Dependence of magnetic field just inside the magnetopause on subsolar standoff distance: Global MHD results

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The subsolar magnetopause is the boundary between the solar wind and the Earth's magnetosphere, where reduced solar wind dynamic pressure is equal to the magnetic pressure of the Earth's outer magnetosphere. We use a global magnetohydrodynamic (MHD) model to estimate the ratio f of the compressed magnetic field just inside the subsolar magnetopause to the purely dipolar magnetic field. We also compare our numerical results to a similar work by Shue, which used Time History of Events and Macroscale Interactions during Substorms (THEMIS) data. Our results show that the ratio f is linearly proportional to the subsolar magnetopause standoff distance (r_0) for both the northward and southward interplanetary magnetic field, properties consistent with Shue but with a smaller proportionality constant. However, previous theoretical studies show that f is nearly independent of the subsolar standoff distance. The global model results also show that f is smaller for the southward Interplanetary Magnetic Field (IMF) under the same r_0 , and that the proportionality constant for the southward IMF is larger than that for the northward IMF. Both conclusions agree with statistical results from observations by Shue.

magnetopause, subsolar standoff distance, solar wind, magnetosphere

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Previous theoretical studies without consideration of the impact of the solar wind take the internal magnetic field of the earth as a purely dipolar field. In the sun-earth line, knowing the distance from the earth, we can calculate the magnetic field at this position, as follows [1]:

$$B_{d0} = -M/r^3, \quad (1)$$

where B_{d0} is the magnetic field for a purely dipolar field, $M=8.1 \times 10^{25}$ Gs cm³ is a constant, and r is the distance from the earth.

When the solar wind flows toward the earth around the magnetosphere, the solar wind dynamic pressure D_p is reduced. The reduced dynamic pressure is equal to the magnetic pressure of the earth's magnetosphere at the subsolar magnetopause [2]:

$$kD_p = B_{g0}^2/2\mu_0, \quad (2)$$

where k is the reduction factor of the solar wind dynamic pressure, B_{g0} is the compressed magnetic field just inside the subsolar magnetopause, and μ_0 is the permeability in free space.

Typically one can assume that k is a constant ($k=0.881$); then, B_{g0} becomes a variable about solar wind dynamic pressure D_p . B_{d0} is a variable about the distance from the earth on the sun-earth line for a purely dipolar field, so we take a ratio f of the magnetic field just inside the subsolar magnetopause (B_{g0}) to the purely dipolar magnetic field (B_{d0}), for quantifying the compression level of the magnetic field. That is [2],

$$f = B_{g0}/B_{d0}. \quad (3)$$

Previous theoretical studies with simplified magnetosphere models assumed that f was nearly independent of r_0

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[3–6]. They did not consider the process of magnetic reconnection in their models. Aubry et al. [7] first reported that the magnetopause moves inward when magnetic reconnection occurs for the southward interplanetary magnetic field (IMF). Sibeck et al. [8] and Holzer and Slavin [9] determined f^2/k from eq. (2) with given observed D_p and r_0 [10,11]. The individual values of f in the above works were not directly obtained from observation data. Recently, Shue [2] determined f for both southward and northward IMF directly, from Time History of Events and their Macroscopic Interactions during Substorms (THEMIS) *in situ* data. On the other hand, numerical global magnetospheric models are becoming increasingly invaluable tools for detailed dynamic studies of solar-magnetosphere coupling. In this work, we examine the ratio f from global MHD model calculations, and then compare with Shue's result. Compared to empirical works from observation data, observation results are limited by averaging effects, whereas the numerical model can give an exact response for certain solar wind and IMF conditions. Another aspect of this work can be considered to achieve further validation of global modeling with the observation models in solar wind-magnetosphere interaction.

1 Data and model

In this section, we introduce our global model to calculate the interaction of solar wind and magnetosphere under typical solar wind conditions, along with a method to determine the subsolar standoff distance from simulation data.

1.1 Global MHD model of Space Weather Modeling Framework (SWMF)

We use the Space Weather Modeling Framework (SWMF), developed by University of Michigan, to simulate the interaction between solar wind and magnetosphere [12]. The SWMF consists of several numerical modules, such as the ideal MHD solver (BATS-R-US) [13,14], Ionospheric Electrodynamics (IE) model [15], and Rice Convection Model (RCM) [16]. The SWMF family of models has been used extensively to study various solar wind influences on the magnetosphere; for example, convection under the northward IMF [17], IMF B_y [18], and Parker spiral [19] conditions and storm dynamics [20,21]. Welling and Ridley [22] discussed validation of the SWMF magnetic field and plasma using satellite measurements. Rae et al. [23] compared locations of observed and modeled open/closed field line boundaries, further demonstrating the effectiveness and reliability of SWMF. Lu et al. [24] constructed a three dimensional magnetopause shape model from global MHD results of SWMF [25,26].

In a typical simulation here, the computational domain is defined by $-70R_E \leq X \leq 20R_E$; $-60R_E \leq Y \leq 60R_E$, with the grid size of $1.25R_E$. Inside $-40R_E \leq X \leq 20R_E$; $-45R_E \leq Y$;

$Z \leq 45R_E$ the grid size is $0.625R_E$ and inside $-25R_E \leq X \leq 12.5R_E$; $-30R_E \leq Y$; $Z \leq 30R_E$, grid size is $0.3125R_E$. The inner boundary is a sphere of $2.5R_E$.

In our calculation, we consider the following combinations of IMF B_z and solar wind dynamic pressure (45 datasets): $B_z = 10, 7.5, 5, 2.5, 0, -2.5, -5, -7.5, -10$ nT, and $D_p = 1, 2, 3, 4, 5$ nPa, IMF $B_x = B_y = 0$ nT and 0° dipole tilt angle. The magnetopause search is done on the $Y_{\text{GSM}}Z_{\text{GSM}}$ plane, until X_{GSM} reaches $-40R_E$.

1.2 Determining subsolar standoff distance

The magnetopause is an important surface in space physics theory where the y component of the current density J_y has its largest absolute value; the change gradient of the plasma density r is the largest; the x component of solar wind velocity u_x changes direction when solar wind flows around the magnetopause; the z component of the interplanetary magnetic field B_z changes direction when the interplanetary magnetic field is southward. The subsolar standoff distance is the distance between the earth and subsolar magnetopause.

Here, we search for the subsolar standoff position from the 45 datasets, according to the u_x change of direction when the solar wind flows around the magnetopause, as shown in Figure 1.

This figure shows the relationship between the x component of solar wind velocity u_x and the distance from earth, on the X axis. The corresponding solar wind condition in this calculation is $B_z = 5$ nT, and $D_p = 1$ nPa. In the figure, each small circle represents one data point. We first select $y=0$ and $z=0$, then we array the data from small to large, by x . Finally, new data is selected by x and u_x , as shown in the figure. We also see that when x is larger than $16R_E$, u_x is constant at 350 km/s because they still reflect conditions within the solar wind, and we use constant solar wind

Figure 1 Relationship between x component of solar wind velocity u_x and distance from earth, on the X axis. Corresponding solar wind condition is $B_z = 5$ nT, and $D_p = 1$ nPa.

driving. At about $16R_E$, u_x suddenly drops, which indicates that the solar wind impacts the bow shock there. When x is close to $10R_E$, u_x changes direction; this is the position of the subsolar magnetopause. In this example, the subsolar magnetopause surface is located at $x = 10.625R_E$. Considering the grid size, we approximate the closest grid point to the subsolar standoff magnetopause as the distance just inside the magnetopause. In this example, this point is $x = 10.3125R_E$. Undoubtedly, this approximate but unavoidable selection of the distance just inside the subsolar magnetopause will produce an error and affect the qualitative result of B_{g0} , B_{d0} , and f .

Following the same procedure, we obtain all the positions just inside the magnetopause subsolar standoff distances in our global data sets from SWMF.

2 Numerical results and discussion

In this section, we present the calculation results of B_{g0} and f for the southward and northward IMF in the data, and discuss their relation to the subsolar standoff distance.

2.1 Relationship between r_0 and B_{g0}

Figure 2 shows the relationship between the compressed magnetic field just inside the subsolar magnetopause B_{g0} and the subsolar standoff distance r_0 , for the northward and southward IMF. The dipolar magnetic field B_{d0} was calculated at the same position where B_{g0} was calculated from the data. The corresponding solar wind condition in this calculation is $B_z = 5, 10, -5, -10$ nT, and $D_p = 1, 3, 5$ nPa.

The upward triangles represent B_{g0} in global MHD simulation data, and downward triangles are B_{d0} at the same position. The solid line is the result of fitting the relationship between B_{g0} and r_0 . From Figure 2, we see that the compressed magnetic field just inside the subsolar magnetopause B_{g0} is linearly proportional to the subsolar standoff distance r_0 , for the northward and southward IMF. B_{g0} is always larger than B_{d0} for the same r_0 . B_{g0} for the northward IMF is larger than for the southward IMF, with the same r_0 .

Figure 3 shows the relationship between the logarithm of the compressed magnetic field just inside the subsolar magnetopause $\ln B_{g0}$ and the logarithm of the subsolar distance $\ln r_0$, for the northward and southward IMF. The corresponding solar wind condition in this calculation is $B_z = 5, 10, -5, -10$ nT, and $D_p = 1, 3, 5$ nPa. $\ln r_0$ and $\ln B_{g0}$ are calculated from the data. The solid line is the result of the fit. We see from the figure that the logarithm of the compressed magnetic field just inside the subsolar magnetopause $\ln B_{g0}$ is strongly linearly proportional to the logarithm of the subsolar standoff distance $\ln r_0$, for the northward and southward IMF. $\ln B_{g0}$ for the northward IMF is larger than for the southward IMF, with the same $\ln r_0$.

As in previous studies, we determine the compressed

Figure 2 Relationship between compressed magnetic field just inside the subsolar magnetopause B_{g0} and the subsolar standoff distance r_0 , for the northward and southward IMF. Dipolar magnetic field B_{d0} was calculated at the same position where B_{g0} was calculated from the data. Corresponding solar wind condition in this calculation is $B_z = 5, 10, -5, -10$ nT, and $D_p = 1, 3, 5$ nPa. Upward triangles represent B_{g0} in global simulation data, and downward triangles represent B_{d0} . Solid line is the result of fitting the relationship between B_{g0} and r_0 .

magnetic field just inside the subsolar magnetopause B_{g0} from r_0 , using the following formula:

$$B_{g0} = Ar_0^B, \quad (4)$$

where A and B are parameters of the function. By taking the logarithm of both sides, we rewrite eq. (4) in linear form:

$$\ln B_{g0} = \ln A + B \ln r_0. \quad (5)$$

Then, we fit the terms $\ln B_{g0}$ and $\ln r_0$. For the northward IMF, the result is

$$\ln B_{g0} = 10.45 - 2.79 \ln r_0. \quad (6)$$

Thus, we have $A = 34544$ and $B = -2.79$. Eq. (4) can be rewritten as

$$B_{g0} = 34544r_0^{-2.79}. \quad (7)$$

Using the same method, we obtain the result for the

Figure 3 Relationship between logarithm of the compressed magnetic field just inside the subsolar magnetopause $\ln B_{g0}$ and logarithm of the subsolar distance $\ln r_0$, for the northward and southward IMF. Corresponding solar wind condition in this calculation is $B_z = 5, 10, -5, -10$ nT, and $D_p = 1, 3, 5$ nPa. $\ln r_0$ and $\ln B_{g0}$ are calculated from the data. Solid line is result of fit.

southward IMF:

$$\ln B_{g0} = 11.71 - 3.46 \ln r_0. \quad (8)$$

That is, eq. (4) can be rewritten as

$$B_{g0} = 121783 r_0^{-3.46}. \quad (9)$$

2.2 Relationship between r_0 and $f = B_{g0}/B_{d0}$

Based on the above results, we further examine the relationship between $f = B_{g0}/B_{d0}$ and r_0 .

Figure 4 shows f as a function of subsolar standoff distance r_0 . The corresponding solar wind condition in this calculation is $B_z = 5, 10, -5, -10$ nT, and $D_p = 1, 3, 5$ nPa. The solid line is the result of the fit. From Figure 4, we see that f of the compressed magnetic field just inside the subsolar magnetopause to the purely dipolar magnetic field is

Figure 4 Ratio (f) of the compressed magnetic field just inside the subsolar magnetopause B_{g0} to the dipolar magnetic field B_{d0} , for the northward and southward IMF. Corresponding solar wind condition in this calculation is $B_z = 5, 10, -5, -10$ nT, and $D_p = 1, 3, 5$ nPa. Solid line is result of fit.

linearly proportional to the subsolar standoff distance r_0 , for both the northward and southward IMF. f for the northward IMF is larger than for the southward IMF, with the same r_0 .

For the northward IMF, the data fit gives

$$f = 0.04 r_0 + 1.39. \quad (10)$$

For the southward IMF, the data fit gives

$$f = -0.07 r_0 + 2.03. \quad (11)$$

Compared with the results of Shue's, we find that (1) The finding that the ratio f is linearly proportional to r_0 is consistent with Shue, but our f values are small. This difference is caused by the selection of the point just inside the subsolar magnetopause standoff distance. We have no alternative to this, except to reduce the grid sizes in the global simulation of solar wind-magnetosphere coupling, which is not easily accomplished at present.

(2) From eqs. (10) and (11), we find that f for the south-

ward IMF is smaller than for the northward IMF, with the same r_0 . This implies that the compression level of the magnetic field by the inward magnetopause for the southward IMF is smaller than for the northward IMF. This result agrees with Shue [2].

(3) The previous theoretical studies show that f is nearly independent of the subsolar standoff distance. In our numerical results, the linear relationship between f and the subsolar standoff distance r_0 exists, but its linear proportion is not strong. The proportional constants are small compared to those of Shue.

3 Summary

We use a global MHD model, the Space Weather Modeling Framework (SWMF), to estimate the ratio f of the compressed magnetic field just inside the subsolar magnetopause B_{g0} to the purely dipolar magnetic field B_{d0} . Model data are for various fixed solar wind conditions, and it helps capture the precise response of the magnetosphere to a specific solar wind condition, and distinguishes the effect of IMF direction.

We first determine subsolar standoff distance r_0 , according to the u_x change of direction when solar wind flows around the magnetopause. Then, using the model data, we calculate B_{g0} and f for the northward and southward IMF. Then, we examine the relationship between f and the subsolar standoff distance r_0 . Finally, we compare our results with Shue. We find that: (1) The ratio of the magnetic field just inside the magnetopause to the purely dipolar magnetic field at that location is linearly proportional to the subsolar standoff distance; (2) The ratio f for the southward IMF is smaller than for the northward IMF, and the compression level of the magnetic field by the inward magnetopause for the southward IMF is smaller than for the northward IMF.

In our next work, we will further investigate the relationship of f and the subsolar standoff distance, including extreme solar wind conditions, such as those causing magnetic storms and substorms.

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