The dipole tilt angle dependence of the bow shock for southward IMF: MHD results


Abstract

The location and shape of the Earth’s bow shock depend on the properties of the upstream solar wind, as well as the size and shape of the downstream magnetopause. Many studies have suggested that the influence of the dipole tilt angle on the magnetopause is significant, especially at the high-latitude region, however, to date there is no bow shock model which depends on the dipole tilt angle. Using a physics-based global magnetohydrodynamic (MHD) model, the Space Weather Modeling Framework (SWMF), we investigate the effect of the dipole tilt angle on the location and shape of the bow shock, and our results show that (1) the subsonar standoff distance and the north–south asymmetry of bow shock increase with the increasing dipole tilt angle; (2) with the dipole tilt angle positively increasing, the flaring angle of the bow shock increases in the northern hemisphere but keeps almost unchanged in the southern hemisphere, and the rotational asymmetry slightly decreases in the northern hemisphere and rapidly decreases in the southern hemisphere; and (3) the influence of dipole tilt angle on the shape of the bow shock is north–south symmetric.

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1. Introduction

The Earth’s bow shock is created by interaction of the supersonic and superalfvenic solar wind with the magnetospheric obstacle; its location and shape depend on the properties of the upstream solar wind, as well as the size and shape of the downstream magnetopause (e.g., Spreiter et al., 1966; Fairfield, 1971; Slavin and Holzer, 1981; Slavin et al., 1996; Nemecek and Safar, 1991; Farris and Russell, 1994; Cairns et al., 1995; Cairns and Lyon, 1996; Peredo et al., 1995; Petrinec and Russell, 1997; Verigin et al., 2003; Dmitriev et al., 2003; Chapman et al., 2004; Merka et al., 2005; Jelinek et al., 2008, 2012). As many studies indicate that the solar wind dynamic pressure ($P_s$) and interplanetary magnetic field (IMF) are the two main parameters defining the global structure of the magnetopause (e.g., Martyn, 1951; Ferraro, 1960; Fairfield, 1971; Coroniti and Kennel, 1972; Roelof and Sibeck, 1993; Shue et al., 1997, 1998; Lu et al., 2010; Jelinek et al., 2012; Wang et al., 2014), the position and the shape of the Earth’s bow shock are primarily controlled by solar wind dynamic pressure ($P_s$), upstream Mach number(s), and the orientation of the interplanetary magnetic field (IMF) (e.g., Chao et al., 2002; Chapman and Cairns, 2003; Merka et al., 2005).

Fairfield (1971) developed the first widely used empirical bow shock model, which actually represents the average position and the shape of the bow shock. Since then many researchers contributed to the parametrization for the size and shape of the Earth’s bow shock. For example, it has been demonstrated that the bow shock standoff distance decreases substantially when the solar wind dynamic pressure increases (e.g., Binsack and Vasyliunas, 1968; Formisano, 1979; Chao et al., 2002; Dmitriev et al., 2003). However, it has also been shown that the dynamic pressure is not a good parameter for modeling the bow shock in the tail region (Dmitriev et al., 2003). The upstream solar wind Mach number dependencies of the bow shock have been analyzed extensively, demonstrating that the bow shock approaches the Earth in response to an increase in the magnetosonic Mach number ($M_{MSS}$) in most models (e.g., Farris and Russell, 1994; Verigin et al., 2001a; Chao et al., 2002). The interplanetary magnetic field (IMF) and its orientation is another parameter commonly used in bow shock models (e.g., Spreiter and Rizzi, 1974; Slavin et al., 1984, 1996; de Sterck et al., 1998; Kabin, 2001; Chao et al., 2002; Verigin et al., 2003; Chapman et al., 2004; Merka et al., 2003, 2005) by controlling the global $M_{MSS}$ on one hand: when $B_{IMF}$ is perpendicular to the shock wave normal direction,
the \( M_{\text{MS}} \) has a small value and the shock should be farther from the Earth; while \( B_{\text{IMF}} \) is parallel to the shock wave normal direction, the \( M_{\text{MS}} \) is larger and a more Earthward shock can be observed. On the other hand, the interplanetary magnetic field can affect the bow shock by influencing the magnetopause obstacle. The size and shape of magnetopause obstacle dependence of the bow shock is introduced in some models (Farris and Russell, 1994; de Sterck et al., 1998; Verigin et al., 2001a, 2001b), which use the magnetopause nose distance and/or the radius of the curvature at the magnetopause nose point to parameterize the bow shock. Of course, the IMF is not the only parameter controlling the size and shape of the magnetopause. Some recent magnetopause models (Tsytanenko, 1998; Boardsen et al., 2000; Lin et al., 2010; Liu et al., 2012) indicate that the most significant factors which influence the shape of the high-latitude magnetopause are the dipole tilt angle and solar wind dynamic pressure. In fact, the IMF dependence of the magnetopause is separable after the effects of the pressure and tilt are removed (Jelinek et al., 2012). The dynamic pressure primarily affects the magnetopause size, while the dipole tilt angle and IMF orientation affect the geometry of the boundary.

Studies of the direct influences of the dipole tilt angle on the location and shape of the bow shock have just started in the recent decade. For example, Merka et al. (2005) investigated the data set of IMP 8 satellite’s bow shock crossings, and found that the dipole tilt angle plays a major role in predicting the location of the bow shock. During the average solar wind conditions, when the dipole tilt angle changes from sunward to antisunward orientations, in the tail region \((-15R_E < X < -10R_E)\) the bow shock was displaced in the north-south direction by up to 3.8\( R_E \). Simultaneously, Merka et al. (2005) also use the global 3-D MHD numerical simulation to further confirm their observational results. Jelinek et al. (2008) used bow shock crossings by four different satellites to show that dayside bow shock \((X > 4R_E)\) moves inside (approximately 0.5\( R_E \)) when dipole tilt angle \( \lambda \) changes from negative to positive. However, for increasing \( \lambda \), the nightside bow shock \((X < 4R_E)\) moves sunward, as \( \Delta R = 0.08 \lambda \sin \alpha \) (see their Eq. (3)).

To date, there has been no thorough modeling study of the bow shock dependence on the dipole tilt angle. We address this question in this paper. We use a physics-based global magnetohydrodynamic (MHD) model, the Space Weather Modeling Framework (SWMF), to investigate the effects of dipole tilt angle on the size and shape of the three-dimensional bow shock.

2. Global MHD model and identification of the bow shock

In this work, the Space Weather Modeling Framework (SWMF) developed by University of Michigan is used to simulate the coupling between solar wind and magnetosphere (see the study by Tóth et al., 2005). The SWMF is integrated by the numerical modules including the Solar Corona, Eruptive Event Generator, Inner Heliosphere, Solar Energetic Particles, Global Magnetosphere, Inner Magnetosphere, Ionoosphere Electrodynamics, and Upper Atmosphere. The SWMF is the current status of the art. It can provide a high-performance flexible framework for physics-based space weather simulations, as well as for various space physics applications. Especially, it has been used extensively to study various solar wind influences on the magnetosphere (e.g., Song and Russell, 1992; Comboset al., 2000; Kabín et al., 2004; Zhang et al., 2007; Tóth et al., 2007), and the validation of SWMF has been also discussed by many works (e.g., Welling and Ridley, 2010; Rae et al., 2010). Recently, we have used the SWMF to check the global magnetopause structure and their dependence on the solar wind conditions and interplanetary magnetic fields (Lu et al., 2010, 2013a; Liu et al., 2012). Lu et al. (2013b) and Jing et al. (2014) further used the SWMF to investigate the energy transfer across magnetopause under different solar wind conditions. Especially Liu et al. (2012) demonstrated the significant influence of the dipole tilt angle on the magnetopause, which motivates to see how important the dipole tilt angle affects the bow shock.

In our calculations, we used three modules in the SWMF, Global Magnetosphere (BATSRUS v8.01), Inner Magnetosphere, and Ionosphere Electrodynamics. The computational domain is defined by \(-40R_E < X < 20R_E, -45R_E < Y < 0 \) and \( Z \leq 45R_E \) in the GSM coordinate, the inner boundary is a sphere 2.5\( R_E \) in radius. The grid size inside 6.5\( R_E \) is 1/8\( R_E \), on the dayside, including the cusps and much of the magnetosheath it is 1/4\( R_E \), and in other areas it is 1/2\( R_E \).

To investigate the dipole tilt effect on the bow shock we perform 14 calculations corresponding to the following dipole tilt angles \( \lambda = -35^\circ, -30^\circ, -25^\circ, -20^\circ, -15^\circ, -10^\circ, 5^\circ, 10^\circ, 15^\circ, 20^\circ, 25^\circ, 30^\circ, \) and 35\( ^\circ \). In all our simulation presented in this paper we use the same upstream solar wind conditions: \( B_x = B_y = 0, B_z = -5 \) nT and \( P_d = 1 \) nPa (SW Number Density \( n = 5 \) cm\(^{-3} \); SW temperature \( T = 100,000 \) K; SW velocity \( V_x = -345.795 \) km/s, \( V_y = V_z = 0 \) km/s). We believe that the assumptions and initial values adopted in this research do not affect the qualitative conclusion of our final results.

An automatic identification technique is developed to locate the bow shock surface according to the Rankine–Hugoniot jump conditions. The solar wind density and the magnetic field strength in the magnetosheath are substantially higher, and the solar wind velocity is smaller than that in the upstream solar wind. Fig. 1 shows the sample of the identified bow shock surfaces for \( \lambda = 35^\circ \). From Fig. 1 we can see that the bow shock shape in the X–Z plane is different from that in the X–Y plane. Similar to the magnetopause (Lu et al., 2010; Liu et al., 2012; Lu et al., 2013a) the shock flaring angle in the X–Y plane is almost symmetric, however, the flaring angle in the northern hemisphere of X–Z plane is larger than that in the southern hemisphere for the positive dipole tilt angle. Due to this north–south asymmetry of the bow shock, we will respectively study the influence of the dipole tilt angle on the northern and southern hemispheres of the bow shock.

3. Dependence of the bow shock’s location and shape on the dipole tilt angle

After identifying the bow shock surface in the Cartesian coordinate system, we convert the coordinates of the bow shock into the spherical coordinate system \((r, \theta, \phi)\), which has its pole aligned with the X axis. Here \( r \) is the radial distance from the center of the Earth, the polar angle \( \theta \) is measured with respect to the Sun–Earth line and the azimuth angle \( \phi \) is measured from the positive Y-axis.

3.1. Parameterization of the bow shock surface

In this section we construct a bow shock surface function to represent the global bow shock shape and size. We based our parameterization on a model similar to Shue et al. (1997), Shue et al. (1998) (magnetopause model) and Chao et al. (2002) (bow shock model). We choose this function because it is simple, but can well represent the open or closed magnetopause and bow shock shape by changing the flaring angle. The surface is given by the following formula:

\[
r = r_0 \left( \frac{2}{1 + \cos \theta} \right)^{\alpha}
\]

where \( r_0 \) and \( \alpha \) represent the subsolar standoff distance and the flaring angle, respectively. This model function gives a closed bow shock when \( \alpha < 0.5 \) and an open bow shock when \( \alpha \geq 0.5 \). In order to describe the north–south asymmetry and the azimuthal asymmetry of the bow shock, similar to the magnetopause investigation.
by Liu et al. (2012), we expand the function to a three-dimensional asymmetric surface function

\[
 r = \begin{cases} 
 r_0 \left( \frac{2}{1 + \cos \theta} \right)^{\alpha_n + \beta_n \cos \phi} ; Z > 0 \\
 r_0 \left( \frac{2}{1 + \cos \theta} \right)^{\alpha_s + \beta_s \cos \phi} ; Z \leq 0 
\end{cases}
\]  

(2)

where \( \alpha_n \) and \( \alpha_s \) represent the flaring angle of the rotationally symmetric bow shock in the northern hemisphere and southern hemisphere, respectively; \( \beta_n \) and \( \beta_s \) describe the azimuthal asymmetry in the northern hemisphere and southern hemisphere, respectively. Thus, we define five configuration parameters \( (r_0, \alpha_n, \alpha_s, \beta_n, \beta_s) \) to describe the three-dimensional asymmetric global bow shocks.

### 3.2. Fitting the bow shock functions

Once the surface function is chosen, the configuration parameters of the bow shock are fitted to the data extracted from the simulations for different dipole tilt angle \( \lambda \) from –35° to 35°. Generally, these configuration parameters would depend on the solar wind dynamic pressure \( P_d \), Mach number, and IMF, however we do not address this aspect of the bow shock modeling in this paper.

Fig. 2 shows the example of the fitting results of the bow shock in the X–Y (Figure (a)) and X–Z (Figure (b)) planes for \( \lambda = 35° \). The small circles stand for the bow shock locations, the solid lines are the fitting results of the bow shock. Clearly, the fits agree with the data very well both in the X–Y and X–Z planes. The fitting results show that the flaring angle in the northern hemisphere of X–Z plane is larger than that in the southern hemisphere for \( \lambda = 35° \).

Fig. 3 shows the fitting results of the bow shock planes for \( \lambda = 5° \) (black lines), 15° (red lines), 25° (green lines), and 35° (blue lines). With the positively increasing dipole tilt angle, the bow shock in the X–Y plane and the northern hemisphere of the X–Z plane move sunward with the almost unchanged flaring angle, while the flaring angle in the southern hemisphere of the X–Z plane becomes small; in the Y–Z plane for \( Z > 0 \) the bow shock moves anti-earthward with the almost unchanged rotational symmetry, while in the Y–Z plane for \( Z \leq 0 \) the bow shock moves earthward in the Y direction and anti-earthward in the Z direction, so that the rotational symmetry changes. From Fig. 3 we can see that the influences of dipole tilt angle on the bow shock are significant. Next, we will compare our fitting results with the several representative bow shock empirical models.

### 3.3. Comparison with the empirical models

Fig. 4 shows the comparison between our fitting results and the empirical bow shock models of Chao et al. (2002), Chapman and Cairns (2003) and Merka et al. (2005). It can be seen that our fitting results basically agree well with these empirical models. In the X–Y plane, at the nightside for \( \lambda = 35° \) the whole dayside our results are more similar to Chao et al. (2002)’s model, at the nightside for \( \lambda = 5° \) our result more agrees with Chapman and Cairns (2003)’s model. In the X–Z plane, except that the southern hemisphere of our result for \( \lambda = 35° \) approaches to Chapman and Cairns (2003)’s model, the other parts are more similar to Chao...
et al. (2002)'s model. The subsolar standoff distance of our result for \( \lambda = 5^\circ \) approximate to Merka et al. (2005), while for \( \lambda = 35^\circ \) our result approximate to Chao et al. (2002). In general, our fitting results are more similar to Chao et al. (2002)'s model. Compared to the previous empirical models, our results can well describe the rotational asymmetry of the bow shock, and the effects of the dipole tilt angle on the bow shock shape and location. When dipole tilt angle \( \lambda \) increases from \( 5^\circ \) to \( 35^\circ \), the whole bow shock moves sunward in the \( X-Y \) plane, the subsolar standoff distance increases, and the flaring angle keeps almost unchanged. In the \( X-Z \) plane, when dipole tilt angle \( \lambda \) increases from \( 5^\circ \) to \( 35^\circ \), the subsolar standoff distance increases, however, the flaring angle decreases in the southern hemisphere. It is also shown that, except that the flaring angle in the southern hemisphere of \( X-Z \) bow shock is smaller than that in \( X-Y \) bow shock for \( \lambda = 35^\circ \), the flaring angle in other parts of \( X-Z \) bow shock is larger than \( X-Y \) bow shock for \( \lambda = 5^\circ \) and \( \lambda = 35^\circ \). The difference between the \( X-Y \) and the \( X-Z \) bow shock for \( \lambda = 35^\circ \) is larger than that for \( \lambda = 5^\circ \).

From the above we can conclude that the influences of \( \lambda \) on the bow shock configuration parameters (\( r_0, \alpha_0, \alpha_s, \beta_0 \) and \( \beta_s \)) are significant. We will discuss the influences in detail in the next section.

4. Relationship between the bow shock configuration parameters and the dipole tilt angle

Now we investigate the dependences of the configuration parameters (\( r_0, \alpha_0, \alpha_s, \beta_0 \) and \( \beta_s \)) on the dipole tilt angle \( \lambda \) (degree measure). Fig. 5 shows the variations of the bow shock standoff distance \( r_0 \) with the dipole tilt angle \( \lambda \), the small circles represent the standoff distances judged directly from the simulations for each \( \lambda \), and the solid line shows the fitting result by the following function:

\[
    r_0 = 14.09 + 7.409 \times 10^{-4} \times \lambda^2
\]

Fig. 5 shows that \( r_0 \) is well described by a quadratic function of \( \lambda \). As the absolute value of \( \lambda \) increases, the subsolar standoff distance \( r_0 \) is increased, and the value of \( r_0 \) for positive \( \lambda \) is equal to that for negative \( \lambda \).

Jelinek et al. (2008) used a set of bow shock crossings from 1994 to 2002 to investigate the dipole tilt angle influence on the bow shock, they indicated that the dayside bow shock moves slightly earthward (\( \approx 0.5R_E \)) when the dipole tilt angle changes from negative to positive values. They also find that the bow shock subsolar standoff distance decreased with the increasing dipole tilt angle, in contrast to our findings. However, their work was based on high latitude data statistics, used a rather limited dataset which did not always allow to distinguish dipole tilt effects from those caused by variations in the solar wind. In fact, many high-latitude magnetopause models (e.g., Spreiter and Briggs, 1962; Mead and Beard, 1964; Spreiter et al., 1968; Choe et al., 1973; Wu, 1984; Sotirelis and Meng, 1998; Safránková et al., 2005) suggest that, with the positively increasing dipole tilt angle, the nose of the magnetopause will move southward below the \( X-Y \) plane of the GSM coordinate, the magnetopause subsolar standoff distance does not change obviously, but the flaring angle of the magnetopause in the northern hemisphere will increase, while in the southern hemisphere the flaring angle will decrease. The whole magnetopause obstacle becomes "blunt". Our physics based model simulations also show the same results about the bow shock flaring angle as these magnetopause models: the flaring angle in one hemisphere of the meridional plane increases with the increasing corresponding \( \lambda \) (northern hemisphere for positive \( \lambda \) and southern hemisphere for negative \( \lambda \)), while the flaring angle in the other hemisphere decreases. Moreover, our results indicate that the whole dayside bow shock moves sunward with the increasing absolute value of the dipole tilt angle, because of the increasing of the flaring angle in one hemisphere of the magnetopause. The mechanism for this phenomenon can be explained by the sunward bulging of the magnetopause for increasing dipole tilts. Thus, if the upstream solar wind parameters are unchanged, when absolute value of the dipole tilt angle is increased, the whole bow shock dayside moves sunward and the bow shock subsolar standoff distance increases. The displacement of the standoff distance can reach about \( 1R_E \). Increased satellite coverage should allow us to verify this result.

\( \alpha_0 \) and \( \alpha_s \) represent the rotationally symmetric flaring angle of the northern and southern hemispheres of the global bow shock, respectively. As the definition of the coordinates conversion, \( \alpha_t \) stands for the flaring angle of the equatorial plane of the bow shock. Fig. 6 shows the variations of \( \alpha_0 \) and \( \alpha_s \) with \( \lambda \), the small circles are the best fit values extracted directly from the simulations for each \( \lambda \), the solid lines show the fitting results by the
following function:
\[
\begin{align*}
\alpha_n & = 0.9299 - 0.01141 \times \cos(0.06198 \times \lambda) + 0.0350 \times \sin(0.06198 \times \lambda); Z > 0 \\
\alpha_n & = 0.9298 - 0.01114 \times \cos(0.06204 \times \lambda) - 0.0355 \times \sin(0.06204 \times \lambda); Z \leq 0
\end{align*}
\]  
\tag{4}

Fig. 6 shows that \( \alpha_n \) and \( \alpha_s \) is well described by a Fourier function of \( \lambda \). As the positive value of \( \lambda \) increases, \( \alpha_n \) increases and \( \alpha_s \) keeps almost unchanged; while for negatively increasing \( \lambda \), \( \alpha_n \) remains unchanged and \( \alpha_s \) increases. Moreover, the value of one hemisphere of the flaring angle on a given positive dipole tilt angle is very similar to the value of the opposite hemisphere on the same negative dipole tilt angle.

\( \beta_n \) and \( \beta_i \) represent the degree of the rotation asymmetry of the northern and southern hemispheres of the global bow shock. Fig. 7 shows the variations of \( \beta_n \) and \( \beta_i \) with \( \lambda \), the solid lines stand for the fitting results by the following function:
\[
\begin{align*}
\beta_n & = -0.1117 + 0.2049 \times \cos(0.03106 \times \lambda) + 0.09871 \times \sin(0.03106 \times \lambda); Z > 0 \\
\beta_n & = -0.1243 + 0.2170 \times \cos(0.02998 \times \lambda) - 0.10030 \times \sin(0.02998 \times \lambda); Z \leq 0
\end{align*}
\]  
\tag{5}

From Fig. 7 we can see that \( \beta_n \) and \( \beta_i \) are well described by the Fourier functions of \( \lambda \). As the \( \lambda \) positively increases, \( \beta_n \) decreases lightly and \( \beta_i \) decreases rapidly; while for negatively increasing \( \lambda \), \( \beta_n \) toboggans and \( \beta_i \) gradually deceases. Similarly as \( \alpha \), the value of \( \beta_n \) at a given positive dipole tilt angle is very close to the value of \( \beta_i \) at the same negative dipole tilt angle.

We think that the influence of \( \lambda \) on \( \alpha \) and \( \beta \) comes from the effects of \( \lambda \) on the magnetopause. As mentioned above, when \( \lambda \) positively increases, the flaring angle of the magnetopause will increase in the northern hemisphere, while decrease in the southern hemisphere. Our results from Fig. 3(a) and (b) also show that the X–Y plane and the northern hemisphere of the X–Z plane of the bow shock moves sunward with positively increasing \( \lambda \). So that \( \alpha_n \) increases with positively increasing \( \lambda \). For the same result \( \alpha_s \) increases with negatively increasing \( \lambda \). Although the X–Y plane of the bow shock moves sunward with the positively increasing \( \lambda \), the southern hemisphere of the X–Z planes of the bow shock moves earthward. As a result, \( \alpha_s \) does not change too much with positively increasing \( \lambda \), and the similar relationship is exist between \( \alpha_n \) and negatively increasing \( \lambda \).

Fig. 3(c) shows that with the positively increasing \( \lambda \), the northern hemisphere of the Y–Z plane moves anti-earthward in both of \( Y \) and \( Z \) directions, as the \( \alpha_n \) also increases, the northern hemisphere of the bow shock became more rotation symmetry, so that the \( \beta_n \) decreases with the positively increasing \( \lambda \). For the same result the \( \beta_i \) decreases with the negatively increasing \( \lambda \). Fig. 3(d) shows that the southern hemisphere of the Y–Z plane moves anti-earthward in \( Z \) directions and earthward in \( Y \) directions with the positively increasing \( \lambda \). As the \( \alpha_s \) remains almost unchanged, for \( \lambda \) increases...
from 0° to about 20°, the southern hemisphere of the Y–Z plane of the bow shock became more close to a circle, so that the $\beta_s$ rapidly decreases to near zero; for $\lambda$ increases from 20° to 35°, the southern hemisphere of the bow shock became asymmetric again, therefore the $\beta_s$ negatively increases. As a result, the $\beta_s$ rapidly decreases with the positively increasing $\lambda$, and the $\beta_n$ rapidly decreases with the negatively increasing $\lambda$.

We further investigate the flaring angle of the meridional bow shock ($\alpha + \beta$) when $\cos^2 \phi = 1$. Fig. 8 shows the variations of $\alpha_n + \beta_n$ and $\alpha_z + \beta_z$ with $\lambda$, the solid lines show the fitting results by the following function:

$$
\begin{align*}
\alpha_n + \beta_n &= 0.9108 + 0.1030 \times \cos (0.04194 \times \lambda) + 0.062 \times \sin (0.04194 \times \lambda); Z > 0 \\
\alpha_z + \beta_z &= 0.9099 + 0.1038 \times \cos (0.04166 \times \lambda) + 0.062 \times \sin (0.04166 \times \lambda); Z \leq 0
\end{align*}
$$

From Fig. 8 we can see that $\alpha_n + \beta_n$ and $\alpha_z + \beta_z$ is also well described by a Fourier function of $\lambda$. As the $\lambda$ positively increases, $\alpha_n + \beta_n$ remains unchanged and $\alpha_z + \beta_z$ decreases sharply; while for negatively increasing $\lambda$, $\alpha_n + \beta_n$ decreases rapidly and $\alpha_z + \beta_z$ barely change too much. It is the same as $\alpha$ and $\beta$, the value of the $\alpha + \beta$ of one hemisphere on a given positive dipole tilt angle is very similar to the value of the opposite hemisphere on the same negative dipole tilt angle.

With the positively increasing $\lambda$, the $\alpha_n$ increases and the $\beta_n$ decreases result in that $\alpha_n + \beta_n$ keeps almost unchanged; the $\alpha_z$ remains unchanged and the $\beta_z$ rapidly decreases, so that $\alpha_z + \beta_z$ decreases. As a result, with the positively increasing $\lambda$ the flaring angle of the northern hemisphere of the meridional bow shock does not change too much and the flaring angle of the southern hemisphere decreases; for the same results, when $\lambda$ negatively increases, the flaring angle of the northern hemisphere of the meridional bow shock decreases and the flaring angle of the southern hemisphere remains almost unchanged. The difference between $\alpha_n + \beta_n \cos^2 \phi$ and $\alpha_z + \beta_z \cos^2 \phi$ for a given azimuth angle $\phi$ describes the north-south asymmetry of the bow shock. With the increasing absolute value of $\lambda$, one of $\alpha_n + \beta_n \cos^2 \phi$ and $\alpha_z + \beta_z \cos^2 \phi$ is decreased and the other remains almost unchanged, so that the difference between $\alpha_n + \beta_n \cos^2 \phi$ and $\alpha_z + \beta_z \cos^2 \phi$ is increased. As a result, the north-south asymmetry of the bow shock is increased with the increasing dipole tilt angle.

5. Summary and conclusions

The physics-based global MHD code, Space Weather Modeling Framework (SWMF), was employed to study the dependence of the Earth’s bow shock on the dipole tilt angle for representative solar wind condition: $P_d = 1$ nPa and $B_z = -5$ nT. We fitted the bow shock surface and proposed an asymmetric global bow shock model. Compared to earlier models, the new model can describe the north-south asymmetry and the rotation asymmetry. We use this model to investigate the influence of the dipole tilt angle on the bow shock size and shape. The main results can be summarized as follows:

I. The bow shock subsolar standoff distance and the north-south asymmetry increase with the increasing dipole tilt angle. The displacement of the bow shock subsolar standoff distance can reach $1R_E$. 

Fig. 4. Comparisons of the bow shock in our fitting results with the empirical bow shock models. (a) and (b) show the X-Y and X-Z planes of the bow shock, respectively. The black solid and dashed lines represent the bow shock of our result for dipole tilt angle $\lambda = 35^\circ$ and $5^\circ$, respectively. The red, green and blue lines represent the bow shock models of Chao et al. (2002), Chapman and Cairns (2003) and Merka et al. (2005), respectively. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

Fig. 5. Variations of bow shock standoff distance $r_0$ with the dipole tilt angle $\lambda$. Small circles represent the $r_0$ judged from the simulation data for each $\lambda$. The solid line is the fitting result.
2. With the positively increasing dipole tilt angle, the rotationally symmetric flaring angle \((\alpha_n)\) increases in the northern hemisphere but \((\alpha_s)\) remains almost unchanged in the southern hemisphere, while the rotation asymmetry \((\beta_n)\) slightly decreases in the northern hemisphere and \((\beta_s)\) rapidly decreases in the southern hemisphere.

3. In GSM coordinates, the influences of the positively increasing dipole tilt angle on the one hemisphere of the bow shock are in
according with that of the negatively increasing dipole tilt angle on the opposite hemisphere. The influence of dipole tilt angle on the shape of the bow shock is north-south symmetric.

This work provides an important building block for a future bow shock model which will be dependent on all relevant parameters. In the future work, we will construct a general global model for the bow shock size and shape with configuration parameters on the solar wind dynamic pressure ($P_w$), upstream Mach number(s), the orientation of the interplanetary magnetic field (IMF) and dipole tilt angle.

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