

Themis: Locations of Dayside Bow Shock and Magnetopause

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Abstract. The paper presents a statistical study of bow shock and magnetopause positions in the subsolar region during the years 2007 and 2008 based on observation of five Themis spacecraft. The main attention is paid to a bias caused by a low apogee of the spacecraft which limits distances where bow shock crossings could be recorded. To overcome these problems, we developed a method eliminating this bias and an automatic technique to recognise bow shock and magnetopause positions. A comparison of results obtained by these methods shows a good agreement for low values of the upstream dynamic pressure. Our results suggest that the generally used scaling of the magnetopause and bow shock with the sixth root of the upstream dynamic pressure is a good approximation for a low pressure but that there is a systematic deviation for pressures above 3–4 nPa.

Introduction

The magnetopause is a boundary which originates by an interaction between the solar wind and Earth's magnetic field and its standoff position results from compensation of the solar wind dynamic pressure and Earth's magnetic field strength. Propagation of the solar wind plasma is supersonic and therefore ahead the magnetopause forms a shock wave which we call the bow shock. Predictions of the bow shock and magnetopause locations is a proof of our understanding of processes governing the solar wind–magnetosphere interaction. Models describing locations of these boundaries as a function of upstream parameters are based on a statistical processing of crossings observed by a single spacecraft and (usually distant) solar wind monitor.

In early published papers, it was found that the magnetopause position is mainly influenced by the upstream dynamic pressure and various model based on this assumption have been discussed in *Fairfield* [1971], *Fairfield* [1976], *Formisano et al.* [1979], *Sibeck et al.* [1991], *Petrinec and Russell* [1996], and *Sotirelis and Meng* [1999]. The generally used scaling with sixth root of the solar dynamic pressure is based on assumption of the dipole Earth magnetic field. In the paper of *Shue et al.* [1997], different scaling is used and is explained by a change of a magnetosphere cavity that leads to increase of the magnetosphere's magnetic pressure near the magnetopause. Further, it was also found that the B_Z -component of the interplanetary magnetic field (IMF) changes the position and shape of the magnetopause *Sibeck et al.* [1991], *Petrinec et al.* [1991], *Petrinec and Russell* [1996] and *Shue et al.* [1997], because the IMF B_Z affects reconnection at the magnetopause. Other parameters causing displacement of the magnetopause position are discussed in the papers of *Šafránková et al.* [2002], *Jeřáb et al.* [2005], *Šafránková et al.* [2005], *Měrka et al.* [2003], etc.

The bow shock (BS) is the most studied example of collisionless shocks (e.g., *Fairfield* [1971]; *Formisano et al.* [1973]; *Tsurutani and Stone* [1985]; *Němeček et al.* [1989]; *Burgess* [1995]; *Russell* [1995], and references therein). According to these and many other papers, the bow shock position depends on the magnetopause position and on the magnetosheath thickness which is a function of the magnetosonic Mach number. In the paper of *Russell and Mulligan* [2002], it was shown that also a curvature of the obstacle (ICME) influences the thickness of the magnetosheath.

In spite of prolonged research of the bow shock and magnetopause locations, current em-

pirical models still exhibit a high scatter to experimental data. Large uncertainty is connected with the dynamic response of both boundaries to abrupt changes of upstream and downstream parameters which are usually neglected for simplicity.

In the present study, we deal with a problem how to unify individual data sets from several spacecraft together with elimination of unfavorable conditions as multiple crossings or orbit limitations. We have developed two methods to find the bow shock and magnetopause positions only from the magnetic field magnitude measured by a particular spacecraft and the IMF from the OMNI database.

Determination of bow shock and magnetopause locations from crossings of the boundaries

Data set

We collected magnetopause (MP) and bow shock (BS) crossings observed through period of the 2007 and 2008 years when the Themis spacecraft traversed upstream of the subsolar magnetosphere. Recorded crossings are shown as projections onto the XY plane (in the GSE coordinate system) in Fig. 1 (grey diamonds and black triangles represent bow shock and magnetopause positions, respectively). Although we have identified crossings in a broad range of local times (LT), only those in the range of 1030 – 1330 LT are considered in the present study. The region under study is distinguished by two black dashed lines in Fig. 1. We expect that shapes of both boundaries can be well approximated by spheres in this limited range and thus the location of a particular crossing can be described by a single parameter – the distance from the Earth’s center, R .

During the 2007 year, in the first phase of the mission, Themis spacecraft were very close each other with the apogee of 14.6 Re. This is enough to register properly magnetopause crossings but positions of bow shock crossings are biased by such a low apogee. In the second stage of the mission, after alternation of the spacecraft apogee, only two of them (Themis B and C with apogee of 20 and 30 Re) could record the bow shock and magnetopause under standard

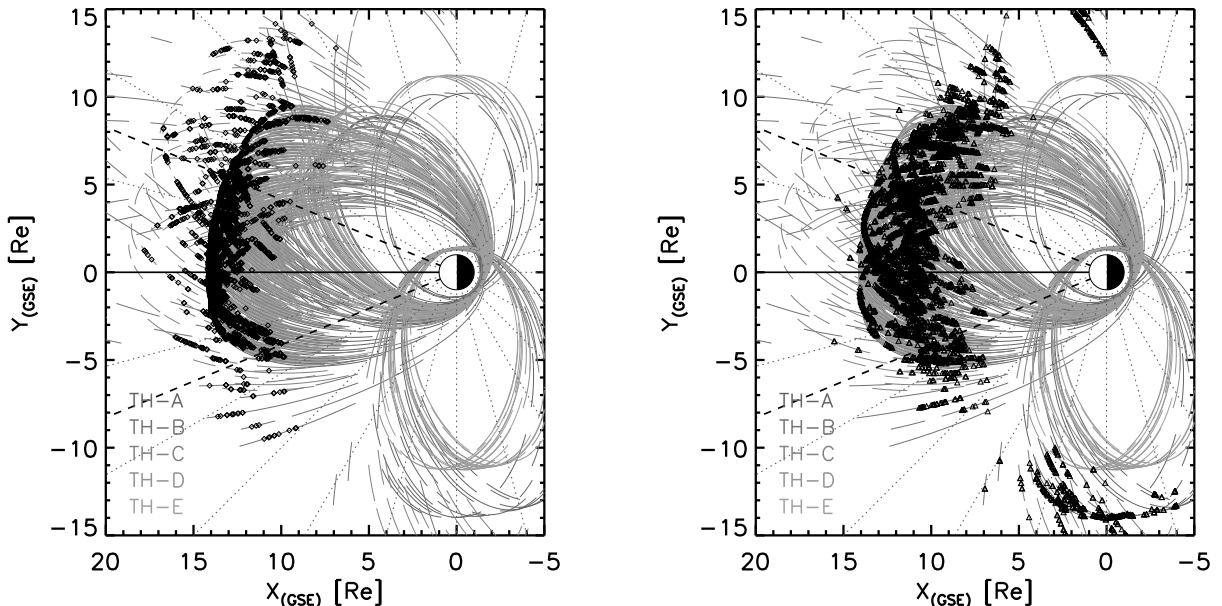


Figure 1. A projection of locations of bow shock (left panel) and magnetopause (right panel) crossings observed by five Themis spacecraft onto the XY plane. The light gray lines represent their trajectories around the time when one spacecraft recorded a particular crossing. The dotted lines show local time. In our study, we focused on the region from 10:30 to 13:30 LT (subsolar region) that is bounded by the thick dashed lines.

upstream conditions. We have identified about 6,660 BS and 5,330 MP crossings as described in the following section.

Bias elimination

We note that the analyzed data were collected during a solar minimum (2007 and 2008) and thus the solar wind dynamic pressure was often well below its average value with the most probable value ≈ 1 nPa. In combination with a low Themis apogee (2007), it represents a bias for bow shock observations. To avoid a misinterpretation of our data, we developed a method which allows us to combine crossings from the 2007 and 2008 years and to suppress bias caused by orbital limitations. Since it is generally accepted that the main parameter controlling the magnetopause (and therefore the bow shock) position is the upstream dynamic pressure, we created $p_{dyn} - R$ histograms of crossings as presented in Fig. 2. We use the OMNI database (http://omniweb.gsfc.nasa.gov/ow_min.html) as a solar wind monitor. In Fig. 2, the gray scale shows the number of observations of bow shock (left) and magnetopause (right) crossings in bins of 0.1 nPa width and 0.1 Re height. Since a majority of crossings was recorded in 2007, one can clearly see a cut-off caused by the Themis apogee, thus this cut-off requires an application of an appropriate data normalization prior to a further analysis. Our normalization is based on following assumptions: (1) All parts of Themis orbits above 8 Re were inspected and all crossings of boundaries were identified, and (2) we used those crossings for which the solar wind data were available. Using solar wind observations according to (2), we construct normalization $p_{dyn} - R$ table from all inspected Themis data. This table is shown in Fig. 3 in the same format as in Fig. 2. The gray scale shows how many minutes the spacecraft spent in a particular bin. The ratio of the number of crossings identified in a particular bin (Fig. 2) and the number of minutes that the spacecraft spent in the same bin (Fig. 3) provides a probability of appearance of the boundary crossings in each bin. The result of this procedure is plotted in two panels of Fig. 4. It can be seen that the bias is almost suppressed (bias cannot be completely suppressed by the presented method because of the bins without any THEMIS data) and it is possible to find mean positions of both boundaries which are shown as the solid lines.

We have to point out that such procedure could be applied on the data used for development of the empirical model of boundaries because a similar bias would exhibit crossings of the spacecraft like Cluster, Prognos series, IMP 8, Hawkey, and others that are often used for this purpose.

This method of normalization is robust and can combine data from the spacecraft with considerable different trajectories, however, it is quite time consuming to identify all crossings by a visual inspection of plots.

Automatic identification of mean locations of boundaries

There were a lot of attempts to develop automated procedures for an identification of bow shock and/or magnetopause crossings. However, the results are not satisfactory because the procedures often produce false crossings and, on the other hand, real crossings are missed. For this reason, we based our procedure on identifications of whole visited regions. This means that we use some parameter (see below) measured by the Themis spacecraft to identify in which region (solar wind, magnetosheath or magnetosphere) the spacecraft is located. Then, it is plotted normalized 2D-histogram (in our case, we use distance from Earth, R and solar wind dynamic pressure p_{dyn} , as coordinates) of occurrence of each region and a border between them represents the bow shock and magnetopause.

Since we are dealing with the subsolar region, we use the magnetic field for an identification of regions. We compute one minute mean value of the ratio between the IMF magnitude from OMNI and the magnetic field measured by the Themis spacecraft ($r_B = |B|_{THEMIS}/|B|_{OMNI}$). Histogram of these ratios (Fig. 5, left panel) exhibits two peaks and a plateau. The first peak with maximum of r_B around 1 can be attributed to the solar wind (r_B is chosen from 0 to

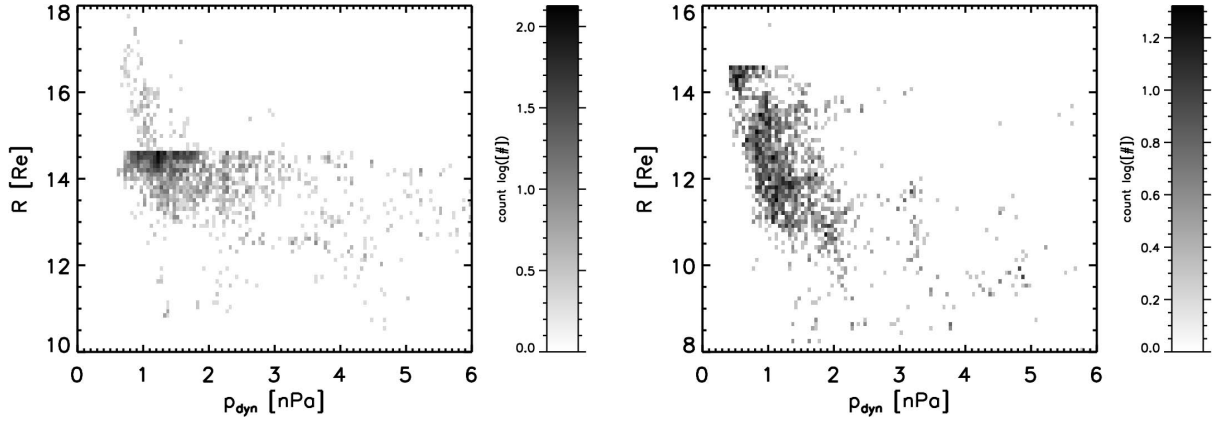


Figure 2. Color coded distribution of bow shock (left panel) and magnetopause (right panel) crossings in the $p_{dyn} - R$ histogram (in all presented histograms, pure white color represents no crossing or no measured data inside intervals).

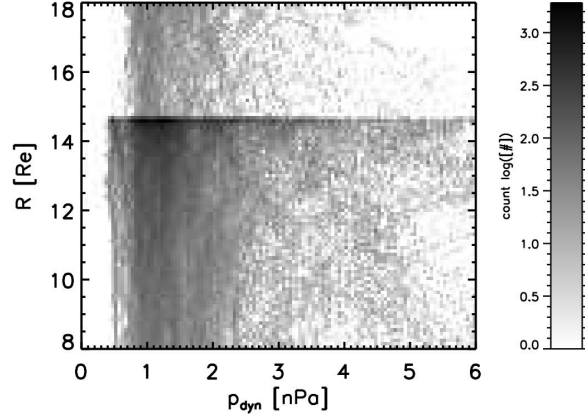


Figure 3. Distribution of one minute intervals in which the Themis spacecraft were located in a particular distance from the Earth and the magnetosphere was under influence of a particular dynamic pressure. Only local times from 10:30 to 13:30 are considered.

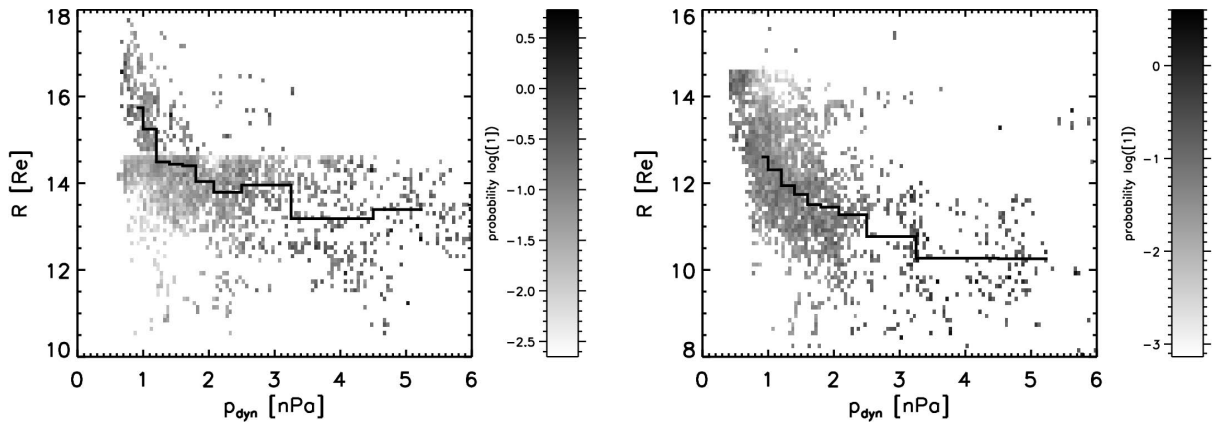


Figure 4. Normalized distribution of bow shock (left) and magnetopause (right) crossings. The solid lines represent mean position of particular boundaries as a function of the dynamic pressure.

1.7), the second peak around 3.8 is recognized as the magnetosheath ($2.3 \leq r_B \leq 6$). The transition between the magnetosheath and magnetopause is not so distinct but it still can be identified (r_B is between 6-8). Furthermore, we eliminated shadowed regions in Fig. 5 that can contain a mixture of two regions. Our procedure provides three tables of times where the satellite was in the solar wind (SW), in the magnetosheath (MSH), in the magnetosphere (MS) and we again build three $p_{dyn} - R$ histograms from each table. These histograms were divided by the normalization $p_{dyn} - R$ table (Fig. 5, right panel). The results for the magnetosheath are shown in Fig. 6. The plot shows a probability that the spacecraft is located in MSH for a particular distance R and dynamic pressure p_{dyn} . Note that the figures for SW and PS are similar and do not provide additional insight to the BS/MP position.

Finally, we can determine bow shock and the magnetopause positions from the MSH observation probability. For this purpose, we applied two methods. First of them uses a threshold of 50% of the probability (shown as solid black lines in Fig. 6) and the second uses a maximum gradient of the probability (dotted lines). As it can be seen from the figure, both methods provide very similar locations of both boundaries.

Comparison of boundary identification methods

In Fig. 6, the gray scale shows a probability of the magnetosheath distribution binned by p_{dyn} and R . The panel is complemented with the bow shock and magnetopause positions as a function of the upstream dynamic pressure. Stepwise functions are from experimental data and smooth functions are two fits with scaling of the dynamic pressure used in magnetopause models (*Petrinec and Russell* [1996] and *Shue et al.* [1997]). It can be seen that all methods provide very similar trends for the dynamic pressure up to 2–3 nPa. As the dynamic pressure increases, the method based on the identification of particular crossings places the boundaries farther from the Earth than the automated method. The reason can be connected with the fact that there is a decreasing number of BS and MP crossings which probably results in a greater error and thus the method based on an identification of crossings starts to be unreliable due to few data points. It is evident that the second automatic method has an advantage in more data points for the enhanced dynamic pressure. We believe that the mean locations of boundaries identified by the automated procedure is more reliable. Nevertheless, this explanation should be confirmed by a analysis of intervals with the enhanced pressure (not during solar minimum).

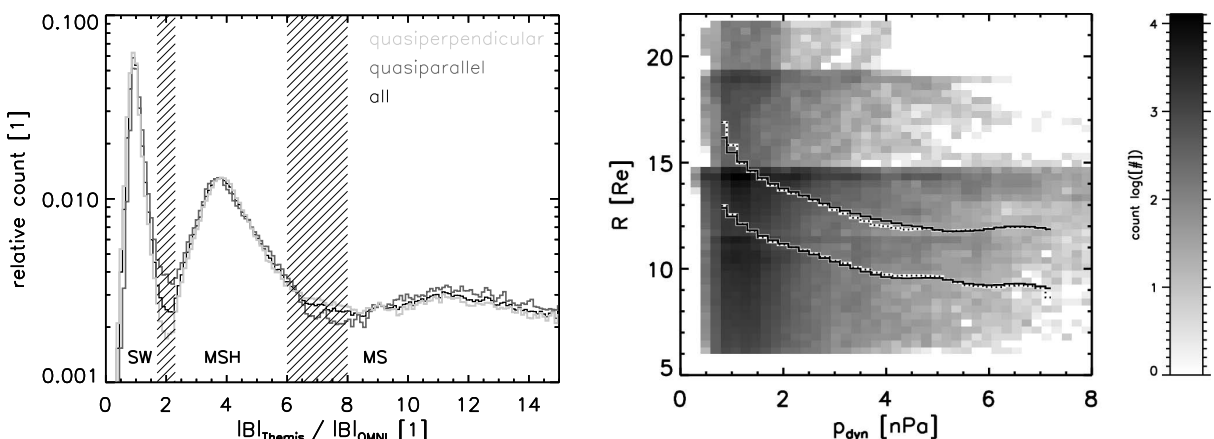


Figure 5. The left panel shows histogram of the $|B|_{Themis}/|B|_{OMNI}$ ratio which was used to distinguish different regions where the Themis spacecraft during orbits were located. The right panel is similar to Fig. 3, however, it represents covering of $p_{dyn} - R$ by all available Themis data during the years of 2007 and 2008 and we do not need information about the bow shock or magnetopause crossings.

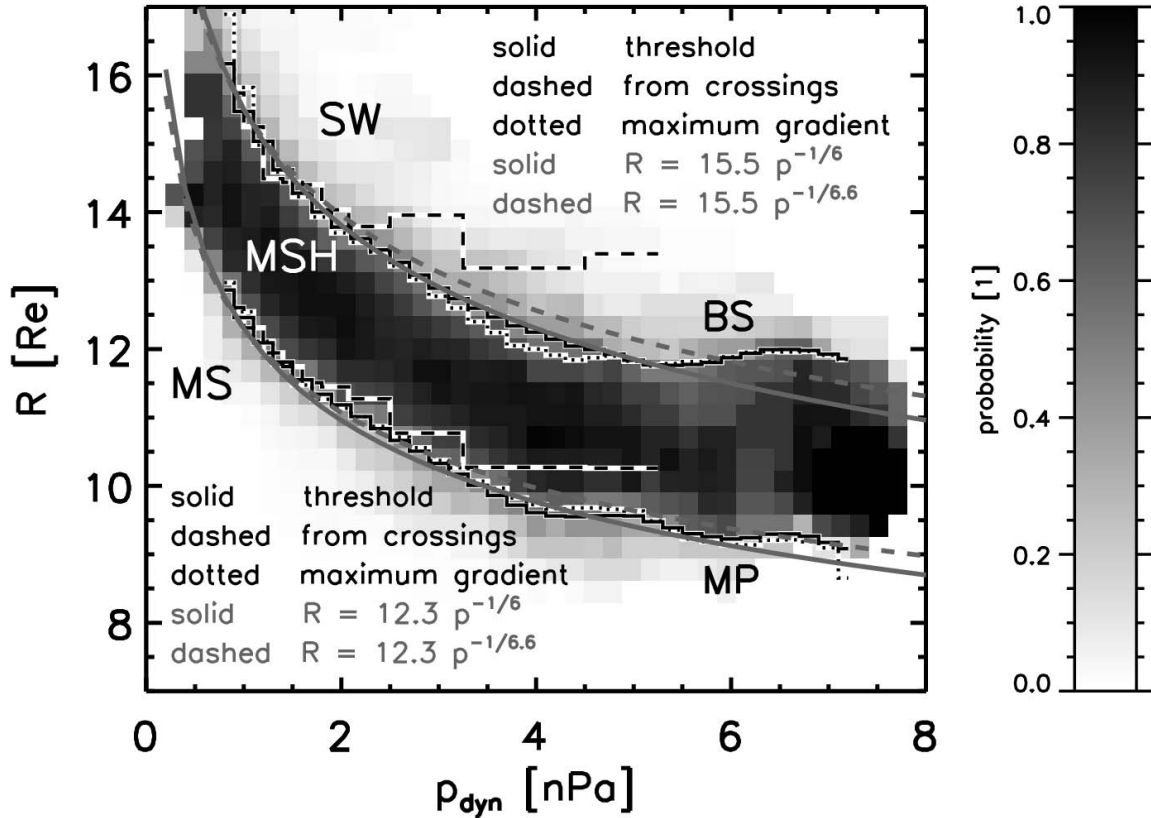


Figure 6. Overview of results obtained from both methods – crossing identification and automated identification of boundaries. See text for detailed descriptions.

Conclusion

We have developed two methods which allow us to combine data from the different spacecraft and which can eliminate bias caused by orbital limitations. We tested both of them in the subsolar region where both boundaries, the bow shock and the magnetopause, can be approximated by spheres. Both techniques use parameters of the solar wind and IMF; we utilize 1-minute data from the OMNI database. We found the automatic method to be more reliable for higher dynamic pressures because more data points were involved in the statistics. Ad absurdum, a whole functional dependence of the bow shock and magnetopause position on the dynamic pressure can be created by spacecraft measurements with only one bow shock and one magnetopause crossing.

A next step of our study will be an analysis of BS and MP positions as a function of other upstream parameters like IMF B_z , magnetosonic Mach number, and inner parameters of the magnetosphere (tilt of the magnetic field, Dst, Kp, and AE indexes). Since the response of the location of boundaries can be non-linear and the investigated parameters are (probably) mutually correlated in a degree, we should perform multidimensional analysis.

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