Dynamic Changes of Magnetopause Locations Under Different Upstream Conditions

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Abstract. Prediction of the magnetopause location in a broad range of upstream parameters can be considered as a test of our understanding of the solar wind–magnetosphere coupling. Present magnetopause models describe the magnetopause location as a function of the solar wind dynamic pressure and IMF BZ component. However, the crossings observed by spacecraft are often far away from the predicted locations and it suggests that other IMF components and/or other factors can be important under particular circumstances. We have found that magnetopause location strongly dependence on the IMF cone angle.

Introduction

The magnetopause is a boundary layer between the geomagnetic field and plasma of the shocked solar wind, which originates at the Sun. It is the location where the planetary magnetic field pressure is balanced by the reduced solar wind pressure. The solar wind dynamic pressure and interplanetary magnetic field (IMF) B Z component control the magnetospheric dynamics and the shape of the magnetopause.

The dynamic pressure is one of the most important parameters which determines the position of the subsolar point and the shape of the magnetosphere. The magnetopause moves inward when the solar wind dynamic pressure increases and moves outward when it decreases. The other important parameter is the IMF B Z component. Its strength and orientation influence the shape of the magnetosphere. One of mechanisms of plasma transfer between the solar wind and magnetosphere which participates in the magnetopause creation is reconnection. Reconnection is the process by which individual field lines lose their links and become reconnected to a new region. When the IMF is southward reconnection which accelerates and heats the plasma in the boundary layers takes place at the subsolar region. Consequently, the subsolar magnetopause moves inward when IMF B Z is southward [Fairfield, 1971]. On the other hand, northward IMF leads to lobe reconnection with a significantly smaller reconnection rate and thus its influence on the magnetopause location is under debate.

Prediction of the magnetopause position is important in magnetospheric physics. Different models of the size and shape of the magnetopause have been suggested [Fairfield, 1971; Formisano et al., 1979; Sibeck et al., 1991; Petrinec and Russell, 1996; Shue et al., 1997; Alexeev et al., 1999; Boardsen et al., 2000; Chao et al., 2002; Lin et al., 2010]. These models use usually a second order surface that is scaled with the solar wind dynamic pressure and IMF B Z.

We have studied the predicted locations of the magnetopause from Petrinec and Russell [1996] and Shue et al. [1997] models. These two models assume a cylindrical symmetry around the aberrated Sun-Earth line and have been obtained by fitting to large sets of the magnetopause crossings. Both Shue et al. [1997] and Petrinec and Russell [1996] suggest that their models are valid over a wide range of upstream parameters and their main difference is the scaling according to the solar wind dynamic pressure (6.6th root vs 6th root).

We have used a large fresh set of magnetopause crossings observed by the fleet of the THEMIS spacecraft with motivation to find the further parameters that control the magnetopause location. The known dependence of magnetopause locations on upstream parameters was taken into account by calculation of differences between observed and predicted by models of Petrinec and Russell [1996] or Shue et al. [1997] locations.
Data set

The study is based on the five-spacecraft THEMIS fleet [Angelopoulos, 2008] that was launched on 17 February 2007 into highly elliptical orbits where the spacecraft will line up at apogee every four days at the beginning of the mission. We have collected crossings in selected regions of the low-latitude magnetopause (subsolar $X_{GSE} > 5$: 5558 events; dusk flank $X_{GSE} < 5$, $Y_{GSE} > 0$: 306 events; dawn flank $X_{GSE} < 5$, $Y_{GSE} < 0$: 785 events) observed in course of the 2007-2008 years and analyzed the deviations of observed magnetopause locations from those predicted by the Shue et al. [1997] and Petrinec and Russell [1996] models. The positions of identified crossings are shown in Fig. 1. The Shue et al. [1997] magnetopause surface calculated for IMF $B_z = 0$ and the solar wind dynamic pressure, $p_{SW} = 2$ nPa is plotted for reference.

Our database of crossings was complemented with corresponding upstream parameters from Wind and ACE spacecraft lagged on the propagation time. The present analysis uses IMF from ACE [Smith et al., 1998] and plasma parameters from Wind [Ogilvie et al., 1995] because such combination provided a best coverage of the crossings with upstream parameters.

We have computed the radial distances of the magnetopause from Earth from Petrinec and Russell [1996] and Shue et al. [1997] models and deviations of observed positions of the magnetopause by THEMIS spacecrafts from these models, $dR = R_{OBS} - R_{MOD}$. Histograms of the differences between observations and predictions of both models, $dR$ reveal (Fig. 2) that their precisions are very similar. Both models predict the magnetopause location on ~ 0.7 – 0.8 $R_E$ closer to the Earth than it is observed and full width at half maximum (FWHM) is rather large, around 2 $R_E$. We will use the Shue et al. [1997] model in further analysis for briefness.

The model is axisymmetric around its X axis, but the magnetopause can be expected to be rotationally symmetric around the solar wind velocity direction. For this reason, we have converted the locations of the magnetopause crossings into aberrated coordinates. We used two ways to aberrate the coordinates. The first is summing the velocity of the Earth’s orbital motion with the $V_Y$ component of the solar wind velocity with respective signs. The second one is to take into consideration the Earth’s orbital motion without taking into account the transversal components of the solar wind velocity. According to the comparison of both ways of aberration, we have concluded that the second method gives better results and thus, we use this approach.

Analysis of the model precision

As we noted, the model [Shue et al., 1997] uses a second order surface that is parametrized with respect to the upstream dynamic pressure and IMF $B_z$ component. The plot of $dR$ as a function of the X-coordinate (Fig. 3) reveals that the model underestimates the magnetopause distance namely for
Figure 2. Distributions of differences between observed and predicted by Petrinec and Russell [1996] and Shue et al. [1997] magnetopause locations in the left and right panels, respectively.

Figure 3. Differences between observed and predicted magnetopause locations vs. the X-coordinate (black: X_{GSE} > 5, grey: X_{GSE} < 5).

X > 10 R_E. Since the magnetopause standoff distance for standard conditions is about 10 R_E, there can be two reasons for this difference: the model surface does not describe the magnetopause shape in the subsolar region and/or the dependence of the subsolar magnetopause location on the dynamic pressure or B_Z should be corrected.

We have analyzed the influence of upstream parameters included in the model, such as the solar wind dynamic pressure, IMF B_Z and some others. Fig. 4 shows the deviations dR as a function of IMF B_Z. The plot does not reveal any systematic dependence of dR on IMF B_Z and we can conclude that the B_Z dependence is probably described rather well by the model.

The deviations dR as a function of the solar wind dynamic pressure p_{SW} are plotted in Fig. 5. Linear fits reveal a systematic dependence of the deviations on the p_{SW}. Generally, the crossings observed under low p_{SW} are nearly 1 R_E farther from the Earth than the model predictions. The reason for this could be that the solar wind dynamic pressure has a stronger influence than 6.6^{th} root, namely because we should note that the Petrinec and Russell [1996] model (with 6^{th} root) gives slightly better results.

Since dR is nearly constant with respect to the solar wind velocity (Fig. 6, left part), its dependence on the dynamic pressure (Fig. 5) is probably connected with the changes of the upstream density.
Suvorova et al. [2010] suggested that the subsolar magnetopause is highly expanded during intervals of radial IMF. We have defined the radial IMF as $|B_x|\sqrt{B_y^2 + B_z^2}$, identified the crossings under this condition, and plotted deviations $dR$ of corresponding crossings as a function of IMF $B_X$. Fig. 6 (right panel) shows that $dR$ is above average for such intervals and that probably even the $B_X$ sign can play a role in the magnetopause formation.

More clearly is this effect shown in Fig. 7 where the deviations $dR$ as a function of the cone angle between the IMF and solar wind velocity vectors are shown for both the subsolar region (left panel) and flanks (right panel) with the parabolic fits to all data in the corresponding panel. Since we have already pointed out the dependence of $dR$ on $p_{SW}$, both sets were divided into two subsets with the breakpoint at $p_{SW} = 1.4$ nPa. We should note that the locations of crossings observed during a radial IMF are in average on about $1 R_E$ farther from the Earth than the crossings observed during periods of the IMF perpendicular to the solar wind velocity in both subsets. This effect could be caused by a less effective transformation of the solar wind dynamic pressure to the pressure imposed onto the magnetopause during intervals of a radial IMF that corresponds to the parallel subsolar bow shock.
Conclusion

Our analysis of Themis observations of the subsolar and flank magnetopause locations under different upstream conditions and comparison of these observations with predictions of the Shue et al. [1997] model revealed that: (1) the model underestimates the magnetopause standoff distance (Fig. 3); (2) the effect is more distinct for low values of the upstream pressure (Fig. 5); (3) the dependence of the magnetopause location on $p_{SW}$ should be corrected (Fig. 5); (4) the magnetopause location is influenced by the IMF cone angle (Fig. 7).

A further study is needed for a better understanding of the magnetopause location and its changes through various upstream and downstream conditions.

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References


