = v_{sw} / v_A$, $v_A = (B_z^2 + B_x^2) / (\rho \mu_0 m)$, $m$ is the mass of proton).

[9] In this study, the bow shock is approximated by a contour of 0.1 of the density enhancement relative to the solar wind density. However, determining the location of the magnetopause is somewhat difficult because of its complex structure. There are four approaches of locating the magnetopause often seen in the literature: pressure gradient maximum, density gradient maximum, current density maximum, and streamline method. Different methods lead to nearly consistent results of the position of the magnetopause [Palmeroth et al., 2003]. For simplicity, we use the mass flux as the criterion and presume that it equals 0.3 times the background solar wind mass flux ($n_{sw}m_{sw}$) at the magnetopause. Our preliminary analysis shows that the results of this method agree well with the method of the maximum gradient of density.

### Table 1. Solar Wind and IMF Parameters Used in the Simulations Along With the Corresponding Alfvén Mach Numbers

<table>
<thead>
<tr>
<th>$B_0$ (nT)</th>
<th>0</th>
<th>10</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_x$</td>
<td>90°</td>
<td>45°</td>
<td>26.6°</td>
</tr>
<tr>
<td>$M_A$ ($v_{sw} = 400 \text{ km s}^{-1}$)</td>
<td>4.10</td>
<td>2.90</td>
<td>1.83</td>
</tr>
<tr>
<td>$M_A$ ($v_{sw} = 800 \text{ km s}^{-1}$)</td>
<td>8.19</td>
<td>5.80</td>
<td>3.66</td>
</tr>
</tbody>
</table>

*Note: $B_0 = -10 \text{ nT}; n_{sw} = 5 \text{ cm}^{-3}; p_{sw} = 0.0126 \text{ nPa}.$

[10] The magnetic merging line is a closed curve around the Earth, which separates the Earth’s closed field lines from the IMF lines. The tangential electric field along the merging line is equivalent to the strength of the reconnection rate (amount of magnetic flux reconnecting per unit time per unit length of the reconnection line [Borovsky et al., 2008]), whereas the total electric voltage on the day side of the merging line represents the total reconnection potential. Hu et al. [2009] proposed diagnosis methods to trace the merging line and to calculate the electric potential along it for Earth’s magnetospheric magnetic fields obtained by global MHD simulations of the SMI system. For the reader’s convenience, we repeat the diagnosis method as follows. The diagnosis of the merging line is based on the fact that it lies on the separatrix spanned by Earth’s last closed magnetic field lines. The construction of the merging line consists of the following steps. First, we draw the last closed field lines starting from the inner boundary ($r = 3 R_E$) in both northern and southern hemispheres, and the starting points are uniformly disposed in longitude at a constant interval of 4°. Each field line is traced by the fourth-order Runge-Kutta method with a step arc length 0.1 ($R_E$). For a given longitude of the starting point, a last closed field line is obtained by iteration with an accuracy of $10^{-4}$ degree in the latitude of the starting point. A last closed field line thus obtained must touch the merging line at a certain point, where the magnetic field strength is assumed to be a minimum. On this basis, we seek the point with minimum magnetic field strength for each last closed field line, and regard it as a “touch point”. It turns out that the touch points thus obtained gather on the magnetic nulls to some extent: those for field lines starting from the northern hemisphere gather on the southern null and those for field lines starting from the southern hemisphere gather on the northern null. As a result, the whole set of touch points can only trace part of the merging line around the nulls in most cases, leaving several spaces between adjacent nulls, in which no touch points appear. Second, we manage to select appropriate last closed field lines to fill up these spaces. Each space is bordered by two touch points, and a last closed field line passes through each of them. We may choose a better one from the two field lines, which passes one touch point and keeps closer to another. The selected last closed field line is then used to fill up the space. Finally, the touch points and
the filled spaces form a closed curve around the Earth, that is regarded as the merging line wanted. As for the evaluation of the electric potential along the merging line, a linear integration of the convective electric field is carried out along various radial rays between their intersection points with the inner boundary and the merging line. The potential at the inner boundary can be inferred from the ionospheric potential through equivalent mapping along the Earth’s dipole field lines, and thus we obtain the potential along the merging line. These methods are used to determine the merging line and to calculate the electric potential distribution along it in the presence of the IMF $B_x$. The difference between the maximum and minimum of the potential is the reconnection voltage $V_R$. The ionospheric transpolar potential $V_{TP}$ is defined as the difference between the positive and negative peaks of the ionospheric potential.

3. Shape of the Magnetopause and Bow Shock

Let us first examine the effects of $B_x$ on the shape of the Earth’s magnetopause and bow shock. The shape of the bow shock was shown by Chapman et al. [2004] to be asymmetric in the $x$-$z$ plane, where the IMF lies. In their simulations, the IMF was set to be generic northward ($B_z > 0$), and the magnetopause was fixed to be an ellipsoid. Under low Alfvén Mach numbers, the asymmetry of the bow shock becomes very clear: a more distant shock in the south ($B_x < 0$) than in the north. Our simulations differ from Chapman et al.’s in two aspects: the magnetopause is obtained self-consistently from the simulations, and the IMF is generic southward ($B_z < 0$). Figure 1 shows density contour plots in the terminator plane ($x = 0$), where the dashed and solid white curves mark the magnetopause and the bow shock, respectively. The top three plots are for cases with $v_{sw} = 400 \text{ km/s}$, whereas the bottom three, $800 \text{ km/s}$. Each plot from left to right corresponds to different IMF $B_z$, as labeled at the top. Both the bow shock and the magnetopause are symmetric with respect to the $y$- and $z$-axes for $B_z = 0$ as expected. As $B_z$ increases, the shape remains symmetric in the dawn-dusk direction, but an asymmetry appears clearly in the north-south direction. The shock is more distant in the north ($z > 0$). This conclusion is reached when the sign of the product $B_x \cdot B_z$ is negative ($B_x > 0, B_z < 0$). Chapman et al. [2004] treated cases with $B_x \cdot B_z > 0$ ($B_x > 0, B_z > 0$), and they arrived at a different conclusion that the bow shock is more distant in the south due to the presence of a positive $B_x$. Through preliminary simulations for cases with $B_x < 0$ and $B_z < 0$, we arrived at the same conclusion on the north-south asymmetry of the bow shock as reached by Chapman et al. [2004]. Therefore, we conclude that the behavior of the bow shock in shape depends on the sign of $B_x \cdot B_z$. A similar conclusion holds for the shape of the magnetopause, but it changes in an opposite way as the bow shock does, more distant in the south for negative $B_x \cdot B_z$ cases treated in this study. This is supposedly related to magnetic reconnection at the dayside magnetopause, which will be discussed in the next section. The change of the shape of the magnetopause does not alter the trend of northward expansion of the bow shock with increasing $B_x$. Through comparing the top three plots ($v_{sw} = 400 \text{ km/s}$) with their counterparts at the bottom ($v_{sw} = 800 \text{ km/s}$), we reach a similar conclusion as Chapman et al. [2004] did: only for low Alfvén Mach numbers, more specifically $M_A < 3$ according to Table 1, can the

![Figure 1](image-url)
Table 2. North-South Asymmetry of the Bow Shock and Magnetopause, Measured by the Ratio of \( r_n - r_s \)/\( r_n \). Where \( r_n \) and \( r_s \) are the Geocentric Distances of Either the Bow Shock or the Magnetopause in the Due North and South Directions, Respectively.

<table>
<thead>
<tr>
<th>( v_{sw} ) (km( \cdot )s(^{-1} ))</th>
<th>( B_x ) (nT)</th>
<th>0</th>
<th>10</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>MP(%)</td>
<td>−0.7</td>
<td>−10.1</td>
<td>−25.8</td>
</tr>
<tr>
<td>400</td>
<td>BS(%)</td>
<td>0.2</td>
<td>17.5</td>
<td>30.5</td>
</tr>
<tr>
<td>800</td>
<td>MP(%)</td>
<td>−0.4</td>
<td>−2.5</td>
<td>−9.7</td>
</tr>
<tr>
<td>800</td>
<td>BS(%)</td>
<td>0</td>
<td>7</td>
<td>13.8</td>
</tr>
</tbody>
</table>

*Bow Shock (BS); Magnetopause (MP).

 IMF \( B_x \) affect significantly the shape of the bow shock and magnetopause.

[12] To make a quantitative estimate, we measure the geocentric distances of the intersection points between the bow shock and the z-axis and between the magnetopause and the z-axis, \( r_n \) for the north and \( r_s \) for the south. Then we calculate the ratio of \( r_n - r_s \) to \( r_n \), which characterizes the north-south asymmetry of either the bow shock or the magnetopause. The results are shown in Table 2, positive ratios for the bow shock and negative ones for the magnetopause. Both the bow shock and the magnetopause are symmetric with respect to the y-axis when \( B_x = 0 \); slight deviations of the ratios from zero may result from intrinsic oscillations of the SMI system [cf. Hu et al., 2005]. The ratios are smaller for \( v_{sw} = 800 \) km\( \cdot \)s\(^{-1} \) cases, for which \( M_A \) is larger. When \( B_x \) increases, the ratio grows for the bow shock and exceeds 30% for the case with \( v_{sw} = 400 \) km\( \cdot \)s\(^{-1} \) and \( B_x = 20 \) nT, a remarkable northward expansion as seen from the top-right plot. In the same plot, one can see a clear southward expansion of the magnetopause, and the ratio becomes negative and greater than 25% in magnitude.

4. Magnetic Merging Line

[13] Figure 2 shows the \( r-\varphi \) and \( \lambda-\varphi \) profiles of the magnetic merging line and the distributions of electric potential \( \Phi_R \) and parallel electric field \( E_R \) along this line, respectively, for cases with \( v_{sw} = 400 \) km\( \cdot \)s\(^{-1} \) and different values of \( B_x \), as labeled at the top. Here \( \lambda \) is the latitude, and \( \varphi \), the longitude, which is zero at the subsolar point, being positive on the dusk side and negative on the dawn side.

[14] The merging line lies in the equatorial plane for the due southward IMF case (\( B_x = 0 \)), but shifts northward on the day side and southward on the night side for \( B_x > 0 \), and the extent of the shift increases as \( B_x \) grows. Similar conclusions hold for the case with \( v_{sw} = 800 \) km\( \cdot \)s\(^{-1} \), although with a smaller shift. The shift of the dayside merging line to the north may be qualitatively explained as follows. In the absence of the IMF \( B_x \), the magnetic field in the magnetosheath is due southward in the equatorial plane, exactly anti-parallel to the Earth’s magnetic field. As a result, the merging line lies exactly in the equatorial plane. The situation changes if a positive \( B_x \) appears: the magnetic field in the magnetosheath deviates from due south in the equatorial plane, so the site, at which the magnetic field in the magnetosheath becomes opposite in direction to that in the magnetosphere, moves northward, leading to a corresponding northward shift of the dayside merging line. Meanwhile, magnetic reconnection across the merging line makes the magnetopause move toward the Earth, similarly to the erosion of the subsolar magnetopause under due southward IMF cases, which results in shrinking of the magnetopause in its northern part, as mentioned in last section and clearly seen in Figure 1. Note that the dayside merging line moves southward and the magnetopause shrinks in its southern part if \( B_x \) is negative.

5. Reconnection Rate and Transpolar Potential

[15] As Figure 2 shows, the existence of the IMF \( B_x \) does not affect the anti-symmetry of \( \Phi_R \) and the symmetry of \( E_R \) with respect to \( \varphi \), but it does reduce the amplitude of \( \Phi_R \) and \( E_R \). The reconnection voltage or the total dayside reconnection rate \( V_R \) is evaluated as the difference between maximum and minimum of \( \Phi_R \).

[16] The potential distribution in both northern and southern ionospheres is structured in a two cell pattern, which is similar to that obtained for due south IMF cases; the presence of the IMF \( B_x \) does not destroy the north-south symmetry and dawn-dusk anti-symmetry of the ionospheric potential distribution as expected. The transpolar potential \( V_{PC} \), defined as the difference between the positive and negative peaks of the ionospheric potential, is calculated for both northern and southern ionospheres, and the two values obtained are nearly the same. We will take an average between the two and regard it as \( V_{PC} \).

[17] Table 3 lists \( V_R \) and \( V_{PC} \) versus \( B_x \) and \( v_{sw} \). For cases with \( v_{sw} = 400 \) km\( \cdot \)s\(^{-1} \), both \( V_R \) and \( V_{PC} \) decrease clearly with increasing \( B_x \). As compared with the \( B_x = 0 \) case (\( V_R = 290 \) kV, \( V_{PC} = 180 \) kV), the relative reduction of both \( V_R \) (230 kV) and \( V_{PC} \) (140 kV) reaches about 20% if \( B_x \) increases to 20 nT. On the other hand, for cases with \( v_{sw} = 800 \) km\( \cdot \)s\(^{-1} \), \( V_R \) and \( V_{PC} \) remain almost invariant as \( B_x \) changes: their relative reduction is within 1%. This tells us that the effect of the IMF \( B_x \) on the dayside reconnection rate and the transpolar potential is negligible under high Alfvén Mach numbers, but becomes significant for Alfvén Mach numbers lower than 3 (see Table 1).

[18] It is generally believed that the reconnection voltage and the transpolar potential are mainly controlled by the solar wind convective electric field \( (E_v = v_{sw} B_x) \). Merkin et al. [2003] and Merkin et al. [2005] established a mapping of the electric potential from the solar wind to the reconnection line on the magnetopause in terms of flow streamlines. They argued that a wider magnetosheath leads to a more efficient braking of the magnetosheath flow, leading to a drop in the electric field on the nose of the magnetopause even the solar wind electric field remains invariant. Although their situation differs from ours in the cause of the magnetosheath widening, an increase in the ionospheric conductance in theirs but an appearance of IMF \( B_x \) in ours, the electric field in the solar wind remain the same for the two situations. Therefore, Merkin et al. [2003] and Merkin’s [2005] conclusion is essentially applicable to our situation, namely, a widening of the magnetosheath leads to a reduction of both the reconnection rate and the transpolar potential. In order to find out the possible physical reason for the effect of \( B_x \) on \( V_R \) and \( V_{PC} \), the \( E_v \) (mV/m) contour plots in the equatorial plane are shown in Figure 3 for the same parameters in Figure 1. To be more quantitative, we also measure the geocentric distances of the subsolar points of the bow shock and the magnetopause, and obtain the associated width of...
the magnetosheath. The results are listed in Table 4. For cases with $v_{sw} = 800 \text{ km} \cdot \text{s}^{-1}$, from Figure 1, Figure 3 and Table 4, we can see that with increasing $B_x$, both reconnection and transpolar potentials remain almost invariant. The introduction of $B_x$ does not significantly change the geometry of the magnetopause and the bow shock. This indicates that the effect of the IMF $B_x$ on the reconnection rate and the transpolar potential is negligible under high Alfvén Mach numbers. On the other hand, for cases with $v_{sw} = 400 \text{ km} \cdot \text{s}^{-1}$, the magnetosheath expands with increasing $B_x$, and the relative increase of the width of the magnetosheath can reach 20.7% if $B_x$ increases to 20 nT, compared with the $B_x = 0$ case. Furthermore, the solution becomes more asymmetrical, the bow shock shifts toward north for $B_x$ positive, whereas the magnetopause expands in the opposite direction. The effect of the asymmetry is somewhat equivalent to a global expansion of the magnetosheath, since the merging line shifts northward at the same

![Figure 2](image)

**Figure 2.** The $r-\varphi$ and $\lambda-\varphi$ profiles of the magnetic merging line and the distributions of potential $\Phi_R$ and parallel electric field $E_R$ along it for different IMF $B_x$: (left) $B_x = 0 \text{ nT}$; (middle) $B_x = 10 \text{ nT}$; (right) $B_x = 20 \text{ nT}$. Here $\lambda$ stands for the latitude, and $\varphi$, the longitude, which is zero at the subsolar point, positive on the dusk side and negative on the dawn side. The solar wind speed is taken to be $400 \text{ km} \cdot \text{s}^{-1}$. A horizontal dotted line displays the zero line of either $\Phi_R$ or $E_R$ in the $\Phi_R$ and $E_R$ plots.

<table>
<thead>
<tr>
<th>$v_{sw}$ (km/s)</th>
<th>$B_x$ (nT)</th>
<th>0</th>
<th>10</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>$V_R$ (kV)</td>
<td>290</td>
<td>270</td>
<td>230</td>
</tr>
<tr>
<td></td>
<td>$V_{PC}$ (kV)</td>
<td>180</td>
<td>170</td>
<td>140</td>
</tr>
<tr>
<td>800</td>
<td>$V_R$ (kV)</td>
<td>467</td>
<td>467</td>
<td>464</td>
</tr>
<tr>
<td></td>
<td>$V_{PC}$ (kV)</td>
<td>272</td>
<td>272</td>
<td>270</td>
</tr>
</tbody>
</table>

$^a$Reconnection rate, $V_R$; transpolar potential, $V_{PC}$.  

Table 3. Reconnection Rate and Transpolar Potential Versus IMF $B_x$ and $v_{sw}$

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time. Hence, it implies that the reduction of the reconnection rate and the transpolar potential results mainly from the expansion of the magnetosheath, a similar conclusion as reached by Merkine et al. [2003] and Merkin [2005].

6. Summary

[19] This paper presents global MHD simulations of the solar wind–magnetosphere–ionosphere (SMI) system under generic southward interplanetary magnetic field (IMF) cases. Our emphasis is placed on the effects of the IMF $B_x$ on (1) the shape of magnetopause and bow shock, (2) the geometry of the magnetic merging line, and (3) the dayside reconnection rate and the ionospheric transpolar potential. Three conclusions are made as follows:

[20] 1. When the Alfvén Mach number of the solar wind is lower than $\sim 3$, both the magnetopause and the bow shock change clearly in shape with increasing magnitude of $B_x$. Under generic southward IMF cases, owing to the presence of a positive (negative) IMF $B_x$ the magnetopause expands more in the south (north), whereas the bow shock expands more in the north (south).

[21] 2. In the presence of a positive (negative) IMF $B_x$ for generic southward IMF cases, the magnetic merging line shifts northward (southward) on the day side and southward (northward) on the night side. This shift increases with increasing magnitude of IMF $B_x$.

[22] 3. The existence of the IMF $B_x$ does not destroy the north–south symmetry and dawn–dusk anti-symmetry of the ionospheric potential distribution, but it does affect the amplitude of the transpolar potential and the dayside reconnection rate. The transpolar potential and the reconnection rate may be reduced by about 20% as $B_x$ increases from 0 to 20 nT under low $M_A$ cases. However, if $M_A$ is high, the effect of the IMF $B_x$ on the two potentials becomes negligible. On the basis of the recent work by Merkin et al. [2005], a wider magnetosheath will lead to a reduction of both the reconnection and transpolar potentials. The suggested physical reason of the $B_x$ effects is as follows. Under low $M_A$ cases, the solution is sensitive to $B_x$. A larger $B_x$ leads to a wider magnetosheath, which leaves more room for the flow to brake, and thus results in smaller reconnection and transpolar potentials. On the other hand, during high $M_A$ cases, the solution is insensitive to the change of $B_x$, the shapes of the magnetopause and the bow shock change little, and hence, the reconnection rate and the transpolar potential remain almost invariant. The above results are all limited to the case of IMF $B_y = 0$. The presence of a finite $B_y$ will destroy the dawn–dusk symmetry of the SMI system and change the so-called IMF clock angle between the IMF projected on the $y$–$z$ plane and the $z$ axis, resulting in a corresponding change of the reconnection rate and the transpolar potential [Hu et al., 2009]. A detailed analysis of the effect of $B_x$ under this situation is interesting but beyond the scope of this study.

<table>
<thead>
<tr>
<th>$v_{sw}$ (km·s$^{-1}$)</th>
<th>$B_x$ (nT)</th>
<th>0</th>
<th>10</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>MP($R_E$)</td>
<td>8.7</td>
<td>8.9</td>
<td>9.4</td>
</tr>
<tr>
<td></td>
<td>BS($R_E$)</td>
<td>14.0</td>
<td>14.6</td>
<td>15.8</td>
</tr>
<tr>
<td></td>
<td>MS($R_E$)</td>
<td>5.3</td>
<td>5.7</td>
<td>6.4</td>
</tr>
<tr>
<td>800</td>
<td>MP($R_E$)</td>
<td>6.9</td>
<td>7.0</td>
<td>6.9</td>
</tr>
<tr>
<td></td>
<td>BS($R_E$)</td>
<td>10.9</td>
<td>11.0</td>
<td>11.0</td>
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<tr>
<td></td>
<td>MS($R_E$)</td>
<td>4.0</td>
<td>4.0</td>
<td>4.1</td>
</tr>
</tbody>
</table>

Table 4. Geocentric Distances of the Subsolar Point of the Bow Shock and the Magnetopause, and the Width of the Magnetosheath$^a$

$^a$Bow Shock (BS); Magnetopause (MP); and Magnetosheath (MS).
The solar wind is often in a high $M_A$ regime [cf. Kallio and Koskinen, 2000], so it is reasonable in normal conditions to exclude the IMF $B_x$ from the SMI coupling, as done in most coupling functions [Newell et al., 2007]. However, in magnetic clouds associated with coronal mass ejection events, the magnetic field strength is high and the mass density is low so that $M_A$ may become very small, being close to and even smaller than 1 [cf. Ridley, 2005]. Under these extreme cases, effects of the IMF $B_x$ should be included in addition to other components.

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