SOLAR WIND PRESSURE AND THE POSITION OF THE MAGNETOPAUSE: A CLUSTER PERSPECTIVE

Johan De Keyser[1], M. Roth[1], M. W. Dunlop[2], H. Rème[3], C. J. Owen[4], and G. Paschmann[5]

[1]*Belgian Institute for Space Aeronomy, Brussels, Belgium*
[2]*Rutherford Appleton Laboratory, UK*
[3]*CESR, Toulouse, France*
[4]*Mullard Space Science Laboratory, UK*
[5]*International Space Science Institute, Berne, Switzerland*

ABSTRACT

Applying empirical reconstruction techniques to Cluster data allows to determine the varying position of the magnetospheric boundary continuously for time intervals of several hours. It has therefore become possible to examine the influence of solar wind pressure on the position of the magnetospheric boundary in more detail. In particular, one can examine the continuous correlation between solar wind pressure and the position and motion of the boundary during such a long time interval, rather than correlating discrete values of solar wind pressure and boundary location that correspond to individual magnetopause traversals, as has been done in the past. We discuss an event study to highlight the degree of solar wind ram pressure control over the magnetopause position.

Key words: Cluster; solar wind-magnetosphere interaction; magnetopause; ram pressure.

1. INTRODUCTION

This contribution focuses on the solar wind – magnetosphere interaction. The magnetosphere constitutes a deformable obstacle for the supersonic solar wind, which leads to the formation of a bow shock upstream, behind which the magnetosheath plasma is forced to flow around the magnetosphere. The interface between the magnetosheath and the magnetosphere is the magnetospheric boundary, which was already detected in the early days of space exploration [1]; later on [see, e.g., 2–5] it was found to consist of both the magnetopause (MP, the transition between interplanetary and terrestrial magnetic field) and a plasma boundary layer (BL, inward of the MP, not always present).

The MP/BL forms where the solar wind pressure balances the geomagnetic pressure: Higher (lower) ram pressure forces the boundary inward (outward) until it equals the higher (lower) pressure of the dipolar geomagnetic field there. Because solar wind ram pressure is variable, the MP/BL position continuously changes in an attempt to re-establish the dynamical equilibrium. Total pressure changes of only a few percent cause the MP/BL to move in- or outward over a few 1000 km; extreme compressions/decompressions of the magnetosphere correspond to inward/outward displacements of several Earth radii. The MP/BL speed may be several tens to hundreds of km/s, larger than the typical speed of the observing spacecraft. As a consequence, a spacecraft usually has multiple encounters with the MP/BL during each pass, as the MP/BL moves back and forth rapidly across the spacecraft. The oscillatory boundary motion thus produces strongly time-varying observations.

With data from a single spacecraft, it is hard to find out whether the observed variability is due to boundary motion or to intrinsic temporal changes of the boundary. ESA/Cluster provides simultaneous four-point in situ measurements as it passes through the MP/BL region. Such a plethora of data can help to resolve this issue. In the present paper, we will focus on an *empirical reconstruction method*, which puts the multi-point information together to create a coherent picture of MP/BL structure and to separate out the effect of MP/BL motion. We will use this method to demonstrate continuous solar wind ram pressure control over the MP/BL position.

2. EMPIRICAL RECONSTRUCTION METHODS

The principle behind empirical reconstruction is straightforward. It is assumed that the MP/BL structure does not change during the time interval under consideration, so that the observed time variability is only due to the time-dependent convection of the MP/BL across the space-

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craft. Empirical reconstruction amounts to identifying the location at which each observation is made in a reference frame that moves together with the MP/BL. The outcome of such methods consists of (1) the position of the MP/BL as it changes with time, and (2) the spatial structure of the MP/BL.

Let $\vec{x}$ be the average outward normal direction. If one assumes that the MP/BL moves along $\vec{x}$ with a speed $v_{\mathrm{mpbl}}(t)$ as a planar incompressible slab, the x component of the plasma velocity, measured in situ, would be identical to the boundary velocity: $v_x = v_{\mathrm{mpbl}}$. Integration over time then gives the position $x_{\mathrm{mpbl}}(t)$ of the MP/BL:

$$x_{\mathrm{mpbl}}(t) = \int_{t'=t_0}^{t} v_{\mathrm{mpbl}}(t')dt' + x_{\mathrm{mpbl}}(t_0)$$

where t_0 is an arbitrarily chosen reference time. This idea goes back to [6]. Although the principle is simple, a number of difficulties prohibit a straightforward implementation, such as the need to intercalibrate observations made by different spacecraft, the limited precision and time resolution of plasma velocity measurements, data gaps, and so on. Moreover, as one integrates an oscillating function, the result quickly becomes meaningless as errors accumulate.

In recent years, empirical reconstruction methods have matured [7–8]. We will use here the optimization-based technique discussed in [9], which is able to overcome many of the difficulties associated with the straightforward integration of v_x. The basic idea is to consider v_x only as a *proxy* for v_{mpbl}. One then attempts to determine a model boundary position profile $x_{\mathrm{mpbl}}(t)$ and the 1-D spatial profiles $f^l(x)$ of a selected set of "guiding variables" by simultaneously minimizing the weighted sum of

- the deviation between the measured proxy $v_x(t_i)$ (possibly measured by several spacecraft) and a model boundary velocity profile $v_{\mathrm{mpbl}}(t_i)$, and
- the deviation between the measurements $f^l(t_i)$ and the values $f^l(x_{\mathrm{sc}}(t_i) - x_{\mathrm{mpbl}}(t_i))$ that follow from the spatial model profiles evaluated at the distance of the spacecraft making the measurements from the MP/BL (again, several spacecraft may be involved).

It may be necessary to impose certain smoothness conditions on the $v_{\mathrm{mpbl}}(t)$ and $f^l(x)$ profiles to regularize the problem. The whole procedure ultimately leads to a nonlinear least-squares optimization problem, which can be solved with an appropriate minimization technique, although often at the expense of some computational resources [for more details, see 9]. With such an empirical reconstruction technique, it has become possible to track the motion of the MP/BL for as long as several hours, throughout an entire in- or outward pass of the four Cluster spacecraft, including multiple complete and/or partial traversals of the boundary.

3. CASE STUDY: APRIL 23, 2001

As an example, we consider the Cluster inbound MP/BL pass on April 23, 2001. The top panel in figure 1 shows the electron density n_e from the PEACE electron spectrometer. For the sake of clarity, the plot shows only data from C1, as the four spacecraft measure very similar profiles. Note that we have first intercalibrated the data from the four spacecraft. The second panel gives B_z from FGM, showing that the spacecraft crossed a high magnetic shear magnetopause around 14:25 UT. We have computed a reconstruction for this case, with a time resolution of 30 s, using the intercalibrated n_e data as the guiding variables, and taking $v_{x,\perp}$ from CIS/HIA on C1 and C3 as a proxy for the boundary speed. The third panel in figure 1 plots the given $v_{x,\perp}$ as well as the v_{mpbl} obtained from the reconstruction. Both are fairly well in agreement, except in the magnetosheath, where obviously the measured $v_{x,\perp}$ is not a good approximation for the motion of the boundary. The fourth panel gives the spacecraft trajectories and the reconstructed position x_{mpbl} of the boundary as a function of time (up to an arbitrary additive constant). Clearly, the reconstruction explains the transients, such as the density increase around 16:30 UT, as a temporary inward incursion of the MP/BL, leading to the observation of boundary layer plasma and even a partial dip into the magnetopause current layer. The last panel gives the solar wind ram pressure obtained by the SWE experiment on Wind, which was located about 41 R_E dawnward from the Earth; the data were time shifted over -2600 s. There is an obvious anti-correlation between the reconstructed boundary position and the ram pressure; this correlation is made explicit in figure 2. Figure 3 shows the spatial profiles for n_e and B_z that result from the reconstruction. Note that the reconstruction was based on n_e data only; nevertheless, the boundary position computed from that also orders the B_z (and other data as well), confirming the interpretation that the data can be understood as being due solely to motion of a one-dimensional boundary structure across the spacecraft during the pass.

4. CONCLUSIONS

The anti-correlation between solar wind ram pressure and reconstructed boundary position is obvious, in spite of the large spatial distance between Wind and Cluster. This implies that, at least for this particular boundary pass, the position of the MP/BL is controlled very well by the solar wind ram pressure, with Figure 2 giving the transfer function, in spite of the fact that the solar wind-magnetosphere interaction is a complicated system and in general cannot be described by the total pressure balance condition alone. Indeed, if the boundary would be subject to the Kelvin-Helmholtz instability for example [10], no such correlation would be expected. Note also that the detailed and deterministic correlation found here is conceptually different from the statistical correlations between solar wind conditions and discrete magnetopause posi-

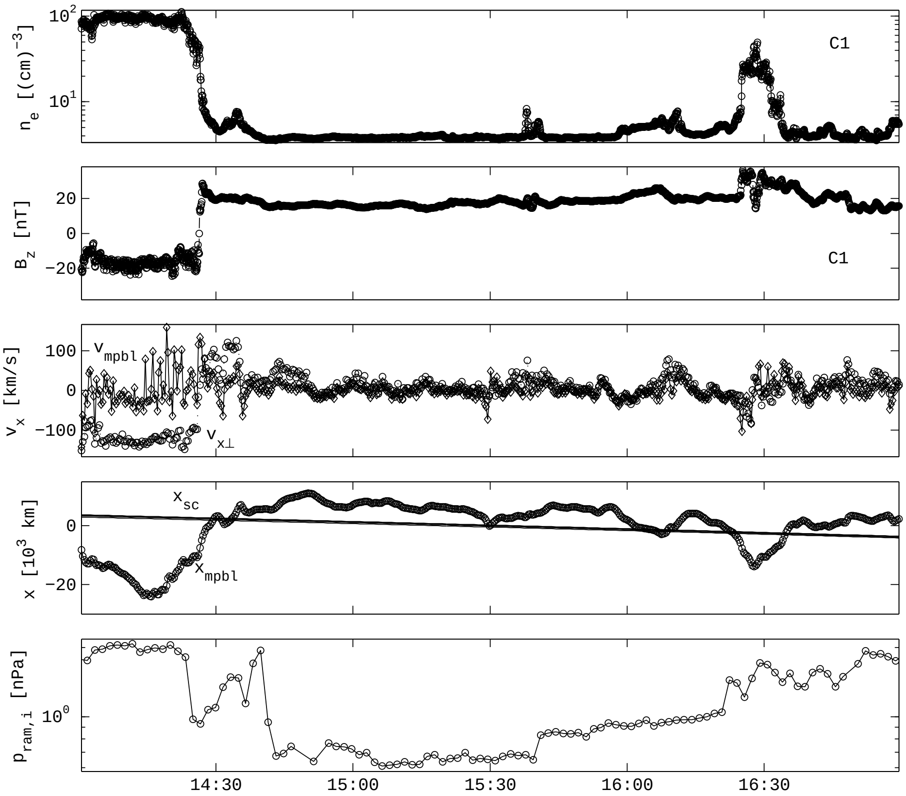

Figure 1. Reconstruction for a Cluster MP/BL pass on April 23, 2001. From top to bottom: (a) Time profile of electron density n_e from PEACE (for the sake of clarity only shown for C1; at this scale, the four spacecraft see essentially the same profile); (b) magnetic field B_z (the maximum variance component) from FGM (again for C1 only); (c) The $v_{x\perp}$ profile obtained by merging the data from CIS/HIA on C1 and C3, resampled at 30 s resolution, as well as the reconstructed boundary velocity $v_{\rm mpbl}$; (d) Trajectories of C1–C4 (almost coincident) and the time-dependent position $x_{\rm mpbl}$ of the boundary; (e) The solar wind ram pressure from Wind/SWE, time shifted over -2600 s.

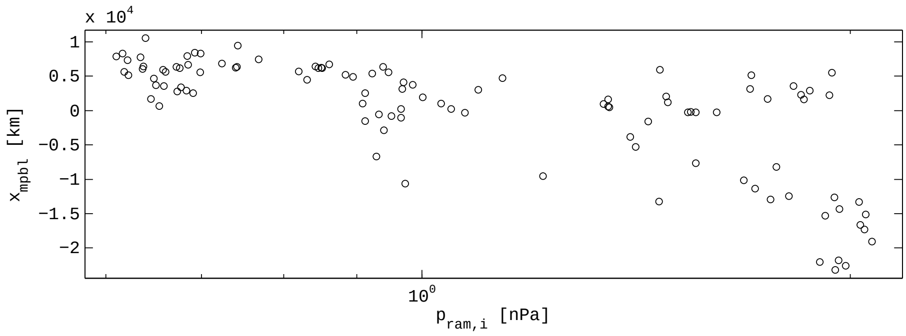

Figure 2. Anti-correlation between the time-shifted solar wind ram pressure and magnetopause position.

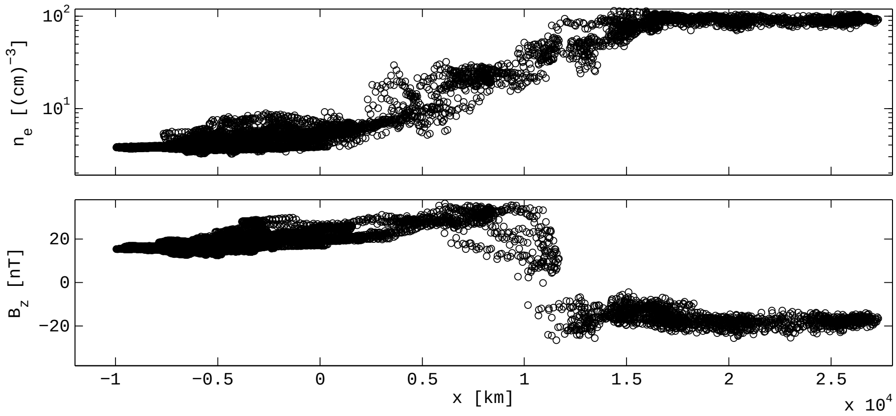

Figure 3. Spatial profiles of n_e and B_z that result from reconstruction; the data points correspond to the data from the four spacecraft. The magnetosphere is to the left, the magnetosheath to the right. While n_e changes fairly monotonously across the boundary layer, B_z behaves non-monotonously.

tions obtained from the identification of individual MP crossings, which have led to empirical determinations of the average shape of the magnetospheric boundary.

The Cluster mission, presently the flagship European magnetospheric research endeavour, has contributed to our being able to assess such a correlation by providing a plethora of data with which an accurate continuous-time reconstruction of the magnetospheric boundary position can be computed. Establishing such a correlation is important for understanding magnetospheric physics, but it also is relevant from the point of view of prediction of the behavior of the magnetospheric boundary in the context of space weather.

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