Local Quasi-Static Response of the Magnetosphere to Magnetosheath Dynamics: A THEMIS Case Study

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Earth's magnetosphere is constantly buffeted by the time-varying solar wind. Previous studies used observations of solar wind dynamic pressure variations to study the dynamic response of the magnetopause and magnetosphere to this buffeting. The THEMIS mission, with its five spacecraft, directly allows, for the first time, to compare measurements in the magnetosheath, the magnetopause boundary region, and the outer magnetosphere. For the time in-

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terval studied, the spacecraft move almost along the stagnation streamline which allows to use Bernoulli's law to relate local observations of the plasma density, temperature, flow velocity, and magnetic field to the stagnation point pressure. Magnetopause distance and velocity are determined assuming a quasi-static response. Magnetopause dynamics inferred in this way is compared with actual observations by three of the THEMIS spacecraft. Furthermore, assuming a moving Chapman-Ferraro current layer allows us to model the outer magnetospheric magnetic field response and to compare it to magnetic field measurements within the magnetosphere. Our study indicates that most of the low-frequency variability of the outer magnetosphere and magnetopause boundary can be understood as the result of a quasi-static response of the magnetosphere to magnetosheath dynamics.

1. Introduction

The magnetopause is the interface between the solar wind plasma and the magnetospheric plasma. Its position is mainly determined by the equilibrium between the magnetic pressure on the magnetospheric side and the total plasma pressure on the magnetosheath side. Neglecting any thermal pressure of the solar wind, the magnetosheath pressure is proportional to the solar wind dynamic pressure. Observations of its variations have been used to predict and explain the dynamic response of the magnetosphere. However, such comparisons are hampered by the fact that only solar wind observations were available while the magnetosphere responds to magnetosheath variations. Interpolations taking into account travel time delays of the solar wind perturbations etc. are necessary to accomplish dynamic response studies [e.g. *Sibeck et al.*, 1989; *Matsuoka et al.*, 1995; *Kepko and Spence*, 2003].

The magnetopause is the interface through which mass, momentum, and energy are transferred from the solar wind into the magnetosphere. Such transfer is accomplished by local magnetic reconnection processes [e.g. *Haerendel et al.*, 1978; *Russell and Elphic*, 1979], changes of the solar wind dynamic pressure, that is constant solar wind buffeting of the magnetosphere and associated compression and relaxation [e.g. *Baumjohann et al.*, 1984; *Sibeck et al.*, 1989; *Kivelson and Southwood*, 1991; *Glassmeier et al.*, 2004], transmission of plasma waves through the magnetopause [e.g. *McKenzie*, 1970; *Verzariu*, 1973], or Kelvin-Helmholtz instability driven mixing at the magnetopause [e.g. *Southwood*, 1968; *Walker*, 1981; *Fujita et al.*, 1996]. Which of these processes is dominant depends on the specific conditions in the magnetosheath, and often different processes are operating at the same time. Discriminating between them and determining the dominant process requires a detailed spatio-temporal analysis of the plasma parameters, that is multi-spacecraft observations are required. Hitherto only the CLUSTER mission [*Escoubet et al.*, 1997] was able to provide such data with suitable analysis tools having been developed to study magnetosheath observations [e.g. *Glassmeier et al.*, 2001; *Dunlop et al.*, 2002].

The five THEMIS spacecraft, launched February 17, 2007 into near-equatorial orbits around Earth, provide for another outstanding opportunity to unravel the statio-temporal structure of magnetospheric processes [*Angelopoulos*, 2008; *Angelopoulos et al.*, 2008; *Sibeck and Angelopoulos*, 2008]. In its early mission phase, the coastal phase, the five spacecraft traversed the dayside magnetopause many times with the spacecraft aligned almost in radial direction. This situation is suitable to study the structure and dynamics of the magnetopause as it allows a direct determination of the magnetopause reaction and magnetospheric response on magnetosheath total and solar wind dynamic pressure variations. Thus, our study is different from previous studies on directly driven solar wind dynamic pressure variations and their magnetospheric response [e.g. *Matsuoka et al.*, 1995; *Kepko and Spence*, 2003] as we are able to compare magnetosheath with magnetosphere observations and do not rely on assumptions such as solar wind travel time delays.

2. Observations

On August 7, 2007, 08:00 - 12:00 the five THEMIS spacecraft are on the inbound lag of their orbit around the Earth. Like pearls on a string they cruise the magnetosheath and the magnetopause before they enter into the magnetosphere (Fig. 1). Spacecraft THEMIS B (ThB) is leading the fleet with ThC, ThD, and ThE following at a distance of about 6 000 km. The separation between these three s/c is about 1 000 km. ThA follows ThB at a distance of about 12 000 km. This configuration is ideal for the study to be performed as one of the s/c is located in the magnetosheath, which dynamic influence on the magnetopause location and the magnetosphere we like to study, three are located right in the magnetopause region, and the fifth one is located just within the magnetosphere.

For our study we use magnetic field measurements made by the THEMIS fluxgate magnetometer experiment [*Auster et al.*, 2008] and the THEMIS plasma instrument [*McFadden et al.*, 2008]. Vector data are represented in GSE-coordinates, that is the X-axis coincides with the direction to the Sun, the Z axis is directed to the ecliptic pole, and the Y axis completes the triad, pointing positive towards dusk. The magnetosheath observations (Fig. 2) show magnetic field fluctuations typical for this region: field direction and magnitude are rapidly changing with amplitudes of a few nT and on time scales of minutes and less. No large scale variations are apparent. The three magnetopause s/c exhibit similar field fluctuations, interrupted by several very distinct magnetic field jumps up to values of 60 nT, indicating repeated entries of the s/c from the magnetosheath into the outer magnetosphere. The final magnetosphere entry occurs at 10:59 UT.

The repeated entries are caused by a rapidly in- and outward moving magnetopause. A distance-time plot allows us to visualize and analyse the situation (see Fig. 3). Spacecraft ThC, ThD, and ThE are successively traversing the magnetopause and tracing its actual position. Using spline interpolation to connect the various crossing the motion of the magnetopause has been reconstructed. Period and amplitude of the magnetopause oscillation at the measuring point near the nose of the magnetopause are of the order of 10 min and 13 000 km, respectively. A constant inward motion with a speed of 21 km/s can be inferred from our multi-spacecraft observations. Maximum inward and outward speeds of 72 km/s and 95 km/s, respectively, are found. As the typical magnetoacoustic phase speed in the outer magnetosphere is of the order of 500 km/s, these observed velocities indicate quasi-static variations of the magnetosphere. The distance-time plot (Fig. 3) also confirms our earlier observation that s/c ThA is always located in the magnetosheath, while s/c ThB is always located in the outer magnetosphere with one exception: at 10:35 UT the magnetopause retreats beyond the position of ThB.

3. Magnetopause motion

Having available observations from the magnetosheath, the magnetopause region, and the magnetosphere enables one to compare the actually observed magnetopause variation with theoretically expected modifications. As shown in Fig. 1 the THEMIS s/c are almost moving along the stagnation stream line in the magnetosheath. We thus restrict our considerations to the stagnation streamline. At the stagnation point the position of the magnetopause is determined by the balance between the stagnation pressure in the magnetosheath, p_{stag}, and the magnetospheric magnetic field pressure, $B^2_{mag}/2\mu_0$ [e.g. *Kuznetsova and Pudovkin*, 1978]:

$$p_{stag} = \frac{B^2_{mag}}{2\mu_0} = \kappa \rho_{sw} v^2_{sw}. \qquad (1)$$

The stagnation pressure is proportional to the solar wind dynamic pressure with ρ_{sw} and v_{sw} denoting the solar wind mass density and velocity, respectively; κ is a factor of proportionality and depends on the character of the interaction of the solar wind particles with the magnetopause [*Spreiter et al.*, 1966]. The stagnation pressure can be determined applying Bernoulli's law to the magnetosheath stagnation flow:

$$\frac{1}{2}\rho_{sh}v_{sh,x}^2 + p_{th} + \frac{B_{sh}^2}{2\mu_0} = p_{stag}. \tag{2}$$

Here p_{th}, B_{sh}, and ρ_{sh} denote the thermal pressure of the magnetosheath, its magnetic field strength, and the mass density, respectively; $v_{sh,x}$ is the component of the sheath flow vector along the stagnation stream line.

With $B_{mag} = 2\ B_{eq}/R_{MP}^3$, where $B_{eq} = 29,9557$ nT is the present strength of the equatorial geomagnetic field and R_{MP} the magnetopause distance, we have:

$$R_{MP} = (\frac{2\ B_{eq}^2}{\mu_0 p_{stag}})^{1/6}, \tag{3}$$

with R_{MP} given in units of R_E. Assuming quasi-static variations of the magnetopause position equation (3) also defines the magnetopause velocity v_{MP} [*Matsuoka et al.*, 1995]:

$$v_{MP} = \frac{dR_{MP}}{dt} = -\frac{R_{MP}}{6\ p_{stag}} \cdot \frac{dp_{stag}}{dt}. \tag{4}$$

With plasma and magnetic field observations from the ThA s/c and equations (3) and (4) we determine the magnetopause position and velocity. As above relations are only valid in the quasi-static approximation we use 2-minute averaged plasma and field data.

The results of our attempt to determine the magnetospheric response to the magnetosheath pressure variations are displayed in Fig. 4. The total pressure shows variations with a period of about 5-7 minutes and amplitude 1 nPa. The pressure is dominated by the thermal pressure with magnetic and kinetic contributions playing a minor role. Associated magnetopause excursions are of the order of 1 R_E. This compares well with those inferred from magnetic field observations of the ThC, ThD, and ThE s/c. The magnetopause velocity is of the order of 50 km/s, which in excellent agreement with our measurements and confirms our quasi-static approach. Furthermore, the theoretical magnetopause position agrees well with the observations. Between 09:47 and 10:01 UT s/c ThB should be back to the magnetosheath according to our model; and indeed the magnetic field observations confirm this. Only the excursion back to the sheath at around 10:35 UT is not predicted. Comparing both, modelled and observed magnetopause motion, indicates an about 40 s time delay caused by s/c ThA being located about 10 000 km away from the magnetopause. Any pressure perturbation observed by ThA needs to be convected with the sheath flow towards the magnetosphere. As the observed velocity along the stagnation line is of the order of 180 km/s a delay time of 55 s is expected, which is in accord with the observations.

4. Magnetospheric magnetic field

To estimate the magnetic field in the outer magnetosphere we use the model suggested by *Choe and Beard* [1974]. The subsolar region magnetic field contribution from the Chapman-Ferraro currents is given as

$$B_{CF,\theta}(r) = \frac{20075}{R_{MP}^3} + \frac{20835}{R_{MP}^4} \cdot r, \tag{5}$$

where both, r, the radial distance and R_{MP} are given in units of $R_E = 6,371$km; the field is given in nT and positive for a northward pointing component. To this surface current generated magnetic field we add the dipole component of the current IGRF field [*IAGA*, 2005]. For each estimated value of the magnetopause distance the corresponding surface current magnetic field has been determined as a function of time. As the Choe-Beard model is based on the 1965 IGRF a systematic error is introduced, which we regard as insignificant for the current calculations, an assumption which is also confirmed by the results of *Matsuoka et al.* [1995] using the same approach. The field is calculated along the trajectory of s/c ThB for the time interval August 7, 2007, 09:30-11:45 UT and is displayed in Fig. 4. Visual comparison with the actually measured field already gives a very good agreement. The modelled value of the field agrees well with the measured one, and all major temporal variations of the field magnitude are reproduced by the Choe-Beard model used. Of course, at around 09:55 UT and 10:35 UT the model fails as the s/c is moving back to the magnetosheath.

A formal cross correlation analysis for the time interval 10:37-11:42 UT gives one a linear correlation coefficient of 0.76, which indicates that most variations of the magnetic field are well explained by magnetosheath pressure variations as estimated with our model. Modelled variations lead the measured ones by 45 s, a time shift consistent with the modelled field being based on pressure observations made at a distance about 10 000 km away from the point where the actual magnetic field measurements were made. This time shift is also consistent with the above discussed delay been the modelled magnetopause motion and the observed one.

The residual magnetic field (Fig. 5), that is the difference between high-resolution measured magnetic field observations and the modelled field, exhibits that this difference is dominated by higher frequency contributions which are due to faster, non quasi-static magnetopause motions, or are the result of magnetosheath waves, or other dynamic processes in the magnetopause boundary region.

5. Conclusions

Using plasma and magnetic field observations, made by the five THEMIS s/c along the stagnation stream line of the magnetosheath flow around the magnetosphere we have been able to explain most of the magnetopause and magnetic field variations in the outer magnetosphere by assuming quasi-static perturbations of the magnetopause position. These perturbations were due to variations of the stagnation pressure determined from the total plasma pressure measurements made by THEMIS and application of Bernoulli's law. Though a case study, our results support the hypothesis that most long-period magnetic field variations of the dayside magnetosphere are just quasi-static responses to pressure induced magnetopause motions.

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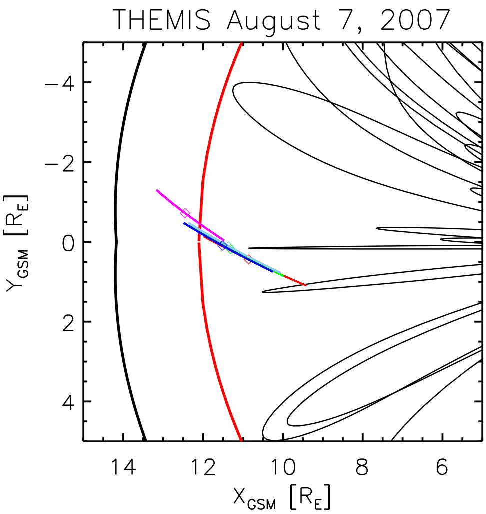

Figure 1. Like pearls on a string: the five THEMIS spacecraft on August 7, 2007, 08:00 - 11:00. The different colors denote the different spacecraft: THEMIS A (ThA)-magenta, ThB-red, ThC-green, ThD-ciel, ThE-blue. The square denotes s/c position at 09:30 UT. The black lines are magnetic field lines based on a Tsyganenko-96 model. Bow shock (black) and magnetopause (red) are also indicated.

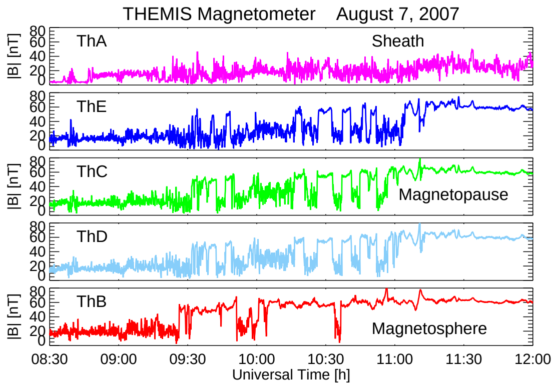

Figure 2. Magnetic field observations of the five THEMIS spacecraft in the interval August 7, 2007, 08:30-12:00 UT.

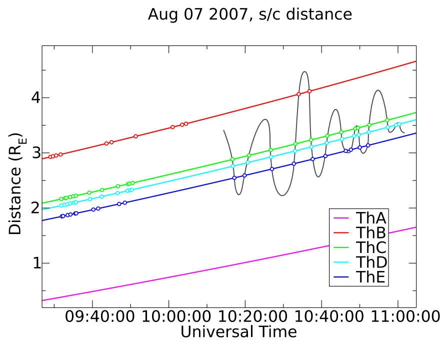

Figure 3. Distance-time-plot visualizing the s/c positions during the time interval August 7, 2007, 09:30-11:15 UT. Distances along the s/c trajectory are given with respect to the position of ThA at 9:00 UT. The larger the distance the closer the s/c is to Earth; ThA is the trailing s/c that remains in the magnetosheath throughout this interval. Colored full circles denote identified magnetopause crossings. The connecting line indicates the inferred magnetopause motion.

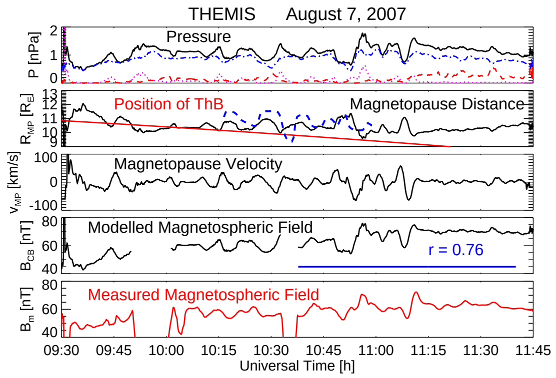

Figure 4. Measured magnetosheath pressure, theoretical magnetopause distance, quasi-static magnetopause velocity, theoretical magnetospheric magnetic field, and measured magnetospheric magnetic field. Total pressure (black line) as well as thermal (blue dashed-dotted line), kinetic (red dashed line), and magnetic pressure (magenta dotted line) are displayed. The solid red line in the second panel from above gives the distance of the ThB s/c. Also shown is the magnetopause motion (blue dashed line) as inferred from using ThC, ThD, and ThE observations. The magnetic field has been determined using the Choe-Beard model; see the text for further details.

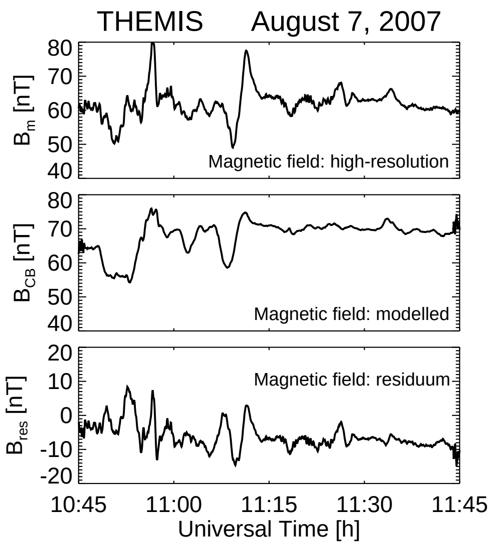

Figure 5. A detailed comparison between the high-resolution, measured magnetic field and the modelled magnetic field.