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Simulation of interplanetary magnetic field $B_y$ penetration into the magnetotail

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Based on our global 3D magnetospheric MHD simulation model, we investigate the phenomena and physical mechanism of the $B_y$ component of the interplanetary magnetic field (IMF) penetrating into the magnetotail. We find that the dayside reconnected magnetic field lines move to the magnetotail, get added to the lobe fields, and are dragged in the IMF direction. However, the $B_y$ component in the plasma sheet mainly originates from the tilt and relative slippage of the south and north lobes caused by plasma convection, which results in the original $B_z$ component in the plasma sheet rotating into a $B_y$ component. Our research also shows that the penetration effect of plasma sheet $B_y$ from the IMF $B_y$ during periods of northward IMF is larger than that during periods of southward IMF. © 2014 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4882243]

I. INTRODUCTION

Theoretical, observational, and simulation studies$^{1-8}$ show that, when the interplanetary magnetic field (IMF) has a large $B_y$ component, it will induce some proportional $B_y$ component in the magnetotail lobes and plasma sheet. This phenomenon is generally referred to as IMF $B_y$ penetration. Previous studies indicate that the $B_y$ penetration effects from the IMF to the magnetotail are weaker in the lobe region and stronger in the near-Earth central plasma sheet.$^{2,5,8-10}$ For the IMF $B_y$ penetration ratio, the results obtained by different authors are different.$^{5,7,11-13}$ There is also some debate as to the mechanism of the penetration.$^5$ Some authors think that the $B_y$ component in the magnetotail is unlikely to be the result of IMF $B_y$ “penetration,” especially in the plasma sheet, but results from convection patterns in the polar caps affected by IMF $B_y$, which cause the magnetotail to twist and finally change the original $B_z$ component into a $B_y$ component.$^{9,14}$

Recently, Petrukovich has made a detailed analysis of this topic.$^{13}$ He also developed a quantitative model of IMF $B_y$ penetration in the plasma sheet based on observational results. In his research, Petrukovich summarized that the magnetotail $B_y$ could originate from the following five factors: magnetotail flaring, magnetotail twisting, plasma sheet tilt caused by the dawn–dusk tilt of the magnetic dipole, plasma sheet warping caused by the day–night tilt of the magnetic dipole, and IMF $B_y$ penetration. Magnetotail twisting and IMF $B_y$ penetration are both caused by IMF $B_y$, and their physical mechanisms are still a subject of debate. In this paper, we will focus on IMF $B_y$ effects; the structural origins of the tail $B_y$ will not be discussed.

IMF $B_y$ can twist the magnetotail, and the rotating direction is determined by the sign of IMF $B_y$. Because the twisting level is obviously higher when IMF $B_y$ is positive than when it is negative,$^{16}$ this raises the question, “Does IMF $B_y$ have a distinct effect on IMF $B_y$ penetration in the magnetotail?” In the model of Petrukovich,$^1$ there is no effect on IMF $B_y$ penetration from IMF $B_z$. When the dayside reconnected magnetic field lines sweep past the magnetopause and propagate tailward, they get added to the north and south magnetotail lobes and dragged toward the IMF direction. This may be the reason why IMF $B_y$ penetrated into the lobes. However, this process does not explain why the $B_y$ component is larger in the plasma sheet than in the lobes.

Because IMF $B_y$ penetration is a typical large-scale global magnetospheric phenomenon, it is very appropriate to investigate it using simulations. In this research, we will try to identify the physical nature of this important magnetospheric phenomenon by analyzing MHD simulation results.

II. MODEL DESCRIPTION

The detailed description of the global MHD model used in this present study can be found in our previous studies.$^{17,18}$ The model is based on the ideal MHD equation; however, magnetic reconnection can be triggered due to the existence of numerical effects.

A. Simulation boundary

We use the Earth-centered GSE (Geocentric Solar Ecliptic) system, with our simulation region extending 56 Re toward the Sun and 220 Re down the tail. The distance perpendicular to the Sun–Earth line is 132 Re. For the dayside boundary, we use the solar wind input condition, and we use a free boundary condition for the other outer boundary. The inner boundary is set to be 2.8 Re relative to the Earth center. We use the method of Raeder et al.$^{19,20}$ to deal with the inner boundary, which entails solving the Poisson equation of the ionosphere potential, $\nabla \cdot \sum \nabla \Phi = -j_{\Phi}$, by using the magnetic field line mapping method and the field-aligned current input condition. In this equation, $\sum$ is the integrated ionosphere conductivity, including $\sum_{\text{Hall}}$ and $\sum_{\text{Pedersen}}$, $j_{\Phi}$ is the field-aligned current, and $\Phi$ is the ionosphere potential mapping to the simulation inner boundary. After solving the equation, we can get the boundary condition by using $V = (-\nabla \Phi) \times B / B^2$. 

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B. Data structure

In our model, we use the upwind scheme and GSE coordinates. Different time steps are used in different regions determined by the CFL (Courant–Friedrichs–Lewy) condition, and the simulation time in different regions is synchronized every 0.6 s. This method can cause small deviations of the conservation laws (of mass, momentum, and energy) but significantly improves the calculation efficiency. The grid size can also be refined to get higher spatial resolution or enlarged to reduce calculating time. Considering both the efficiency and resolution, we use the following grid size distributions: 0.25 Re near the Earth and the plasma sheet, 0.5 Re in regions within 40 Re from the Earth, and 2 Re in regions of the distant magnetotail and solar wind.

C. Initial conditions

The calculating region is initially filled with an undeformed dipole field, and the particle density and temperature are $n = 1 \text{ cm}^{-3}$ and $T = 1 \text{ eV}$, respectively. The solar wind speed, plasma density, and temperature are 450 km/s, 5 cm$^{-3}$, and 10 eV, respectively. The value of the IMF is 5 nT and it is directed duskward. In this research, we use clock angles of $60^\circ$ ($B_z = 2.5 \text{ nT}, B_y = 4.3 \text{ nT}, B_x = 0$) and $120^\circ$ ($B_z = -2.5 \text{ nT}, B_y = 4.3 \text{ nT}, B_x = 0$) to represent the northward and southward IMF conditions, respectively. To research the IMF $B_y$ penetration process independently, we let the magnetic dipole axis coincide with the $Z$ axis of the GSE coordinate.

III. RESULTS AND ANALYSIS

Three typical situations are simulated to analyze the origin of the $B_y$ component in the lobes and the plasma sheet: no IMF, southward IMF, and northward IMF. Figure 1 shows the projections of magnetic field lines in the $Z = 8 \text{ Re}$ plane for these three situations.

From Fig. 1(a), we can see that, when IMF = 0, in the north lobe, $B_y$ is negative on the dusk side and positive on the dawn side owing to magnetotail flaring. For the south lobe, $B_y$ is positive on the dusk side and negative on the dawn side according to symmetry (not shown). When the IMF is not zero, dayside magnetopause reconnection can occur. Whether antiparallel or component reconnection, the reconnected field line, with one foot on the Earth and the other in the solar wind, will be draped over the magnetopause and gradually added to the lobe field. Besides the tailward movement, the reconnected magnetic field lines can also be dragged toward the direction of the IMF. This process can cause the magnetotail lobe field to tend to have the same sign of $B_y$ component as that of the IMF $B_y$, as shown in Figs. 1(b) and 1(c). Comparing Figs. 1(b) with 1(c), we can see that the lobe field lines tend to be dragged along the IMF direction more severely under the northern IMF condition.

Figure 2 shows the $B_y$ dawn–dusk distributions of the tail lobe field at $X = -30 \text{ Re}$ and $Z = 8 \text{ Re}$. The thick dashed line, the thick solid line, and the thin solid line represent situations with no IMF, northward IMF, and southward IMF, respectively. Without the IMF, the $B_y$ distribution is obviously central symmetric. Together with the Fig. 1(a), we can conclude that this symmetry is due to magnetotail flaring.
When the IMF has a $B_y$ component, some field lines of the tail lobes, which originated from dayside magnetopause reconnection, spread out into the solar wind. This pattern can make the lobe field exhibit a quite even dawn–dusk $B_y$ distribution with the same sign of IMF $B_y$ (Fig. 2). Furthermore, we can see that the $B_y$ component of the IMF (whether northward or southward) does not have an obvious influence on the lobe $B_y$ distribution. Figure 2 indicates that the lobe magnetic field is not a simple superimposition of the IMF and the original terrestrial lobe field. The peak and valley in the dash-thick line are both flattened for both northward or southward IMF, and this must partially come from an overall rotation of the manetotail: That is a anti-clockwise rotation of thick-dash line in Fig. 2, so the IMF $B_y$ penetration effect in the tail lobes likely comes from the reconnected field lines between the IMF and the terrestrial field, as well as from the contribution of the tail rotation caused by IMF $B_y$.15

Figure 3 shows the dawn–dusk distributions of the $B_y$ component in the plasma sheet at $X = -30$ Re. The thick dashed line, thick solid line, and thin solid line represent the situations with no IMF, northward IMF, and southward IMF, respectively. Without the IMF, the magnetic field in the plasma sheet should not have a $B_y$ component because of symmetry, but practical simulations always contain some numerical deviations, as indicated by the thick dashed line in Fig. 3. When the IMF exists, we do see an obvious $B_y$ penetration effect into the plasma sheet (thin and thick solid lines in Fig. 3). We also find that the penetration efficiency is higher when the IMF is northward. When the IMF is northward, the averaged $B_y$ at $X = -30$ Re ($-20\text{Re} < Y < 20\text{Re}$) is 1.98 nT. However, when the IMF is southward, the averaged $B_y$ at $X = -30$ Re ($-20\text{Re} < Y < 20\text{Re}$) is 0.95 nT.

A large part of the IMF $B_y$ component can penetrate into the plasma sheet, and this effect is stronger near the center than at the dawn and dusk flanks. Our results are qualitatively consistent with observations and a statistical model.10,13 From Fig. 3, we can see that the IMF $B_y$ (4.3 nT) penetration efficiency generally exceeds 50% in the plasma sheet at $X = -30$ Re under northward IMF conditions, which is larger than predicted by the model of Petrukovich13 but consistent well with some other observational results.11,12

Further analysis indicates that the $B_y$ component in the plasma sheet arises from anti-convection of the plasma in the north and south lobes, which makes the magnetotail twist and rotate, especially affecting the relative slip of the north and south lobes, causing the original $B_z$ component to convert to a $B_y$ component, as shown in Figs. 4 and 5.

Figure 4 demonstrates the flow patterns (the $Y$ and $Z$ components of bulk flow velocity) in the plane of $X = -16$ Re. Here, each arrow’s direction and length represent flow direction and strength. Because the velocities in different regions vary greatly, the arrows have been non-linearly demonstrated so as to get the clear pictures of the flows. The highest speed of plasma bulk flow near the plasma sheet is about 50 km/s. Because IMF $B_y$ is positive and a large shear angle is required for both antiparallel and component reconnection,21 dayside magnetopause reconnection will occur at the north-dusk and south-dawn flanks. A reconnected magnetic field line with one foot in the north polar cusp and the other in the solar wind dawn side of the Earth will move

**FIG. 3.** Dawn–dusk distributions of the $B_y$ component in the plasma sheet at $X = -30$ Re.

**FIG. 4.** Flow patterns in the plane of $X = -16$ Re. (a) Northward IMF (at a clock angle of 60°). (b) Southward IMF (at a clock angle of 120°).
tailward around the north-dawn flank and add to the north-
dawn tail lobe, whereas a reconnected magnetic field line
with one foot in the south polar cusp and the other in the so-
lar wind dusk side of the Earth will add to the south-dusk tail
lobe. This process can generate the convection picture shown
in Fig. 4, causing rotation of the magnetotail and the reverse
rotation of the magnetic nodes, as shown in Fig. 5.

Figure 5 shows the projection of magnetic field lines
and particle thermal pressure in the plane of $X = -16 \text{ Re}$
when the IMF is northward and southward. Owing to the
convection effect shown in Fig. 4, the magnetic field in the
plasma sheet undergoes remarkable horizontal stretching. In
our opinion, this is the origin of the plasma sheet $B_y$ com-
ponent and the main reason why IMF $B_y$ can penetrate more
strongly into the plasma sheet than into the lobes. Because
the magnetic field in the central plasma sheet is stronger than
that at the flanks, the tail rotation and horizontal stretching
of the magnetic field may produce a larger $B_y$ component in the
central part than at the flanks of the plasma sheet, as shown
in Fig. 3.

As shown in Figs. 4 and 5, the convection and the corre-
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IV. SUMMARY AND DISCUSSION

In this work, we simulated the IMF $B_y$ penetration into
the magnetotail, especially into the plasma sheet, and the
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