Comparison of three magnetopause prediction models under extreme solar wind conditions

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[1] A database, the largest one to date, of magnetosheath encounters by geosynchronous satellites during 1986–1992 and 1999–2000 and upstream observations by Wind, IMP 8, or Geotail in the magnetosheath, is used to estimate the forecasting capability of the models of Chao et al. [2001], Shue et al. [1998], and Paterson and Russell [1986]. For each of the 1-min resolution data points obtained by GOES spacecraft, we check the following two things: if the magnetosheath was observed by the spacecraft, and if each of the three models predicted a magnetosheath encounter by the spacecraft. Three parameters are defined to quantify the models’ forecasting capability: probability of prediction (PP), probability of detection (PoD), and false alarm rate (FAR). A higher PoD and PoD with a lower FAR imply a better forecasting model. In the 1986–1992 period we found that most of the magnetosheath encounters observed at 6.6 R$_e$ were detected. In particular, the Chao et al. [2001] model predicts the lowest FAR compared with those of the other two models. We have also studied the magnetosheath encounters made by GOES spacecraft for the period from 1999 to 2000 using Wind and Geotail as the solar wind monitor. This independent database of magnetosheath encounters during 1999–2000 confirms our previous anticipations. The PoD of Paterson and Russell [1996] model (94%) is much higher than those of Shue et al. [1998] (75%) and Chao et al. [2001] (84%) models. The Chao et al. [2001] model has a higher PoD than the other two models. The values of FAR for Chao et al. [2001], Shue et al. [1998], and Paterson and Russell [1996] models are 25, 32, and 40%, respectively. INDEX TERMS: 2722 Magnetospheric Physics: Forecasting; 2724 Magnetospheric Physics: Magnetopause, cusp, and boundary layers

1. Introduction

[2] The magnetopause plays an important role in protecting Earth from the intense solar wind. Under normal solar wind conditions the subsolar point of the magnetopause is generally located at ~10 R$_e$ from Earth. Under extreme solar wind conditions, namely, a large southward interplanetary magnetic field (IMF, Bz) and/or a high solar wind dynamic pressure (PD), the magnetopause can move inside geosynchronous orbit (6.6 R$_e$). At that time, geosynchronous satellites that use the local magnetic field for orientation information may become misoriented in the randomly directed field in the magnetosheath.

[3] Chapman and Ferraro [1931] first suggested the existence of a magnetopause boundary. They proposed that dynamic pressure

\[ PD = \text{the factor that controls the location of the magnetopause.} \]

On January 4, 1967, the magnetopause was first detected to penetrate within geosynchronous orbit by the ATS 1 satellite [Opp, 1968; Cummings and Coleman, 1968, and references therein]. Iauritì et al. [1970] suggested that erosion of magnetic flux from the dayside magnetosphere to the tail also results in an inward motion of the magnetopause during southward IMF. The Fairfield [1971] study of magnetopause crossings supported this suggestion and showed that more earthward crossings are associated with larger southward IMF. Fairfield’s study did not include any geosynchronous magnetopause crossings. Russell [1976] first analyzed geosynchronous magnetopause crossings systematically by using two years (1966–1968) of magnetic field data from ATS 1. His study showed that the magnetopause crosses inside of geosynchronous orbit ~0.3% of the time. On the basis of studies of geosynchronous magnetopause crossings identified from the magnetosheath data of GOES 3, 5, and 6 between 1978 and 1986, Roelof et al. [1989] found that both a high PD and a large southward IMF are required for the magnetopause to move inside 6.6 R$_e$. Later, McCullough et al. [1993, 1994] used particle data to identify crossings at geosynchronous orbit.

[4] Many magnetopause models have been proposed in the past [Fairfield, 1971; Heber and Storm, 1978; Formisano et al., 1979; Sibeck et al., 1991; Paterson et al., 1991; Paterson and Russell, 1993, 1996; Roelof and Sibeck, 1993; Shue et al., 1997, 1998; Kuznetsov and Savushin, 1998a, 1998b; Kavanov et al., 1999], but few papers have studied the forecasting capability of such models for geosynchronous magnetopause crossings. Recently, Shue et al. [2000] discussed the applicability of each of the magnetopause models and found the Shue et al. [1998] model (SM) and Paterson and Russell [1996] model (PPM) to be the most suitable for extreme solar wind conditions. Shue et al. [2000] used the subsolar distance r$_s$ to check whether the predicted location magnetopause.
<table>
<thead>
<tr>
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<th>Month</th>
<th>Day</th>
<th>Satellite</th>
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<tr>
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<td>8</td>
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<td>1532-09-13</td>
<td>1,1</td>
</tr>
</tbody>
</table>

is within 6.6 Rₚ or not. However, it is possible that the magnetopause had already moved inside 6.6 Rₚ at the subsolar point where geosynchronous satellites were still in the magnetosphere at other local times. They required that individual crossings be separated by 20-min or 60-min intervals, and then they individually calculated the number of crossings. Chao et al. [2001] improved the magnetopause crossing database used by Shee et al. [1997, 1998] and derived a model (CM) that is used for both normal and extreme solar wind conditions.

2. Data Selection

[a] The data of GOES 5, 6, 7, 8, 10, IMP 8, Wind, and Geotail are used in this study, of which only the GOES 5, 6, 7, and IMP 8 data are used to create the CM for extreme solar wind conditions. The GOES spacecraft provide good opportunities to observe the structure of crossings at geosynchronous orbit. IMP 8, Wind, and Geotail provide the upstream IMF and plasma data used in this study to obtain predicted magnetopause locations of the PRM, SM, and CM. All of the geosynchronous field and solar wind data are 1-min or 90-s averages, which are more accurate than the 5-min averages used by Shee et al. [2000]. By comparing the predicted duration when the magnetopause moves inside 6.6 Rₚ with the observations of GOES spacecraft, we estimate the models’ forecasting capability for magnetosphere encounters at geosynchronous orbit.

2.1. Geomagnetic Field

Under normal solar wind conditions, the GOES spacecraft are in the magnetosphere and measure a northward geomagnetic field. If the magnetopause moves inside geosynchronous orbit owing to an enhanced Dₛ and a large southwestward Hₛ, a GOES spacecraft can be exposed to the magnetosphere environment and observe the IMF. Since it is difficult to identify a crossing from the magnetospheric field data alone when IMF is northward, the duration when GOES spacecraft observe southward magnetic field is recognized as the period of GOES in the magnetosphere. GOES 5, 6, and 7 were operated during the period 1986–1992, and GOES 8 and 10 were operated during 1999–2000. The geomagnetic field of data 1-min averages from GOES spacecraft are obtained from the National Geophysical Data Center (NGDC). In general, a crossing is identified if the north-south component of the geomagnetic field Hₛ changes its direction suddenly. When the northward (southward) geomagnetic field turns south (north), it means that the magnetopause motion near 6.6 Rₚ causes a GOES to enter (exit) the magnetosphere. A sudden change in direction of a single data point of Hₛ is not used to identify a magnetopause crossing.

[b] During 1986–1992, the GOES spacecraft were in the magnetosphere for a total of 4818 min, but only 114-min periods of these had accompanying upstream solar wind parameters. These magnetosphere encounters are shown in Table 1. The first through third columns show the year, month, and day of a crossing, respectively. The fourth column identifies the observing satellite: GOES 5, 6, and 7, which are denoted by G5, G6, and G7, respectively. The fifth and sixth columns record the times when gas satellite entered (i.e., Hₛ turned southward) and exited (i.e., Hₛ turned northward) the magnetosphere, respectively. Local time is given in parentheses. The first number in the seventh column represents the available IMP 8 data in minutes, and the second number represents the total duration when the GOES spacecraft stayed in the magnetosphere. Since the data of Wind and Geotail have much fewer bad data points than that of IMP 8, a total of 1220 min of magnetosphere entering by GOES spacecraft with available solar wind parameters during 1999–2000 (not shown here) is obtained compared to only 114 min obtained during the 1986–
2. Solar Wind Data

In our prediction scheme we assume that only \( B_0 \) and \( D_0 \) affect the location and shape of the magnetopause. In this study, the averages of \( B_0 \) and \( D_0 \) are used to calculate \( D_{mp} \), which includes also the heliospheric contribution if it is available to the dynamic pressure. We also consider the time shift \( \Delta t \) of the solar wind from IMP 8, Wind, or Geotail to the GOES spacecraft. In general, we let \( \Delta t = (t - 6.6) \) \( V_{sw} \), where \( t \) is the location of the IMP 8, Wind, or Geotail position in interplanetary space, 6.6 is the distance of geocentric orbits in \( R_0 \) and \( V_{sw} \) is the component of the solar wind velocity measured by the solar wind monitors, when for GSM coordinate system is used. However, when the fluctuations associated with the upstream solar wind parameters are large, the predicted time shift can be in error. Therefore we compare the magnetic field variations in the solar wind (IMP 8, Wind, and Geotail) with those in the magnetosphere (GOES) to obtain a more accurate time shift. The response time of the magnetopause to the solar wind change, coming from solar wind-magnetosphere interactions, is not included here. This is equivalent to assuming that the whole magnetopause responds instantaneously when the upstream solar wind parameters reach the subsolar point at 6.6 \( R_0 \). Since the size and shape of the magnetopause vary with upstream solar wind conditions, we predict the size and shape of the magnetopause as a function of \( B_0 \) and \( D_0 \) under equilibrium conditions. Predictions will not be made under one or more of the following situations: (1) IMP 8, Wind, or Geotail move inside the magnetosphere or magnetosheath, (2) either the data of the GOES spacecraft or the upstream solar wind parameters are unavailable, and (3) the GOES spacecraft are on the magnetosphere's nightside.

3. Models

3.1. Pritchard and Russell (1994a) Model

Using the ISEE 1 and 2 magnetometer data over a 10-year period and the corresponding solar wind parameters from IMP 8, Pritchard et al. (1991) obtained a model for the size and shape of the dayside magnetopause. Pritchard and Russell (1993) further developed a model of the near-Earth magnetopause according to the total pressure balance between lobes plasma and the solar wind. By combining their dayside and nightside magnetopause models with a smooth connection at the terminator, Pritchard and Russell (1996) derived a model for the entire magnetopause. The functional form of their dayside model is

\[ r = \frac{14.65}{\sqrt{1 + \left( \frac{264}{\max(2,1)D_0} \right)^2}} \]

where \( r_0 = 0 \) for northward IMF and \( r_0 = 0.16 \) for southward IMF. Here \( r \) is the radial distance of the magnetopause, and \( D_0 \) is the solar wind angle; thus the dayside magnetopause location is independent of \( B_0 \) for northward IMF.

3.2. Shaw et al. (1998) Model

Selecting the crossings observed by ISEE 1, 2, Active Magnetospheric Particle Tracer Explorers (AMPTE)/Ion Release Satellite (ISAS) and IMP 8, Shaw et al. (1997) developed a new functional form,

\[ r = r_{0\text{CM}} \left( \frac{2}{1 + \cos \theta} \right)^{\alpha} \]

where \( r_{0\text{CM}} = 0.00137 \) for northward IMF and \( r_{0\text{CM}} = 0.00644 \) for southward IMF.

3.3. Chao et al. (2001) Model

Chao et al. (2001) improved the magnetopause crossings database used by Shaw et al. (1997, 1998) based on the following considerations. In the original database, for simplicity, the time shift for solar wind propagation from IMP 8 (or ISEE 1) to Earth is assumed to be constant (10 min for IMP 8 and 50 min for ISEE 3). Because the speed of the solar wind can vary substantially especially during the disturbed times we are studying and because the spacecraft locations are not fixed, the true time delay can vary by a large amount; therefore Chao et al. (2001) use the actual satellite positions and the measured solar wind speed to estimate a more accurate time shift in the database. Magnetopause crossings by geosynchronous spacecraft during 1986—1992 were included so that the database can be used for extreme solar wind conditions. Possible bias due to a data selection criteria has been minimized in the model of Chao et al. (2001) by fitting the \( r_0 = 0 \) IMF \( R_0 \) to the center boundary of the phases in Figure 14, simultaneously requiring the estimated errors of the fitting staying at a minimum value. Thus the coefficients of the model for the dayside solar wind conditions are obtained. Along the flank of the magnetopause, \( r_0 \) is difficult to distinguish shock magnetopause from unshocked solar wind. In the past some data of IMP 8 have been incorrectly considered to be solar wind values when the satellite was actually in the magnetosheath. Such situations are eliminated in the new database. All crossings are corrected for aberration in the GSM coordinate system. The CM has the same
functional form for the magnetopause as does the SM, but the dependence of \( r_p \) on \( D_P \) and \( D_S \) is different. In order to distinguish magnetopause responses under normal and extreme solar wind conditions, respectively, the dependence of \( r_p \) is derived separately. Those observed enhancements with \( r > 1.6 \) \( R_P \) and \( r \leq 1.6 \) \( R_P \) are used to derive a relationship for normal and extreme solar wind conditions, respectively. Then the relationships are used as the models for normal and extreme solar wind conditions with \( r_p \geq 7.0 \) \( R_P \) and \( r_p \leq 6.4 \) \( R_P \), respectively. For \( r_p \) between 6.4 and 7.0 \( R_P \), interpolation is applied for smooth and continuous transition, where a natural log variation of \( r_p \) with \( D_P \) is applied to the region of \( \alpha \leq \alpha_0 \approx 3.7 \) \( R_P \) and a linear variation of \( r_p \) with \( D_P \) applied to a range of the region of \( 6.4 \leq \alpha \leq \alpha_0 \approx 7.0 \) \( R_P \). It is found that if \( r_p = 6.7 \) \( R_P \), we can have a continuous and smooth transition such that neither \( r_p \) nor \( d^2r_p/dD_P^2 \) show a jump at any value of \( D_P \), and \( d^2r_p/dD_P^2 \) is always negative from normal to extreme conditions. The total error of the best fit with interpolation are found to remain the same as that without an interpolation; then the CM is obtained as follows:

\[
\begin{align*}
\alpha & = \left( \frac{a_1}{a_2} \right)^2 \frac{B_1}{B_2} + \left( a_3 - 5 a_2 + 3 a_3 \right)^2 \frac{B_2}{B_1} \leq 0, \\
\alpha & = \frac{a_1}{a_2} \left( 1 + \alpha_0 \right),
\end{align*}
\]

(15) Under normal solar wind conditions (i.e., for \( r_p \geq 7.0 \) \( R_P \)) the coefficients \( a_1 = 1.1664, a_2 = 0.216, a_3 = 0.122, a_4 = 0.215, a_5 = 0.578, \alpha_0 = -0.009 \), and \( a_0 = 0.012 \) are derived, while under extreme conditions (i.e., for \( r_p \leq 6.4 \) \( R_P \)) the coefficients are \( a_1 = 11.646, a_2 = 0.169, a_3 = 0.135, a_4 = 0.580, a_5 = -0.009, \) and \( a_0 = 0.012 \). In the region of \( 6.4 \leq r_p \leq 7.0 \) \( R_P \), interpolations are applied. The \( r_p \) is independent of \( D_P \) when IMF is normal. Note that \( \alpha_0 \approx 3.7 \) \( R_P \) in Figure 14d shows the CM under normal and extreme conditions.

(16) In deriving the CM model for extreme solar wind conditions, the following assumptions have been imposed. First, the functional form in terms of \( D_S \) and \( D_P \) for normal and extreme conditions are assumed to be the same except the coefficients are different. Second, the subplots distances \( r_p \) for \( D_S \neq 0 \) depend on \( D_P \) only with a power equal to \( 1/(1+a_0) \), where \( a_0 \) can be different between normal and extreme conditions. Third, the coefficients \( a_1, a_2, a_3, a_4, a_5, \) and \( a_0 \) do not change between normal and extreme conditions. Then, from the magnetopause encounters shown in Figure 14, the values of \( a_0 = 0.169, a_1 = 0.158, \) and \( a_5 = 6.80 \) are obtained by best fitting all the plots for least error.

3.4. Characteristics of the PRM, SM, and CM

(17) Figures 14a–1c show the contours of \( r_p \) for various \( B_i \) and \( D_i \) of the three models. From top to bottom are the PRM, SM, and CM, respectively. It can be seen that \( r_p \) predicted by the PRM is always smaller than those of the SM and CM under the same solar wind conditions; hence it is expected that more periods of GOES in the magnetosheath should be predicted by the PRM. Under a strong southward IMF (e.g., \( B_I = -20 \) nT) condition, a smaller \( D_P \) is needed for the PRM (e.g., \( D_P = 1.2 \) nT) than for the other two models to push the magnetopause inside 6.6 \( R_P \) at the subsolar point. The \( r_p \) of the SM is independent of \( B_i \) for the same \( D_P \), while \( B_i \) for \( B_i \) greater than 20 nT. Under northward IMF, a larger \( D_P \) is needed for the CM (e.g., \( D_P = 45.0 \) nT) than the PRM and SM to move the \( r_p \) of the magnetopause to 6.6 \( R_P \). All three models have the characteristic that a larger \( D_P \) is needed to push the magnetopause closer to the Earth when \( r_p \) is smaller. Figure 14d shows the comparison of \( r_p \) contours of these three models under normal (i.e., \( r_p \geq 10 \) \( R_P \)) and extreme (i.e., \( r_p \leq 6.4 \) \( R_P \)) solar wind conditions. Dotted, dashed, and solid curves represent the PRM, SM, and CM, respectively. The \( r_p \) contours of these models are similar for normal solar wind.
conditions, while their behaviors are different for extreme solar wind conditions. The associated $B_x$ and $B_y$ values of GOES spacecraft in the magnetosphere during 1996–1992 are shown as planes in Figure 1d. Since for $r_p = 6.6 R_E$ contour of CM is obtained from the idea that it should be as close to the outer edge of these phases as possible, CM has the largest $r_p$ for most of these phases.

Contours of $\alpha$ of the SM and CM are plotted, respectively, in Figure 2. The PSR does not contain an $\alpha$ factor, and the tail is assumed to be cylindrical in shape; hence it is not shown here. The $\alpha$ value changes slowly with $D_x$ and $D_y$ for the SM, while for the CM, $\alpha$ changes more sensitively with $D_x$ and $D_y$.

### 4. Method of Analysis

[15] Predicting the locations of the magnetopause along the same radial direction as the GOES spacecraft at 1-min resolution is our objective. If the predicted $r$ in the Earth-GOES direction is less than or equal to 6.6 $R_E$, which means the GOES spacecraft should be

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**Figure 2.** Contours of tail flaring, $\alpha$, for the SM and CM.

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**Table 2.** The Possible Situations for Observation and Predictions

<table>
<thead>
<tr>
<th>Observation</th>
<th>Yes</th>
<th>No</th>
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</thead>
<tbody>
<tr>
<td>Prediction</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>
| HT, hit time; FAT, false alarm time; MT, miss time; CRT, correct rejection time. Probability of prediction (PoP) HT + CRT + MT + FAT + CRT. Probability of detection (PoD) HT + FAT + MT + FAT + CRT inside the magnetopause, and GOES is in (is not) located, we also classify a model's prediction as correct (incorrect). We record the predicted crossing times when the magnetopause moves inside or outside geosynchronous orbit, from which the predicted duration of the GOES spacecraft being in the magnetosphere can be obtained, and then, by comparing the observations at each data point, the forecasting capability of each model can be estimated. Comparisons are limited to within 0800–1000 LT, owing to no occurrence of crossings during the nighttime. The data resolution of IMP 8, Geotail, and the GOES spacecraft is 1 min, and the Wind is 1.5 min, which is much better than the previous studies, which used 5-min or 1-hour time resolution.

[20] There are four comparison conditions, which are defined in units of minutes (as shown in Table 2): hit time (HT), false alarm time (FAT), miss time (MT), and correct rejection time (CRT). The format is the same as in Table 3 of Shue et al. [2000]. A model has a correct prediction when the predicted periods agree with observations as given in the HT and CRT, while a model has an incorrect prediction as given in the FAT and MT when the predicted periods disagree with observations. The HT refers to the length of time during which predictions are observed. The FAT refers to the length of time during which predictions are not observed. The MT refers to the length of time during which observed events are not predicted. The CRT refers to the length of time during which no shear encounter is observed but predicted. TT is the total time satisfying the relation $HT + FAT + MT + CRT$. TT is the same for all three models. The statistics are done only when the magnetopause encounter is observed or predicted at least by one of the three models. Consequently, the values of each model's CRT are reduced substantially.

[21] Parameters are defined from the above four quantities to determine the forecasting capability. They are probability of prediction (PoP), probability of detection (PoD), and false alarm rate (FAR). Table 3a shows the probability of prediction (PoP) for the three models, and Table 3b shows the probability of detection (PoD) for the three models. The statistics are done only when the magnetopause encounter is observed or predicted at least by one of the three models. Consequently, the values of each model's CRT are reduced substantially.

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**Table 3a. Prediction Results of the Three Models During 1986–1992**

<table>
<thead>
<tr>
<th>Model</th>
<th>HT</th>
<th>MT</th>
<th>FAT</th>
<th>CRT</th>
<th>TT</th>
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</thead>
<tbody>
<tr>
<td>Chao et al. [2001]</td>
<td>109</td>
<td>5</td>
<td>238</td>
<td>781</td>
<td>1133</td>
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<tr>
<td>Shue et al. [1998]</td>
<td>106</td>
<td>8</td>
<td>367</td>
<td>652</td>
<td>1133</td>
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<tr>
<td>Pasch ke and Russell [1996]</td>
<td>141</td>
<td>3</td>
<td>615</td>
<td>404</td>
<td>1133</td>
</tr>
</tbody>
</table>

*Units are minutes.

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**Table 3b. Prediction Results of the Three Models During 1999–2000**

<table>
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<tr>
<th>Model</th>
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<th>FAT</th>
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<th>TT</th>
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</thead>
<tbody>
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<td>Chao et al. [2001]</td>
<td>1027</td>
<td>193</td>
<td>347</td>
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<td>Shue et al. [1998]</td>
<td>496</td>
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<td>324</td>
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<td>Paschke and Russell [1996]</td>
<td>1145</td>
<td>75</td>
<td>774</td>
<td>694</td>
<td>2688</td>
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</table>

*Units are minutes.*
Figure 3. Observations by IMP 8 and predictions by the three models in GOES 6 and 7 locations on (a) April 25, 1989, and (b) June 12, 1990. The black regions denote the periods when predicted magnetopause is within geosynchronous orbit. Hatched bars indicate the GOES spacecraft inside the magnetosphere. The upside-down triangles denote local noon of the GOES spacecraft.

as HT (HT = MT), and the FAR refers to the percentage of predicted sheet encounters that are not observed and is defined as FAR(HT = FAT). It is necessary to consider all three parameters at the same time for comparing a model's forecasting capability. Higher Pop represents a better prediction of GOES staying either in the magnetosphere or magnetosheath, while higher PopD represents a better prediction of sheet encounters only. Higher FAR represents less reliable predicted results; therefore higher Pop and PopD with lower FAR represent a better forecasting model.

5. Results
[2] Our comparisons are given for the periods of 1986–1992 and 1999–2000, respectively. Since the relationship of (R, a) with (B, D) of CM for the extreme solar wind conditions is derived from the crossings in the period of 1986–1992, it is likely the CM gives a better prediction than one other two. Therefore an independent database of geosynchronous crossings in the period 1999–2000 is selected for examining the forecasting capability of these models. The predicted results of these two periods are described separately as follows.

5.1. During 1986–1992
[2] Figures 3a and 3b show the IMF B and D measured by IMP 8 and the predicted results for the crossings on April 25, 1989, and June 12, 1990, respectively. The top two panels show B and D with time shifted for comparison with GOES data. The next six panels show the differences of radial distances between the predicted magnetopause and the GOES spacecraft (i.e., r = 6.6 R_E) shown as a vertical line. The distance differences predicted by the CM, SM, and PRM, respectively, are shown in Figure 3. Black regions are where r is less than 6.6 R_E, thus these regions represent the predicted periods that a GOES should be in the magnetosphere. The hatched bars show the periods that a GOES actually stayed in the magnetosphere. The upside-down triangles indicate when the GOES spacecraft are at local noon. The periods of cocentrism between hatched and black regions indicate the HT during which sheet encounters can be detected by models. The periods when hatched bars alone occur refer to the MT during which sheet encounters cannot be detected by models. Periods of black without hatched bars refer to the FAT during which models predict the magnetopause inside 6.6 R_E but the GOES spacecraft is still in the magnetosphere. Periods with-
Table 4a. Comparison of Prediction Capability for the Three Models During 1986–1992

<table>
<thead>
<tr>
<th>Model</th>
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<th>PoD</th>
<th>FAR</th>
</tr>
</thead>
<tbody>
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<td>Chu et al. [2001]</td>
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<td>96</td>
<td>69</td>
</tr>
<tr>
<td>Nie et al. [1999]</td>
<td>87</td>
<td>93</td>
<td>78</td>
</tr>
<tr>
<td>Perreault and Russell [1996]</td>
<td>45</td>
<td>97</td>
<td>85</td>
</tr>
</tbody>
</table>

*Units are percentage.

Table 4b. Comparison of Prediction Capability for the Three Models During 1999–2000

<table>
<thead>
<tr>
<th>Model</th>
<th>PoP</th>
<th>PoD</th>
<th>FAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chu et al. [2001]</td>
<td>80</td>
<td>64</td>
<td>77</td>
</tr>
<tr>
<td>Nie et al. [1998]</td>
<td>78</td>
<td>94</td>
<td>74</td>
</tr>
<tr>
<td>Perreault and Russell [1996]</td>
<td>68</td>
<td>94</td>
<td>40</td>
</tr>
</tbody>
</table>

*Units are percentage.

out black and hatched regions refer to the CRT during which no sheet encounter occurs.

Comparing three magnetopause models in Figure 3, we find that the PRM has more black regions than the SM and CM under the same solar wind conditions. Besides, the periods of successful forecasting for observed sheet encounters are similar for all three models. Thus it is expected that the PRM may have the largest FAT. The HTs for the three models may not be very different one another. This is consistent with the implication in Figure 1d.

The forecasting results of sheet encounters at geosynchronous orbit during 1986–1992 are shown in Tables 3a and 4a. Four quantities of the three models are shown respectively in units of minutes in Tables 3a and 3b. The PRM has the largest HT and FAT as a result of more earthward magnetopause locations predicted by this model, while the CM has the smallest FAT. Table 4a and 4b summarizes the prediction capability of these three models. The definitions of PoP, PoD, and FAR are described in section 4 and calculated from those values in Tables 3a and 3b. It shows that the PoP of the CM (79%) is the highest and that the PoD of the PRM is the highest (97%). The FARs of the CM, SM, and PRM are 69, 78, and 85%, respectively.

5.2. During 1999–2000

Figures 4 and 5 illustrate the observations and predictions of April 6 and September 17, 2000, respectively, which have the
same format as Figure 3. For the April 6 event the upstream values of \( B_x \) and \( D_y \) measured by Wind, which is close to the Sun-Earth line, are used. Since the location of Wind (\( X_{COM} \approx 33 R_E, Y_{COM} \approx -233 R_E \)) is far from the Sun-Earth line on September 19, 2000 the data of Geotail (\( X_{COM} \approx 30 R_E, Y_{COM} \approx -2.5 R_E \)) at the upstream solar wind parameters from Figure 4 predict the most periods of magnetopause inside 6.6 \( R_E \). The associated \( B_x \) and \( D_y \) values when GOES spacecraft are in the magnetosheath during 1999–2000 are plotted as points in Figure 6, in which the contours of \( r_x = 6.6 \) \( R_E \) of the three models are also plotted for comparison. These points are distributed over large ranges of \( B_x \) and \( D_y \). Tables 3 and 4 show the forecasting results of sheet crossings made by geosynchronous satellites during these two years. The PRM has the highest PoD (84%) and FAR (40%), while the CM has the highest PoP (80%) and the lowest FAR (25%). This means the most of the direction of GOES spacecraft in the magnetosheath can be predicted by the PRM but for the warning of sheet crossings the PRM has the least reliability while the CM has the highest. However, considering the PoP, for forecasting GOES spacecraft whether in the magnetosheath or not, the CM has the best prediction.

6. Discussion

[21] The radial distance \( r \) is used to check whether the magnetopause moves inside geosynchronous orbit or not, which is different from the previous [Shue et al., 2000] study using \( r_x \) instead. It is presented that the nose region of the magnetopause is within 6.6 \( R_E \) but the GOES spacecraft still stay in the magnetosheath. For example, during 1600–1800 UT on April 25, 1989, the PRM [Shue et al., 2000] predict the GOES spacecraft should be inside the magnetosheath (see Figure 8 of Shue et al. [2000]), while we predict GOES 6 should be in the magnetosheath, which agrees with observations. Figure 6. The IMF \( B_z \) and dynamic pressure \( D_y \) corresponding to the intervals in 1999–2000 during which GOES resided in the magnetosheath, shown with plus. Also shown are the contours of \( r_x = 6.6 \) \( R_E \) for the PRM, SM, and CM.

Figure 7. The IMF \( B_z \) (dotted curve) and \( B_x \) (solid curve) measured by Geotail during 2010–2300 UT on September 17, 2000.

[22] In this study the PoD and PoP never approach 100% for the SM, PRM, and CM, which is different from the results of Shue et al. [2000]. In their study the PoD is almost 100% for the SM and PRM, namely, all geosynchronous crossings are detected by these two models. This high PoD is due to Shue et al. [2000] defined 20-min or 60-min intervals to separate two crossings. If two crossings are separated by less than 20 (or 60) min, Shue et al. [2000] regard them as one crossing event. When a large separating interval is used, many crossings will be included; thus the probability of detecting the crossings increases, which results in a high PoD. On the other hand, the very low values of PPF (probability of false prediction) of Shue et al. [2000], which means both the PRM and SM can predict crossings and noncrossings successfully, are due to the inclusion of intervals with normal solar wind conditions in their forecast. Consequently, it is difficult to differentiate the superpose of the models during extreme conditions.

[23] In general, the periods of southernward \( B_z \) observed by GOES spacecraft are taken to indicate that GOES is in the magnetosheath, but only those crossings with corresponding southernward IMF \( B_z \) can be found by using magnetic field alone for identification. However, two points in Figure 1c and several points in Figure 6 are found with northward \( B_z \) which are obtained by comparing the variations of \( H_x \) and \( B_z \). For example, southward \( B_z \) lasts a long period before 2217 UT and after 2224 UT on September 17, 2000, as shown in Figure 5, and the GOES 10 is always outside the magnetosphere. However, during 2217–2224 UT the \( B_z \) changes its direction quickly while the GOES 10 is still in the magnetosheath. This implies that the direction of IMF \( B_z \) is reversed in the magnetosheath just outside the magnetopause, especially when the \( B_z \) magnitude is much larger than the \( B_x \) magnitude. Figure 7 shows the IMF \( B_z \) and \( B_x \) measured by Geotail during 2210–2230 UT on this day. The magnitude of \( B_z \) is larger than that of \( B_x \) in most of the interval except during 2217–2224 UT when a reversed \( B_z \) is observed. Therefore we suggest that the points with positive \( B_z \) in Figures 1d and 6 are probably due to the magnetic field orientation when detecting the magnetopause.

[24] For the PRM and CM a small \( D_y \) can push the magnetopause inside 6.6 \( R_E \) as long as the value of \( B_x \) is large enough. The \( r_x \) predicted by SM cannot be less than 6.6 \( R_E \) when \( B_x < -15 \) nT unless a larger dynamic pressure exists on the

![Figure 6](image-url) (6. Discussion)

![Figure 7](image-url) (9. Discussion)
magnetosphere (i.e., $D_p > 7.5$ nT). The distribution of plasmas in the range $B_p < -10$ nT and $D_p < 10$ nT shows in Figure 6 suggests this tendency that the influence of sunward $B_p$ on $D_p$ may approach a critical value when the $-\mathbf{B}$-magnetopause is near the geosynchronous orbit. Moreover, the threshold of the southwest $B_p$ may be a function of $D_p$.

7. Conclusions

(1) A database, the largest one to date, of magnetosheath encountering by geosynchronous satellites during 1986-1992 and 1995-1996 and upstream observations by Wind, IMF, or OGO in the solar wind is compiled for estimating the forecasting capability of PRM, SM, and CM.

(2) Higher PoD and PoF with lower FAR imply a better forecasting model. The tendency of forecasting capability of PRM, SM, and CM is similar for the periods of 1986-1992 and 1995-1999.

(3) The highest PoF of CM means this model can predict well whether the GOES is inside or outside the magnetosphere when the magnetopause’s location is near 6.0 R$_E$. The lowest FAR of CM implies that the other two models are an overprediction for magnetosphere encounters. On the other hand, the PRM has a higher PoD, owing to its more earthward locations of magnetopause under the same solar wind conditions, while the PRM has the highest FAR.

(4) From the distribution of plasmas in the range $B_p < -10$ nT and $D_p < 10$ nT shows in Figure 6, we suspect that the subharmonic magnetopause cannot be closer to the Earth when the southward IMF $B_p$ exceeds a critical value unless a higher $D_p$ exists on the threshold of $B_p$ depends on the value of $D_p$.

(5) From the plasmas with positive $B_p$ in Figure 6, we suspect and confirmed for one case in Figure 7 that the IMF $B_y$ was much larger than IMF $B_z > 0$. That is, the IMF was mostly horizontal, and thus the sheath field draped over the magnetopause could have a negative $B_y$.

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