Interaction between an interplanetary magnetic cloud and the Earth’s magnetosphere: Motions of the bow shock

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Abstract. An interplanetary magnetic cloud (IMC) is an important solar-terrestrial connection event. It is an ideal object for the study of solar-terrestrial relations and space weather because the Earth’s space environment can be affected considerably during an IMC passage. An IMC was observed to pass the Earth during October 18–20, 1995. Wind recorded its interplanetary characteristics at \( \sim 175 R_E \) upstream of the Earth’s bow shock, and \( \sim 45 \) min later, Geotail, being near the nominal location of the dawn bow shock, detected IMC-related multiple bow shock crossings. Using simultaneous measurements from Wind and Geotail, we analyzed, with a semiempirical bow shock model with two parameters, the bow shock motion caused by the interaction of the IMC with the magnetosphere during the passage. We also compared the bow shock motion predicted by the model, and hence the predicted Geotail bow shock crossings, with Geotail observations of the actual crossings. The results showed that the observed multiple bow shock crossings, which were obviously due to temporal variations of the upstream solar wind, can be well explained by the model-predicted bow shock motion.

1. Introduction

An interplanetary magnetic cloud (IMC) is a typical kind of interplanetary disturbance that is characterized by the following properties: (1) relatively strong magnetic fields (hence low plasma beta), (2) a smooth rotation of the magnetic field direction over a \( \sim 1 \) day period at 1 AU, and (3) a low ion temperature [Burlaga, 1991]. In most cases, an IMC is preceded by an interplanetary shock, and several hours later, a front boundary of an IMC is observed, usually as a tangential discontinuity. A high-density region between the preceded shock and the front boundary of IMC is often called the “magnetosheath” of the IMC, and hence IMC sometimes is called an “interplanetary magnetosphere.” It is believed that an IMC is caused by solar activity such as a coronal mass ejection (CME) and can be the interplanetary manifestation of solar filaments (seen as prominences on the limb) or can be an interplanetary CME [Gosling, 1990, Dryer, 1994; Chen, 1996, 1997; Wu and Guo, 1997]. A model for an IMC magnetic structure can be described well by a magnetic flux rope with a helical force-free magnetic field and with a diameter \( \sim 0.25 \) AU at 1 AU [Burlaga, 1988, 1991; Lepping et al., 1990]. To date, an IMC is a unique solar-terrestrial connection event that can be tracked from its solar eruption source to its interaction with the Earth’s magnetosphere [Fox et al., 1998]. Therefore an IMC is an ideal object for research on solar-terrestrial physics and space weather not only because (1) it has this obvious solar-terrestrial connection and effectiveness in its interaction with the Earth’s magnetosphere, but also because (2) it provides coverage in temporal and spatial scales and (3) its own magnetic structure is modeled well by a simple field geometry.

The interaction between an IMC and the magnetosphere manifests itself mostly by the following two aspects. One is the change of position and shape of the magnetospheric boundary, i.e., the motion of the bow...
shock and the magnetopause due to changes of the upstream solar wind parameters, such as the dynamic pressure, the southward component of the interplanetary magnetic field, and the magnetosonic Mach number during the IMC passage. The other is geomagnetic activity and various energy burst phenomena which occur inside the magnetosphere and are triggered by the IMC’s energy into the magnetosphere. The triggering effects of IMCs can be described by the parameter $\epsilon$, which is defined by the following expression [Akasofu, 1981]:

$$\epsilon = \mu_0^{-1} v B^2 \rho_0^2 \sin^4(\Psi/2),$$

where $v$, $B$, and $\Psi$ are the upstream solar wind velocity, magnetic field, and clock angle of the magnetic field, respectively. The parameter $\epsilon$ is related to the Poynting flux of the solar wind onto an effective area of the magnetosphere, $\rho_0^2$, and is rendered in units of power.

The change of position and shape of the magnetospheric boundary can be determined by the dynamic balance between the solar wind and the magnetosphere. Previous work in both theory and observation [Shue et al., 1997; Petrinec and Russell, 1996; Fairfield, 1971; Farris and Russell, 1994; Peredo et al., 1995; Cairns et al., 1995; Lepidi et al., 1996; Slavin et al., 1996; Bennett et al., 1997; Hutner et al., 1997] showed that the position and shape of the magnetopause and the bow shock depend mainly on the dynamic pressure, the southward magnetic field component, and the magnetosonic Mach number of the upstream solar wind. When IMC arrives at the Earth, the above parameters of the upstream solar wind all can change considerably because the magnetic field, plasma velocity, proton temperature, etc., inside IMCs can be remarkably different from those in the ambient interplanetary medium [Burlaga, 1991].

Lepping et al. [1996] and Takeuchi et al. [1998] have reported changes of the bow shock position and shape due to the arrival of IMCs on February 8, 1995, and May 13, 1995, respectively. In the case reported by Lepping et al. [1996] the distance of the bow shock from the Earth in the dusk side reached at least 39 $R_E$ during the February 8, 1995, IMC passage. In contrast to the average value, $< 30 R_E$ for this distance [Peredo et al., 1995], the remarkable motion of the bow shock must have occurred during the IMC passage. Takeuchi et al. [1998] presented the other May case as a first example of the observation of a deformed bow shock shape. The authors explained that the bow shock shape distorted from an axially symmetric geometry because of the incidence of the inclined front boundary of the May 13, 1995, IMC.

The October 18–20, 1995, IMC (hereinafter called Oct95) is another very interesting solar-terrestrial connection event and has been investigated by many authors [Lepping et al., 1997; Smith et al., 1997; Larson et al., 1997; Farrugia et al., 1998; Janoo et al., 1998; Jordanova et al., 1998; Huang et al., 1998; Burke et al., 1998] from various points of view. Lepping et al. [1997] described the global interplanetary properties of Oct95; Jordanova et al. [1998] and Farrugia et al. [1998] reported the geomagnetic storm activities triggered by Oct95; Huang et al. [1998] and Burke et al. [1998] discussed the response of the ionospheric current and the polar electric potential to Oct95, respectively; Janoo et al. [1998] paid attention to the existence of some fine structure, i.e., discontinuities inside Oct95; and Smith et al. [1997] and Larson et al. [1997] proposed its possible sources from the solar erupting events.

In this study, we investigated the interaction of Oct95 with the Earth’s magnetosphere but stressed a different aspect, that is, the motion of the bow shock during Oct95’s passage. The front boundary of Oct95 was observed by Wind at $\sim 175 R_E$ (where $R_E$ is the Earth’s radius) upstream of the Earth’s bow shock at 1558 UT on October 18, 1995. At $\sim 146$ UT, Geotail, at the position in GSE coordinates of (9.31, -22.74, -1.56) ($R_E$), detected this front boundary and recorded the first sunward crossing at $\sim 1905$ UT and the first earthward crossing at $\sim 2118$ UT. The passage of Oct95 lasted till early October 20, 1995. During the 21 hour period from the first crossing at $\sim 1905$ UT on October 18, 1995, to the last crossing, $\sim 1640$ UT on October 19, Geotail recorded 26 crossings of the bow shock. On the basis of the model for the magnetopause by Shue et al. [1997] and the model for the bow shock standoff distance by Farris and Russell [1994] we proposed a two-parametric semiempirical model for the bow shock, and these two parameters, representing the standoff distance and flaring of the bow shock, can be determined by the upstream solar wind dynamic pressure $P_w$, the north-southward component of interplanetary magnetic fields (IMF) $B_z$, and the magnetosonic Mach number $M_{ms}$. Taking Wind as the upstream monitor, we analyzed temporal variations of the upstream solar wind parameters during the Oct95 passage, and then, with the semiempirical model we also predicted changes of position and shape of the bow shock due to variations of the upstream solar wind during the Oct95 passage. By comparing the predicted bow shock motion with the observations of the bow shock crossings by Geotail we found that the observed multiple bow shock crossings can be modeled well by the bow shock motion that was caused by temporal variations of the upstream solar wind parameters. This result also indicates that the semiempirical model with two parameters for the bow shock, which was proposed in this paper, can describe well the response of the bow shock on variations of the upstream solar wind conditions.

This paper is organized in the following fashion. After describing briefly the semiempirical model for the bow shock in section 2, we try to predict the bow shock motion during the Oct95 passage, taking Wind as the upstream monitor, in section 3. Then, in section 4 we report the observations of the bow shock crossings by Geotail and compare them with the prediction of the
2. Semiempirical Model for Bow Shock

When the Earth travels through the interplanetary medium, its magnetosphere acts as an impenetrable obstacle in the high-velocity solar wind environment. The magnetopause, the boundary of the magnetosphere, can be determined by the dynamic balance between the solar wind and the magnetosphere. The position and shape of the bow shock and the structure of the magnetosheath have been the subject of active research since the existence of the bow shock was first predicted by Kellogg [1962].

A study of experimental results and previous theories from aerodynamics led Seiff [1962] to derive a semiempirical relation between the ratio of the magnetosheath thickness along the stagnation streamline to the standoff distance of the magnetopause and the density ratio across the shock. Later, by use of the Rankine-Hugoniot relation for the density ratio and upstream sonic Mach number, Spreiter et al. [1966] rewrote the relation of Seiff [1962] in terms of the upstream sonic Mach number and the polytropic exponent (i.e., the ratio of specific heat) as the following form:

$$\frac{\Delta}{R_{MP}} = 1.1\frac{(\gamma - 1)M_s^2 + 2}{(\gamma + 1)M_s^2},$$  \hspace{1cm} (2)$$

which can be rewritten as

$$\frac{R_{BS}}{R_{MP}} = 1 + 1.1\frac{(\gamma - 1)M_s^2 + 2}{(\gamma + 1)M_s^2},$$  \hspace{1cm} (3)$$

where \(R_{BS}\) and \(R_{MP}\) are the standoff distances of the bow shock and magnetopause, respectively, \(\Delta\) is the magnetosheath thickness along the Sun-Earth line, and \(M_s\) and \(\gamma\) are the upstream sonic Mach number and the polytropic exponent, respectively. Spreiter et al. [1966] had pointed out that equation (3) should be used only for \(M_s > 5\) because an extrapolation of equation (3) to low Mach numbers reveals that the ratio of bow shock to magnetopause standoff distances becomes 2.1 at \(M_s = 1\), which is a nonphysical value and is contrary to the expectation that the shock should retreat to infinity as the Mach number approaches unity [Landau and Lifshitz, 1959]. Recently, Farris and Russell [1994] proposed a concise and attractive conjecture to replace the above Spreiter et al. relation by the following equation:

$$\frac{R_{BS}}{R_{MP}} = 1 + 1.1\frac{(\gamma - 1)M_{ms}^2 + 2}{(\gamma + 1)(M_{ms}^2 - 1)},$$  \hspace{1cm} (4)$$

where \(M_{ms}\) is the upstream magnetosonic Mach number, which replaces the upstream sonic Mach number \(M_s\) in equations (2) and (3) because the bow shock is a magnetosonic wave mode [Farris and Russell, 1994]. This Farris-Russell relation not only results in the same asymptotic values as those at high upstream Mach numbers but also causes the ratio of bow shock to magnetopause standoff distances to retreat to infinity as the Mach number becomes unity.

On the other hand, Fairfield [1971], who was the first to model the shape of the bow shock, found that the hyperboloidal model can provide the best fit to the bow shock. He used 389 near-ecliptic crossings observed by Imp 1-4, Explorer 33, and Explorer 35. Since then, various models, including ellipsoidal and paraboloidal models, have been used to model the bow shock shape with various standoff distances.

In principle, the position and shape of the bow shock can be determined by the following two factors: (1) the size and shape of the magnetopause and (2) the magnetosheath thickness. In a recent work, Shue et al. [1997] proposed a new function to fit the size and shape of the magnetopause by using two-satellite data (the one acts as the identifier for the magnetopause crossings, and the other acts as the monitor for the upstream solar wind conditions) as follows:

$$r = R_{MP} \left(\frac{2}{1 + \cos \theta}\right)^{\alpha_{MP}},$$  \hspace{1cm} (5)$$

where \((r, \theta)\) are the polar coordinates in the ecliptic plane with the origin at the Earth's center and the \(x\) axis along the Sun-Earth line and the parameters \(R_{MP}\) and \(\alpha_{MP}\) describe the standoff distance and the degree of tail flaring of the magnetopause, respectively. By using a multiple-parameter fitting scheme, Shue et al. [1997] obtained the standoff and flaring parameters of the magnetopause as explicit functions of the upstream solar wind parameters, the dynamic pressure \(P_d\) and the north-southward IMF component \(B_z\), in the GSM coordinates as follows:

$$R_{MP} = \begin{cases} (11.4 + 0.013B_z)D_p^{-1/6.6} & B_z \geq 0 \\ (11.4 + 0.140B_z)D_p^{-1/6.6} & B_z < 0 \end{cases},$$  \hspace{1cm} (6)$$

$$\alpha_{MP} = (0.58 - 0.010B_z)(1 + 0.010D_p).$$  \hspace{1cm} (7)$$

Following Shue et al. [1997], we introduce a function similar to equation (5) to model the bow shock, i.e.,

$$r = R_{BS} \left(\frac{2}{1 + \cos \theta}\right)^{\alpha_{BS}},$$  \hspace{1cm} (8)$$

where the parameters \(R_{BS}\) and \(\alpha_{BS}\) describe the standoff distance and the degree of tail flaring of the bow shock, respectively. When writing the model of the bow shock in the form of equation (8), we have assumed that the bow shock has an axially symmetric geometry about the Sun-Earth line. In general, the magnetosonic Mach number in an IMC is usually low \((M_{ms} < 5)\) because of its relatively strong magnetic field [Burlaga, 1991]. Because of its reasonableness in physics the Farris-Russell relation of equation (4) is possibly a better expression than equation (3) for the ratio of bow shock to magnetopause standoff distances for IMC cases which have low magnetosonic Mach numbers. On the other hand, anal-
ysis of observation data of the bow shock shows that the
dependence of the standoff distance of the bow shock on
the southward component of \( B_z \) is not so strong as that
of the magnetopause in equation (6). Thus, combining
equation (4) with equation (6), we suggest the standoff
distance of the bow shock \( R_{BS} \) as an explicit function of
\( D_p, B_z, \) and \( M_{ms} \) in the following form:

\[
R_{BS} = \frac{1 + 1.11(\sqrt{2} - 1) \frac{M_{ms}^2 + 4}{(1.14 + 0.013B_z)D_p^{1/6}}}{1.14 + 0.013B_z} \]

(9)

where \( B_z \) is in the GSM coordinates as suggested by Shue et al. [1997].

On the other hand, if we denote the ratio of the bow
shock to magnetopause sizes along the dawn-dusk line
(i.e., the direction of \( \theta = 90^\circ \)) as \( \eta \), we have from
equations (5) and (8)

\[
\eta = \left( \frac{R_{BS}}{R_{MP}} \right)_{\theta=90^\circ} = \left( \frac{R_{BS}}{R_{MP}} \right)^2 \left( \frac{\alpha_{BS} - \alpha_{MP}}{\alpha_{BS} - \alpha_{MP}} \right) \]

(10)
in terms of the bow shock and magnetopause boundary
flaring. This equation can be rewritten as

\[
\alpha_{BS} = \ln \left( \frac{\eta R_{MP}}{R_{BS}} \right) / \ln 2 + \alpha_{MP} \]

(11)

Under the average solar wind conditions the values of
\( R_{MP} \) and \( R_{BS} \) can be taken as \( \sim 11 \) and \( 14 R_E \), re-
spectively, and a reasonable range for the value of \( \eta \)
may be 1.89–1.93 [Peredo et al., 1995]. Thus the range
for the value of \( \ln(\eta R_{MP}/R_{BS})/\ln 2 \) is 0.57–0.60. On
the other hand, from equation (7), \( \alpha_{MP} \) depends on \( B_z \)
in the same form for both \( B_z < 0 \) and \( B_z > 0 \). How-
ever, to take into account the effect of the southward
magnetic field (which is more important here than that
of the northward magnetic field), it is also possible that
the flaring parameter \( \alpha_{BS} \) depends on the upstream \( B_z \)
component in different forms for \( B_z < 0 \) and \( B_z > 0 \).

By use of the best fit way we find that the model of equation (8) can better fit the observed bow shock crossings if we take the value of \( \ln(\eta R_{MP}/R_{BS})/\ln 2 \) as 0.6 (i.e.,
the \( \gamma \) value of 1.93) and the polytropic exponent \( \gamma \) as
1.8 and assume the flaring parameter \( \alpha_{BS} \) to depend on
\( B_z \) in the following form:

\[
\alpha_{BS} = 0.6 + (1 + 0.01D_p) \left\{ \begin{array}{ll}
0.58 & B_z \geq 0 \\
0.58 - 0.02B_z & B_z < 0.
\end{array} \right.
\]

(12)

The above equations (8), (9), and (12) constitute a two-parameter semiempirical model for the bow shock
that is still valid under the low upstream magnetosonic
Mach number condition, especially in cases of IMCs.

3. Variation of Upstream Solar Wind
Parameters During Oct95 Passage:
Motion of Bow Shock

IMC Oct95 was observed by Wind at \( \sim 175 R_E \) up-
stream of the Earth with a duration of \( \sim 30 \) hours start-
ing from 1858 UT on October 18, 1995. Lepping et al.
[1997] showed, based on the constant alpha force-free
model of Burlaga [1988], that Oct95 has a flux rope
magnetic field line geometry, an estimated diameter of
\( \sim 0.27 \) AU, and an axis that was almost in the ecliptic
plane (\( \theta_A = -12^\circ, \phi_A = 291^\circ \) in the GSE frame). The
spacecraft, Wind, nearly intercepted the axis of Oct95,
and the closest approach distance to the axis by Wind is
\( 0.08 R_A \), where \( R_A \) is the radius of the flux rope.

Figure 1 shows the upstream solar wind magnetic
field and plasma data from experiment MFI [Lepping et al.,
1995] and SWE [Opitue et al., 1995], respectively, on
Wind in an interval of 40 hours starting from 0500 UT
on October 18, 1995, where the time resolution of the
data used here is 1.5 min (i.e., 0.025 hour). From top
to bottom, the plots in Figure 1 are the magnetic field
strength \( B \), the north-southward component \( B_z \) in
the GSM coordinates, the \( x \) component of the plasma
velocity \( v_x \), the proton number density \( N_p \), and the most
probable proton thermal speed \( v_T \). The front boundary
of Oct95 at 1858 UT (marked by B) in Figure 1 was
well defined as a tangential discontinuity with a nor-
amal almost along the Sun-Earth direction (\( \theta_A = -3^\circ, \phi_A = 184^\circ \) [Lepping et al., 1997]). An upstream shock
at 1042 UT (marked by A) and a high-density “mag-
etosheath” region with a duration \( \sim 8 \) hours (i.e., the
region between A and B) can be seen clearly in Figure
1. The rear boundary of Oct95 occurred at \( \sim 0100 \)
UT on October 20, 1995 [Lepping et al., 1997], which is
beyond the interval of Figure 1.

After \( \sim 45 \) min lag time, Oct95 was observed by Geo-
tail near the bow shock (see section 4). Then, the in-
teraction of Oct95 with the magnetosheath causes motion
and distortion of the bow shock that could have been
recorded by Geotail. According to the semiempirical
model of the bow shock proposed in section 2, the pos-
tion and shape of the bow shock depends on three
upstream solar wind parameters, that is, \( D_p, B_z, \) and
\( M_{ms} \). Their temporal variations during Oct95 passage
are, in turn, shown in the first three plots of Figure
2, where the time axis has been shifted by an amount
of 0.82 hours, which includes a travelling time of the
solar wind from the position of Wind at \( \sim 175 R_E \) to
the nose magnetopause (\( \sim 0.75 \) hours) and a delaying
time due to the magnetosphere responding on vari-
tions of the upstream solar wind (\( \sim 0.07 \) hours). Here
the delaying time is estimated by assuming an average
magnetosheath thickness of 4 \( R_E \) and an average infor-
mation propagating speed of 200 km s\(^{-1}\) in the mag-
etosheath. Thus it takes a total time of \( \sim 0.07 \) hours
(i.e., \( \sim 255 \) s) for the solar wind variation to propa-
gate from the bow shock to the magnetopause and cause
the magnetosphere response, and then this response prop-
gagates back to the bow shock. However, the choice
of this shift period of 0.82 hours is not exact because it is
very difficult to estimate the delaying time owing to the
magnetosphere responding, and the time resolution of
the data used here is only 0.025 hours.
From Figure 2 it is easy to see that the solar wind dynamic pressure $D_p$ was enhanced remarkably from its average value of $\sim 2$ nPa in the ambient solar wind to $\geq 10$ nPa in both the sheath (between A and B in Figures 1 and 2) and rear (after C in Figures 1 and 2) regions owing to their high plasma density and that the magnetosonic Mach number $M_{ms}$ decreased remarkably from its average value of $\sim 9$ to $\sim 2$ inside Oct95, except for a few short intervals (1 to 1’ and 2 to 2’ in the third plot of Figure 2) and last few hours (3 to C in the third plot of Figure 2). It even decreased to $< 1.4$ (i.e., $M_{ms}^2 < 2$) for a very short period near hour 24. The north-southward magnetic field component $B_z$ varied obviously from a strong southward field (about -20 nT) to strong northward one ($\sim 25$ nT) inside Oct95 owing to the rotation of the IMF.

In the semiempirical model presented in section 2, the determination of the shape and size of the bow shock can be determined by two parameters, that is, the standoff distance $R_{BS}$ and flaring parameter $\alpha_{BS}$ that depend on the upstream solar wind parameters $D_p$, $B_z$, and $M_{ms}$ in the form of equations (9) and (12), respectively. Temporal varia-
tions of the two parameters $R_{BS}$ and $\alpha_{BS}$ describe the bow shock motion and distortion when the upstream solar wind conditions vary. The last two plots in Figure 2 show the temporal variations of $R_{BS}$ and $\alpha_{BS}$ during the Oct95 passage, which were calculated by equations (9) and (12), respectively. Here we have assumed that the interaction of Oct95 with the magnetosphere did not affect the symmetry of the bow shock shape with respect to the $z$ axis in the GSE frame of reference (i.e., the Sun-Earth line).

From the fourth plot in Figure 2, it is easy to see that the standoff distance $R_{BS}$ of the bow shock was depressed from its average value of $\sim 14 R_E$ under the ambient solar wind condition to only $\sim 10 R_E$ by the Oct95 "magnetosheath" region A to B because of its remarkable high solar wind dynamic pressure $D_p$. When the front boundary of Oct95, B, arrives, the model predicts that the bow shock should move quickly outward to $\sim 18 R_E$ from the Earth's center along the Sun-Earth line (see Figure 5) and should remain at that or a further distance for most of the Oct95 passage. This is because the magnetosonic Mach number inside Oct95 is remarkably lower than that in the ambient solar wind. For a very short period near hour 24, the model predicts that the bow shock should reach even beyond 35 $R_E$ from the Earth's center because the magnetosonic Mach number

![Figure 2. The upstream solar wind parameters: from top to bottom, the dynamic pressure $D_p$ (in units of nPa), the north-southward magnetic field component in the GSM coordinates $B_\parallel$ (in units of nT), the magnetosonic Mach number $M_{ms}$, the bow shock standoff distance $R_{BS}$ (in units of $R_E$), and the bow shock flaring parameter $\alpha_{BS}$, where the time axis has been shifted by an interval of 0.82 hours.](image-url)
Table 1. Data of the 26 Bow Shock Crossings by Geotail

<table>
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<th>Time</th>
<th>X_{GSE}</th>
<th>Y_{GSE}</th>
<th>N_X</th>
<th>N_Y</th>
<th>N_Z</th>
<th>r_o</th>
<th>r_p</th>
<th>r_p - r_o</th>
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The bow shock crossing time is in units of hour starting from 0000 UT on October 18, 1995. Also given are X and Y coordinates in units of R_E in the GSE, local normal direction (N_X, N_Y, N_Z), the observed and predicted distances from the Earth's center along the Earth-Geotail line r_o and r_p in units of R_E, their deviations r_p - r_o, and the accuracy of the prediction.

* Here the value of r_o represents only the distance between Geotail and the Earth.

† These are the two additional crossings predicted by the model but not observed by Geotail.

decreases below 1.4. The bow shock was depressed by the rear of Oct95 (i.e., the region after C in Figures 1 and 2), again, to a location inside its average position because of the increase of both the magnetosonic Mach number and the solar wind dynamic pressure due to a high plasma density, which was possibly caused by the interaction of Oct95 with a corotating stream in the rear boundary [J. Lepping et al., 1997].

On the other hand, it is predicted that the position of the bow shock oscillates quickly in the Sun-Earth line direction with an amplitude ~ 3 R_E during the Oct95 passage, which is remarkably larger than that under the ambient solar wind conditions. One possible reason is that the position of the bow shock depends on the magnitude of the magnetosonic Mach number M_ms and more sensitively for low M_ms values, so that small fluctuations of M_ms can cause large oscillations of the position of the bow shock, which is the case for the Oct95 event.

The predicted thriving parameter α_HS of the bow shock also has obvious variation during the Oct95 passage, as seen in the last plot of Figure 2. This is especially true when the front boundary of Oct95 arrives, and the thriving parameter increased quickly by a factor of 0.4 owing to a strong southward magnetic field component of ~ -20 nT. The thriving parameter α_HS affects the bow shock shape mostly on the nightside (i.e., X_{GSE} < 0). Therefore the effect of the thriving parameter cannot be tested very well by the analysis of the bow shock crossings discussed in the section 4 because all crossings have X_{GSE} > 10 R_E (see Table 1).

4. Observations of Bow Shock Crossings by Geotail: Comparison With Model

Figure 3 shows the magnetic field data from the MGF experiment on Geotail [Kataoka et al., 1994] during the MAG Oct95 passage, where the dotted line is the
magnetic field data observed by Wind. It has been shifted in time by the solar wind transit time between Wind and Geotail (∼ 0.75 hours), so that the front boundary of the IMC Oct95 observed by Geotail coincided with that observed by Wind. In Figure 3, the part of the magnetic field with a magnitude of ∼ 45 nT, which is well above the dotted line with a magnitude of ∼ 20 nT, obviously should be the magnetic field measured when Geotail was in the Earth’s magnetosheath. The outline of the interplanetary magnetic field observed by Geotail coincides rather well with the dotted line observed by Wind when the magnetosheath part is eliminated. In particular, 26 crossing events of the bow shock, which represent Geotail crossings of the interface between the magnetosheath and the interplanetary space, can be very clearly seen in Figure 3, and they have been denoted by numbers 1–26.

Figure 4 shows the distance of Geotail from the Earth’s center (the dotted line) and the distance of the bow shock from the Earth’s center along the Earth-Geotail direction (the solid line) which is predicted by the semiempirical model of equation (8) with equations (9) and (12) and with the time resolution of 1.5 min. In Figure 4 it is very clear that Geotail should be on the outside of the bow shock (i.e., interplanetary space) when the dotted line is above the solid line or inside of the bow shock (i.e., the magnetosheath or the magnetosphere) when the dotted line is below the solid line. Especially, the intersection points of the dotted and solid lines in Figure 4 express the bow shock crossings predicted by the semiempirical model. The bow shock crossings actually observed by Geotail are denoted by small diamonds in Figure 4. It is easy to find from Figure 4 that they do coincide rather well with the intersection of the two lines except for two crossing events near hour 32.

Figure 4 shows that the bow shock had remained inside Geotail’s orbit before the front boundary of the Oct95 arrival. Then the bow shock moved quickly out-
ward from ~15 to ~30 \(R_E\) along the Earth-Geotail line and crossed Geotail at ~1950 UT (~25 \(R_E\)) on October 18, 1995, this is also the first crossing denoted by 1 in Figure 4. Figure 5 shows the spacecraft trajectory around this first crossing, where the solid line represents the predicted bow shock at 1950 UT (the arrival time of the Oct95 front boundary) and the dashed line represents the bow shock at the average background solar wind condition. The circle and the dotted line represent Geotail and its orbit, respectively, and the Earth is at the origin. It is easy to see from Figure 4 that the bow shock had remained at a large distance outside the Geotail orbit for most of the Oct95 passage. The two exceptional intervals are the periods of hours 21–23 and hours 32–35, which correspond to 1 to 1' and 2 to 2' in the third plot of Figure 2, respectively. In these intervals the bow shock moved inside the Geotail orbit owing to the magnetosonic Mach number increases. These were obviously caused by the two small plasma density humps in these two intervals (see the fourth plot in Figure 1). As a consequence, the two groups of the bow shock crossings, 2–7 and 8–15 in Figure 4, did occur in these two intervals. In another period of hours 37–41, corresponding to the region between 3 and C in the third plot of Figure 2, since the plasma density and hence the magnetosonic Mach number gradually increases, the bow shock, again, moved inward. This led to another group of bow shock crossings in this interval, i.e., 16–26 in Figure 4, which occurred in the interval of hours 37–41. After that, the bow shock remained inside the Geotail orbit because of the high plasma density and solar wind dynamic pressure.

In addition, from Figure 4, two additional bow shock crossings, which are denoted by arrows at 36.7 and at 40.9 hours, respectively, are predicted but are not observed by Geotail. In fact, they consist of couples of in-
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Figure 5. The predicted position and shape of the bow shock on the dayside where the solid line represents the case at 1950 UT on October 18, 1995, when the bow shock is moving outward and crossing Geotail and the dashed line represents the bow shock under the average background solar wind conditions. The circle and the dotted line represent Geotail and its orbit, respectively, and the Earth is at the origin.

ward/outward (at 36.7 hours) and outward/inward (at 40.9 hours) crossings which are temporally very close. There are only two and one data points that cross the Geotail orbit (i.e., the dotted line in Figure 4) for the cases at 36.7 and 40.9 hours, respectively, and this indicates that the durations between inward and outward are < 4.5 min for the case at 36.7 hours and < 3 min for the case at 40.9 hours, respectively. One possible reason for these two missing crossings in the data of Geotail is that the upstream solar wind varies too quickly, so that the bow shock could not respond quickly enough to obtain a position of equilibrium. Hence the predicted crossings did not occur.

Table 1 lists the data of the 26 crossings of the bow shock observed by Geotail and two “false” crossings predicted by the model, where the first three columns are the bow shock encountering time in hours from 0000 UT on October 18, 1995, and positions in units of $R_E$. All crossings have been rotated into the solar wind aberrated geocentric solar ecliptic (GSE) coordinates by an angle of $\sim 4.3^\circ$ to remove asymmetries due to the Earth’s orbital motion at the speed of 30 km s$^{-1}$. At the same time, all crossings also have been projected onto the ecliptic plane through a rotation around the x axis, that is, $\sqrt{Y_{GSE}^2 + Z_{GSE}^2} \rightarrow Y_{GSE}$. In fact, we have $|Z_{GSE}| < 1.6 R_E$ for all of the 26 crossings. This indicates that they are all near-ecliptic plane crossings. The $N_X$, $N_Y$, and $N_Z$ in Table 1 are the local bow shock normal directions that are calculated by the formula (Chao, 1970)

$$N = \pm \frac{(B_u \times B_d) \times (B_u - B_d)}{|(B_u \times B_d) \times (B_u - B_d)|}$$

for crossings 8–26, in which the bow shock is an oblique shock, and by the formula

$$N = \pm \frac{B_u \times [B_u \times (v_u - v_d)]}{|B_u \times [B_u \times (v_u - v_d)]|}$$

for crossings 1–7, in which the bow shock is a quasi-perpendicular shock (Chao, 1970), where $B_{u(d)}$ is the magnetic field of the upstream (downstream) solar wind and $v_{u(d)}$ is the flow velocity of the upstream (downstream) solar wind. Both B and v are in the GSE coordinates. In Table 1, $r_O$ and $r_P$ are the observed and predicted distances of the bow shock from the Earth's center along the Earth-Geotail line, respectively, and $r_P - r_O$ represents the deviation of the predicted to the observed distances. To compare the observed and predicted distances of the bow shock, we take the allowable errors as $\Delta t < 3$ min and $\Delta r < 0.02 r_O$ for the time and the distance of crossings, respectively. The “prediction” column in Table 1 denotes the accuracy of crossings predicted by the semiempirical model, where signs “C” (22 crossings) and “T” (4 crossings) indicate the crossings predicted correctly and incorrectly, respectively, within the above allowable error ranges, and the dagger indicates the two additional crossings that are predicted by the model but not observed by Geotail. The result implies that the semiempirical model for the bow shock, which is described by equation (8) with equations (9) and (12), can predict reasonably well the bow shock motion in response to variations of the upstream solar wind conditions.

5. Conclusions

In this paper, using simultaneously two-satellite data, in which Wind acts as the monitor for the upstream solar wind conditions and Geotail acts as the identifier for the bow shock crossings, we investigated the bow shock motion that was caused by the interaction of the IMC Oct95 [Lepping et al., 1997] with the magnetosphere during its passage. In this section we summarize our conclusions as follows.

First, on the basis of the model of the magnetopause by Shue et al. [1997] and the model of the bow shock standoff distance by Farris and Russell [1994], we pro-
pose a semiempirical model for the bow shock in the form of equation (8), with two essential parameters, \( R_{BS} \) and \( \alpha_{PS} \). And these two essential parameters can be determined by the explicit functions of the three upstream solar wind parameters \( D_p, B_z \), and \( M_{ms} \) in the form of equations (9) and (12).

Second, by use of the magnetic field and plasma data observed by Wind at 175–176 \( R_E \) upstream of the Earth, we analyzed the variations of the above three upstream solar wind parameters during the Oct95 passage. At the same time, with a semiempirical model for the bow shock we also predicted the bow shock motion due to these variations. The result showed that the subsolar point of the bow shock (i.e., \( R_{BS} \) of the fourth plot in Figure 2) could move outward to a distance \( \sim 18 R_E \) from the Earth for most of the Oct95 event and could even reach beyond 35 \( R_E \) from the Earth for a short period near hour 24 according to the calculation of our proposing model. We suggest that the cause for this predicted abnormal behavior of the bow shock could be the remarkably low magnetosonic Mach number inside Oct95. On the other hand, in the Oct95 magnetosheath interval the bow shock could move inward to only \( \sim 10 R_E \) because the high plasma density and hence the strong solar wind dynamic pressure.

Then, we studied the multiple bow shock crossings observed by Geotail during Oct95 and found that the observed 26 crossings could be separated into four groups. The first group is the first crossing denoted by 1 in Figures 3 and 4 and showed in Figure 5, which occurred because the decrease of the upstream magnetosonic Mach number led to an outward bow shock motion when the front boundary of Oct95 arrived (see Figure 5). The second and third groups are crossings 2–7 and 8–15, respectively, in Figures 3 and 4. We suggest that their cause was two small plasma density humps in the intervals of hours 21–23 and hours 32–35 in the fourth plot of Figure 1. These led to the magnetosonic Mach number increase in the intervals of 1 to 1' and 2 to 2' in the third plot of Figure 2 and, as a consequence, to the bow shock moving inward to the distance of \( \sim 15–16 R_E \) close to the Geotail orbit. In fact, the bow shock crossings, 2–7 and 8–15 in Figure 4, did occur, respectively, in the above two intervals. The fourth group of crossings of 16–26 in Figures 3 and 4 were caused by an increase in plasma density and hence also by the increase of the magnetosonic Mach number in the rear of Oct95 (i.e., the region between 3 and C in the third plot of Figure 2). As a consequence, this led the bow shock again to move inward to the neighborhood of Geotail.

Finally, we compare the observed and predicted distances of the bow shock, taking the allowable errors as \( \Delta \theta < 3 \text{ min} \) and \( \Delta R < 0.02 r_O \) for the time and the distance of the crossings, respectively. The result shows that the 22 events of crossings, which are denoted by the C in Table 1, can be predicted correctly within the above allowable error range. This implies that the two-parameter semiempirical model for the bow shock, which is described by equation (8) with equations (9) and (12), can describe correctly the response of the bow shock in the motion to the variations of the upstream solar wind conditions and therefore can predict accurately changes of the bow shock in position and shape that can be caused by the variations of the upstream solar wind parameters.

The bow shock represents the outermost boundary between the geospace which is dominated by the Earth's magnetic field and the interplanetary medium streaming from the Sun. This boundary is important because it is here that the streaming solar wind is slowed, heated, and partially deflected around the Earth's magnetosphere. Therefore, it can play an important role in the research of the solar-terrestrial relation and the space weather to predict correctly its position and shape. Our model proposed in this paper provides a simple and actual way to predict with a reasonable accuracy the motion of the bow shock (at least the bow shock on the dayside) when the upstream solar wind is varying.

Acknowledgments. Authors are grateful to the MFI and SWE teams for providing the Wind data, to the MGP team for providing the Geotail data, to C. H. Lin for his help on data handling, and to the referees for their helpful comments and suggestions on this paper. One of the authors, D. J. Wu, would like to thank the Institute of Space Science, National Central University for their hospitality during his visit. This study has been supported by grant 49990452 of NSFC and grant NSC88-2111-M-008-007-A-p8.

Janet G. Luhmann thanks Stefania Lepidi and another referee for their assistance in evaluating this paper.

References


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(Rceived July 19, 1999; revised January 31, 2000; accepted January 31, 2000.)