The Earth’s Magnetosphere Plasma Boundaries

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Abstract

In the present work, the interactions between two systems - the solar wind and the magnetosphere - are investigated. The basic background needed for the understanding of the magnetosphere physics is reviewed, together with a presentation of the instruments available for space observations of magnetosphere boundaries dynamic. Three different days of observations were analysed and the measurements were made by two complementary experimental techniques, including the preliminary results of the four CLUSTER spacecraft, and satellite monitoring of the interplanetary magnetic field (IMF) and solar wind. It comes out that the location, motion and shape of the magnetosphere boundaries appear to be in a constant state of flux, and that its small-scale plasma structures seem to be quite different from theoretical model predictions. Thus, further studies will be needed to understand magnetospheric dynamics, in order to be able to predict the perturbations generated by solar activity on our planet’s environment.

Key words : Magnetospheric physics (magnetopause, boundary layers, solar-wind – magnetosphere interactions) • Interplanetary physics (interplanetary magnetic fields) • Instrumentation (CLUSTER II)
Nous présentons, dans le cadre de cette étude, les interactions entre deux systèmes, le vent solaire et la magnétosphère. Nous rappelons les concepts de base qui permettent de comprendre les phénomènes physiques rencontrés dans la magnétosphère, et nous présentons également les instruments disponibles pour l’observation depuis l’espace de la dynamique des frontières de la magnétosphère. Trois différentes journées d’observation ont été analysées en utilisant les données de deux instruments complémentaires : nous avons pu utiliser les premiers résultats des quatre satellites de la mission CLUSTER, et les données d’un satellite sondant le champ magnétique interplanétaire (IMF) et le vent solaire. Au terme de cette étude, il apparaît que la position, le mouvement et la forme des frontières de la magnétosphère semblent être dans un état constamment fluctuant, et que les plasmas rencontrés ont des structures qui s’éloignent des prédictions des modèles théoriques à petite échelle. Ainsi, une étude plus approfondie sera nécessaire pour comprendre la dynamique de la magnétosphère, ceci dans le but de pouvoir prédire les perturbations générées par l’activité solaire sur l’environnement de notre planète.

Mots clés : Physique de la Magnétosphère (magnétopause, couches frontières, vent solaire – interactions avec la magnétosphère) • Physique du milieu interplanétaire (Champs magnétiques interplanétaires) • Instrumentation (CLUSTER II)
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I really wish to be working with all of you again during my thesis.

CETP, June 2001, F. CULOT.
Introduction

The buffeting of the magnetosphere by the solar wind and the interactions between magnetospheric and near-Earth solar wind plasma is the cause of many phenomena in the magnetosphere and the ionosphere, and affects the way in which we observe many other features.

For many years, scientists have tried to understand the physical phenomena involved in the transfer of plasma from the solar wind into the magnetosphere and down to the ionosphere. To improve our knowledge of this drag or transfer of momentum through the magnetosphere boundary, it was necessary to reach a global comprehension of the dynamical magnetospheric processes.

Although the global view of the magnetosphere is now quite well known, many questions remain concerning the microphysics that governs those transfer of energy from the solar wind to the Earth’s magnetosphere and from the magnetosphere to the ionosphere. One major unknown in this Sun-Earth system concerns the size and shape of the small-scale plasma structures and their role in the transfer of energy. ESA’s CLUSTER, with four spacecraft travelling together through the magnetosphere, is the first mission to study these plasma structures in three dimensions.

In this paper, we concentrate on the study of the magnetopause crossings observed by those four CLUSTER spacecraft, which is discussed in Part 3.

First of all, a brief presentation of the studied medium is given in Part 1, followed by a description of the instruments (Part 2).
1 Presentation of the studied medium

1.1 The Solar Wind

The quiet sun does not only radiate electromagnetic waves in the frequency range from a few nanometers to a few hundred meters, but also particles. This stream of particles is called the solar wind (Parker, 1963).

More precisely, the solar wind is a flow of ionized particles and a remnant of the solar magnetic field that pervades interplanetary space. It is a result of the huge difference in gas pressure between the solar corona and interstellar space. This pressure difference drives the plasma outward, despite the restraining influence of solar gravity.

Furthermore, because of the heating, compression, and subsequent expansion, the solar wind becomes supersonic above several solar radii. Due to this supersonic nature of the solar wind, shock waves are formed upstream of the planets.

As the solar wind expands to the interplanetary space, its density decays with distance \( R \), as \( 1/R^2 \). At \( R = 1 \text{ AU} \), i.e. at the distance of the Earth, the density is \( \sim 5 \text{ cm}^{-3} \) on average. It consists largely of ionized hydrogen (or of protons and electrons in nearly equal numbers), with a small (5 percent by number) admixture of ionized helium and still fewer ions of heavier elements. The solar wind owns substantial kinetic pressure (a few nPa) because of its high speed, which is \( \sim 400 \text{ km.s}^{-1} \) on average. Some of the physical properties of the plasma and magnetic field at a distance of one astronomical unit from the sun are summerized in Table 1.
<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton density</td>
<td>6.6 cm$^{-3}$</td>
</tr>
<tr>
<td>Electron density</td>
<td>7.1 cm$^{-3}$</td>
</tr>
<tr>
<td>He$^{2+}$ density</td>
<td>0.25 cm$^{-3}$</td>
</tr>
<tr>
<td>Flow speed (nearly radial)</td>
<td>450 km.s$^{-1}$</td>
</tr>
<tr>
<td>Proton temperature</td>
<td>$1.2 \times 10^5$ K</td>
</tr>
<tr>
<td>Electron temperature</td>
<td>$1.4 \times 10^5$ K</td>
</tr>
<tr>
<td>Magnetic field (induction)</td>
<td>$7 \times 10^{-9}$ tesla (T)</td>
</tr>
</tbody>
</table>

Table 1: Observed Properties of the Solar Wind near the Orbit of the Earth (From Kivelson & Russel), 1995

1.2 The Magnetosphere

The planets, their moons, and the comets are immersed in the magnetized solar wind. With magnetized bodies such as Mercury, Jupiter, Earth, Saturn, Uranus, and Neptune, the interaction includes large-scale currents that can confine the planetary magnetic field. A major magnetic structure called a magnetosphere is formed around each of these bodies. The terrestrial magnetosphere results from this interaction of the interplanetary medium with the planet Earth, and its atmospheric and magnetic environment.

The Earth’s magnetic field can be described by a dipole with its axis slightly titled relative to the rotation axis. In the magnetosphere, the dipolar model mainly holds with a very good approximation for the inner regions within about 10 Earth’s radii ($R_e \approx 6375$ km). Beyond, the solar wind influence contributes to compress it on the dayside and to stretch it along the nightside tail.

The dynamic of the terrestrial magnetosphere is controlled by the Earth’s magnetic field so that the magnetosphere can be divided into several regions which are created by the topology of this magnetic field. The outer boundary of the magnetosphere is called the magnetopause. The distance from the magnetopause to the Earth is only about 10 terrestrial radii at the dayside subsolar point, whereas the tail extends to more than 100 terrestrial radii on the nightside. The region between the bow shock and the magnetopause is called the magnetosheath.

We now understand that the magnetic field lines of the Earth can be divided into two parts according to their location on the sunward or tailward side of the planet. Between these two parts on both hemispheres are funnel-shaped areas called
the polar cusps (the term cleft is often used in dayside morphology studies). The high-altitude cusp, or the exterior cusp, can be considered to be part of the magnetospheric boundary layer system. The exterior cusp is a region of hot magnetosheath plasma connected to the low altitude cusp, defined as the dayside region in which the entry of magnetosheath plasma to low latitude is most direct.

The topology of the dayside magnetosphere with its boundary layers is shown in Figure 2, together with a few other magnetosphere regions, including the central plasma sheath (CPS) and boundary plasma sheath (BPS).

Table 2 summarizes typical values of some parameters in those different magnetospheric regions, and Table 3 introduces the energy range for the magnetosphere electrons found in previous studies measurements.
Magnetosheath

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Magnetosheath</th>
<th>Plasma Sheet</th>
<th>Lobe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (cm$^{-3}$)</td>
<td>2-50</td>
<td>0.1-1.0</td>
<td>$10^{-3}$ to $10^{-2}$</td>
</tr>
<tr>
<td>Electron velocity (km.s$^{-1}$)</td>
<td>200-500</td>
<td>10-50</td>
<td>no reported measurement</td>
</tr>
<tr>
<td>Proton velocity (km.s$^{-1}$)</td>
<td>200-500</td>
<td>10-50</td>
<td>no reported measurement</td>
</tr>
<tr>
<td>Electron temp. ($^\circ$K)</td>
<td>$10^5$ to $10^6$</td>
<td>$2 \times 10^6$ to $2 \times 10^7$</td>
<td>$&lt;10^6$</td>
</tr>
<tr>
<td>Proton temp. ($^\circ$K)</td>
<td>$5 \times 10^5$ to $5 \times 10^6$</td>
<td>$6 \times 10^6$ to $10^8$</td>
<td>$&lt;10^7$</td>
</tr>
<tr>
<td>Magn. field (nT)</td>
<td>2-15</td>
<td>9 in deep tail</td>
<td>increases in north IMF</td>
</tr>
</tbody>
</table>

Table 2: Typical parameters of plasmas in the magnetosphere

<table>
<thead>
<tr>
<th>electrons energy</th>
<th>Magnetosheath</th>
<th>Magnetopause</th>
<th>Cusp</th>
<th>LLBL</th>
<th>Magnetosphere</th>
</tr>
</thead>
<tbody>
<tr>
<td>E&gt;10 eV</td>
<td></td>
<td></td>
<td>E&gt;100 eV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E&lt;100 eV</td>
<td>~ 200 eV</td>
<td>&lt;3000 eV</td>
<td>E&gt;a few keV</td>
<td></td>
<td>~1 keV</td>
</tr>
</tbody>
</table>

Table 3: Energy range of the electrons in different magnetosphere regions
1.3 The Magnetopause

The magnetopause is the thin plasma layer that separates the solar wind magnetic field from the Earth’s magnetic field. It is the locus where the plasma pressure of the solar wind is in equilibrium with the magnetic pressure inside the magnetosphere. Due to a continuous variation of the solar wind pressure, this boundary moves continuously.

1.3.1 Magnetopause location

In a very simplified approach, considering that there is no magnetic field in the solar wind, that the solar wind pressure is everywhere perpendicular to the magnetopause, and considering the magnetosphere as a vacuum, Paschmann (1991) explains that the magnetopause is determined from pressure balance:

\[ p_{MS} + \frac{B_{MS}^2}{2\mu_0} = p_M + \frac{B_M^2}{2\mu_0} \]

where \( p \) is the thermal plasma pressure and \( \frac{B^2}{2\mu_0} \) is the pressure of magnetic field with strength \( B \). The subscripts MS and M refer to the magnetosheath and magnetosphere sides of the magnetopause, respectively. The plasma pressure is related to its density \( n \) and temperature \( T \) via \( p = n k T \), where \( k \) is the Boltzmann constant.

One can obtain a simple estimate of the subsolar distance of the magnetopause by observing that this is a stagnation point in the solar wind flow where all its ram pressure has been converted into thermal pressure. Ignoring the magnetic pressure from the interplanetary magnetic field as well as assuming the magnetosphere to be a vacuum, expression (1) reduces to

\[ \rho_{SW} v_{SW}^2 = \frac{B_M^2}{2\mu_0} \]

where \( \rho_{SW} \) and \( v_{SW} \) are the mass density and speed of the solar wind, respectively. Noting that for a dipole magnetic field \( B_M \) should fall off with geocentric radial distance, \( R \), as \( R^{-3} \), one obtains for the stagnation point distance

\[ R_S \sim M^{1/3} \left( \rho_{SW} v_{SW}^2 \right)^{-1/6} \]

where \( M \) is the Earth’s dipole moment.

This usual one sixth power law has been used again in a more recent study
from Khan and Cowley (1999), based on the Roelof and Sibeck model (Roelof and Sibeck, 1993) which is described in next section. This study gives a parametrisation of the subsolar magnetopause position $R_{MP}$, valid for a typical dynamic pressure of 2 nPa, which is correct for our purposes. Thus, we are now able to estimate the magnetopause subsolar point position with the following formula:

$$R_{MP} = \frac{12.1}{p(nPa)^{1/6}} = \frac{111}{[n(cm^{-3})V^2(km.s^{-1})]^{1/6}}R_E$$

(4)

1.3.2 Magnetopause shape

The solar wind dynamic and thermal pressures and the interplanetary magnetic field control the shape and location of the Earth’s magnetopause. The well-known Roelof and Sibeck empirical magnetopause model (Roelof and Sibeck, 1993) is based on the largest statistics of magnetopause crossings (1821) by high-apogee satellites during 1967-1986. It points out that when the IMF $B_z$ turns southward, the dayside magnetopause moves inward to restore pressure balance and the magnetotail moves outward. It is also shown that the magnetopause moves inward when the solar wind dynamic pressure $p$ increases and outwards when it decreases.

This model is the first attempt to describe the magnetopause shape as a bivariate function of $p$ and $B_z$. Unfortunately, the effective range of the Roelof-Sibeck model is limited because it does not cover extreme values of either the pressure and $B_z$ component (the input data being limited to $p < 8$ nPa ; $|B_z| < 7$ nT).

An alternative to this model is the one by Kuznetsov and Suvorova (1998), which uses larger statistics and wider effective range of model parameters, due to geosynchronous satellite magnetopause crossings added to the basic data on high-apogee crossing. They suggest the following analytical semi-empirical approximation by a paraboloid of revolution with shift $\rho_0 = y_0$ towards the dusk side:

$$x = X_0 - g(\rho - \rho_0)^2$$

$$X_{01} = 8.6 \cdot \left(1 + 0.407 \cdot exp\left(-\frac{(|B_z| - B_z)^2}{200p^{0.15}}\right)\right) \cdot p^{-0.19}$$

$$g = \left(0.48 - 0.0018(|B_z| - B_z)\right) / X_0$$

$$\rho_0 \leq 0.66/1R_E \quad \text{for} \quad X_0 \sim 6.6 \ R_E, B_z > 0$$

$$\rho_0 \approx 2 \ R_E \quad \text{for} \quad X_0 \sim 6.6 \ R_E, B_z < -6 \ nT$$

12
where $\rho^2 = y^2 + z^2$ and $x, y, z$ are the solar-ecliptic coordinates of the magnetopause position. The $x$ axis directs from the center of geomagnetic dipole to the sun, the $z$ axis is perpendicular to the ecliptic equator and the $y$ axis is a right-hand coordinate system. $X_0$ is a standoff distance of the magnetopause and $X_{01}$ is the standoff distance for the nose part of the parabola, which means that $\theta$, the angle between directions to the Sun and to the point of magnetopause from dipole’s center, is inferior or equal to $40^\circ$.

Caution must be taken regarding to those results because the magnetosphere is quite frequently in an oscillating mode, and thus a certain dispersion in the experimental data is associated with this.

1.3.3 Magnetopause structure

From the study of satellite observations of slow crossings of the magnetopause, which allow the spatial variations in the plasma to be clearly resolved, we have access to the structure of this region. Some of those studies clearly identify three different layers composing the magnetopause: a sheath transition layer, an outer boundary layer and an inner boundary layer.

Song et al. (1990) describe those layers as follows:

- The Sheath Transition Layer: this region, the thickness of which is about 500 to 1300 km, is the layer in which the sheath plasma decreases in density and the magnetic field increases so that the total pressure is constant. This layer carries the current associated with the increase in field strength upon entering the magnetosphere. At the inner edge of the transition layer the magnetic field has nearly reached the magnetosphere value, but the particles still consist entirely of magnetosheath particles. In other words, the transition from an IMF configuration to a near geomagnetic field configuration occurs totally within the magnetosheath plasma.

- The Outer and Inner Boundary Layers: in the outer boundary layer, the ion density drops significantly from the transition layer level with little increase in the temperature. In the inner boundary layer, a further density drop accompanies a large increase in the temperature.
1.3.4 Magnetopause Transfer Processes

Almost anywhere near the surface of the magnetopause, the Earth’s magnetic field is tangential to the magnetopause, acting like a natural barrier to the solar wind particles. We have seen that there are only two regions, one in each hemisphere, where the magnetic field is approximately perpendicular to the magnetopause, namely the polar cusps, allowing a more direct entry of solar wind particles into the magnetosphere.

Although to first order, the magnetopause is considered as an impenetrable boundary, some plasma from the solar wind can enter the magnetosphere. Various processes have been proposed to account for this penetration of plasma:

- reconnection between the interplanetary magnetic field and the Earth’s magnetic field, which is likely to occur while the IMF points southward
- viscous interaction
- impulsive penetration where plasma filaments which have a higher momentum than the surrounding solar wind plasma hit and possibly penetrate through the magnetosphere
- transient processes

All these mechanisms have been proposed to explain the penetration of solar wind plasma into the magnetosphere, but there is still no consensus on which plays the major role. Nevertheless, we will now linger over the transient processes in order to understand the phenomena seen on the data recorded on February 14th, 2001, which we will study in part 4.

As we will see, what once had been thought to be multiple crossings of the magnetopause could be in fact something quite different, the possible formation of magnetic ropes on the boundary. Those reconnections of single flux tubes were first studied by Russell and Elphic (1978) who called them Flux Transfer Events (FTEs). The concept put forward by Russell and Elphic was that an isolated tube of newly opened magnetic flux containing a mixture of magnetosphere and magnetosheath plasma was dragged over the magnetopause, giving the model of FTEs demonstrated by Figure 3. This Figure illustrates how the flux tube, in moving relative to the ambient medium, causes the ambient magnetic field to drape around
Figure 3: Qualitative sketch of a flux transfer event (from Russell and Elphic, 1979)
the tube (magnetosheath field lines, slanted arrows, have connected with magnetospheric field lines, vertical arrows). The flux tube itself is also twisted as a result of currents $j$ flowing along it.

Subsequent studies showed that these events occur predominantly during southward IMF, with a mean repetition period of about 8 min. In order to recognize those events on CLUSTER’s magnetometers data, we will use Paschmann et al. (1982) work, in which they showed that the following features appear to be invariant characteristics of FTEs:

1. A southward pointing magnetosheath magnetic field (negative $B_L$ in $L,M,N$ boundary normal coordinate system, where $N$ is the estimated outward normal to the magnetopause, $L$ lies in the boundary and points north, and $M$ also lies in the boundary and points west, orthogonal to $L$ and $N$ such that $L,M,N$ form a right-handed coordinate system)

2. A 'bipolar' variation of $B_N$, consisting of a positive pulse followed by a negative pulse: if one imagines the flux tube moving upward across the spacecraft, the magnetometer will first record an outward (positive) and later an inward (negative) deflection of the field, which produces the bipolar signature in the normal component

3. An enhancement in the magnetic field strength $B$, often to substantially larger values than those observed in the adjacent magnetosphere

4. An imbalance of $p + B^2/8\pi$, the sum of magnetic and plasma pressures, measured inside and outside the events

5. The appearance of a particle population representative of the opposite side of the magnetopause; that is, both magnetosheath and magnetosphere particles are observed in FTEs

Despite the fact that transient process models are able to reproduce a number of these observed features, it is fair to say that the theoretical understanding of non-steady small-scale reconnection is only at a beginning.
2 Instrumentation

During my training, I mainly worked on the first sets of data given by the four CLUSTER spacecraft, representing the time period from January to April 2001. I had also the opportunity to combine these observations with data from one other spacecraft : the Advanced Composition Explorer (ACE).

Each of the instruments on board the CLUSTER spacecraft provides valuable information on certain aspects of the magnetosphere, but the paper demonstrates that taken together, the different experiments complement each other to give a consistent and comprehensive picture of the magnetospheric physics.

2.1 CLUSTER II

CLUSTER is one of the two missions - the other being the Solar and Heliospheric Observatory (SOHO) - constituting the Solar Terrestrial Science Programme (STSP), the first ‘Cornerstone’ of ESA’s Horizon 2000 programme. SOHO was launched in December 1995, and CLUSTER’s launch was scheduled for June 1996 on the first Ariane-5 flight, but the rocket exploded with the four CLUSTER spacecraft on board. After extensive discussion on the future of the mission (for details, see Escoubet et al., 1997), it had been decided to launch four identical spacecraft (called Rumba, Salsa, Samba and Tango) in summer 2000 : CLUSTER II was born! Each Cluster spacecraft is cylindrical with a diameter of 2.9 m and a height of 1.3 m. The total mass of each spacecraft is 1200 kg, 72 kg for the 11 experiments, 478 kg for the spacecraft dry mass and 650 kg for the propellant.

The main goal of the CLUSTER mission is to study the small-scale plasma structures in space and time in the key plasma regions :

- solar wind and bow shock,
- magnetopause,
- polar cusp,
- magnetotail,
- auroral zone.

The orbital parameters of the four spacecraft will be slightly different to obtain a tetrahedral configuration in the regions of scientific interest, allowing a 3-D mapping
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Instrument</th>
<th>Principal investigator</th>
</tr>
</thead>
<tbody>
<tr>
<td>FGM</td>
<td>Fluxgate magnetometer</td>
<td>A. Balogh (IC, U.K.)</td>
</tr>
<tr>
<td>STAFF</td>
<td>Spatio-temporal analysis of Field fluctuation experiment</td>
<td>N. Cornilleau-Wehrlin (CETP, France)</td>
</tr>
<tr>
<td>EFW</td>
<td>Electric field and wave experiment</td>
<td>G. Gustafsson (IRFU, Sweden)</td>
</tr>
<tr>
<td>WHISPER</td>
<td>Waves of high frequency and sounder for probing of electron density by relaxation</td>
<td>P.M.E. Décréau (LPCE, France)</td>
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<td>WBD</td>
<td>Wide band data</td>
<td>D.A. Gurnett (Iowa U., U.S.A.)</td>
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<td>Digital wave processing experiment</td>
<td>H. Alleyne (Scheffield U., U.K.)</td>
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<td>EDI</td>
<td>Electron drift instrument</td>
<td>G. Paschmann (MPE, Germany)</td>
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<td>ASPOC</td>
<td>Active spacecraft potential Control</td>
<td>W. Riedler (IWF, Austria)</td>
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<tr>
<td>CIS</td>
<td>Cluster Ion spectrometry</td>
<td>H. Rème (CESR, France)</td>
</tr>
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<td>PEACE</td>
<td>Plasma electron and current Experiment</td>
<td>A. N. Fazakerley (MSSL, U.K.)</td>
</tr>
<tr>
<td>RAPID</td>
<td>Research with adaptative particle Imaging detectors</td>
<td>B. Wilken (MPA, Germany)</td>
</tr>
</tbody>
</table>

Table 4: Instruments on CLUSTER

of those regions.

The four CLUSTER spacecraft are identical and each contain 11 instruments, giving a total of 44 instruments built by the Principal Investigators (Table 4).

All those instruments will allow, during this two-year mission, to measure with very high accuracy the electric and magnetic field, the ion and electron distribution function and the electromagnetic waves, in order to study in three dimensions the small-scale plasma structures in the near-Earth environment.
2.2 ACE

The Advanced Composition Explorer (ACE) is an Explorer mission that was managed by the Office of Space Science Mission and Payload Development Division of the National Aeronautics and Space Administration (NASA). The ACE spacecraft carrying six high-resolution sensors and three monitoring instruments samples low-energy particles of solar origin and high-energy galactic particles. ACE orbits the L1 libration point which is a point of Earth-Sun gravitational equilibrium about 1.5 million km from Earth and 148.5 million km from the Sun. With a semi-major axis of approximately 200,000 km the elliptical orbit affords ACE a prime view of the Sun and the galactic regions beyond.
3 Observations : March 17th 2001, A straight crossing of the magnetopause

3.1 Introduction

In this part, we chose to expose a set of data, obtained on March, 17th 2001, which is particularly favourable to the study of a magnetopause crossing by the CLUSTER spacecraft, with relatively calm conditions regarding to the IMF and solar wind parameters, and thus a straight and easily identifiable crossing. This study will allow us to introduce a reference frame and to get used to the first CLUSTER II sets of data.

3.2 CLUSTER data

In order to put back the recorded data in their context, the orbit of the reference spacecraft (#3 : Samba) is shown in Figure 4 in the GSE frame of reference : the X-axis is pointing from the Earth towards the Sun, the X-axis and the Y-axis are include in the ecliptic plane with the Y-axis pointing toward the dusk, opposing to the planetary motion, and the Z-axis is parallel to the ecliptic pole. Thus, we have three panels, one for each plane (X-Y plane on the upper left corner, X-Z on the upper right, and Y-Z on the lower left corner), with two paraboloïds representing the bow shock for the one on the left, and the magnetopause for the one on the right. This representation allows us to say that the four CLUSTER spacecraft shall have crossed the magnetopause before 12:00.

We focused on the electron signatures available with the PEACE instrument, which measures on board the four spacecraft the electron fluxes in the energy range from 0.59 eV to 26.4 keV (see Johnstone et al., 1997). This energy range is divided into two sets of data because the recording is handled by two different sensors. Thus are presented two panels for each spacecraft : one for the low-energy range centered around 100 eV, and the second one for the high-energy range, centered around $10^3$ eV. Those data are shown on Figure 5, with the flux per time unit represented by a colour code on the right side of each panel (from $2 \times 10^2$ to $10^6$ counts per second). The time interval represented on those figures is from 09:00 to 09:40, a period of great interest during which we see a sharp transition in the electron energies.

A first quicklook at those data allows us to notice two very different kinds of
Figure 4: CLUSTER Orbit on 17 March 2001
Figure 5: CLUSTER spectrogram recorded by the PEACE instrument on 17 March 2001
electron populations. The first one is composed of electrons having relatively high energies \((2 \times 10^2 \text{ eV} < E < 10 \text{ keV})\). The second population is composed of electrons of weaker energies (mainly between 10 and 100 eV) but higher density. Those populations can be identified from previous studies measurements (see Table 3) as being magnetosheath electrons for the cold and dense population, whereas the hot population with energies centered around 1 keV represents magnetosphere electrons. In fact, in the magnetosheath the electrons have slightly larger energies than in the solar wind (in table 1 we indicated an electron temperature of \(1.4 \times 10^5 \text{ K}\), which represents an energy of \(\sim 10 \text{ eV}\)), whereas in the magnetosphere, those particles are accelerated along the magnetic field lines and acquire a higher energy. Between those two populations, we can see a sharp transition representing the magnetopause.

This is confirmed by another experiment on board CLUSTER II, which measures the ion fluxes in the vicinity of the Earth’s magnetosphere: the Cluster Ion Spectrometry (CIS) experiment (see Rème et al., 1997). On Figure 6 are represented the data recorded by CIS on 17th March 2001, showing the ion distributions for spacecraft 1 and 3, obtained by two different instruments: the HIA (Hot Ion Analyser) experiment and the CODIF (Ion Composition and Distribution Function Analyser) experiment. The major difference between those two instruments is that CODIF allows to differentiate the ion species (H\(^+\), He\(^{++}\), He\(^+\) and O\(^+\)) for more detailed solar wind studies. The three panels at the bottom of the figure indicates the density, the velocity and the temperature deduced from the HIA ion distribution. The ion signatures seen on this figure show the same characteristics as the electrons signatures seen on PEACE data: an energetic magnetosphere population \((E\) centered around 10 keV) and a more dense magnetosheath population with energy values centered around 200 eV. Again the magnetopause crossing appears as a sharp transition between both.

The magnetopause crossing well identified on the particle data, has also electromagnetic signatures. In order to characterize those signatures, we look at the magnetic field recorded by the Flux-Gate Magnetometer (FGM) and its fluctuations by the Spatio-Temporal Analysis of Field Fluctuations (STAFF) experiment (see Cornilleau-Wehrlin N. et al., 1997). The FGM data are represented on Figure 7 with a 4 second sampling (see Balogh et al., 1997). Each panel represents one component of the magnetic field in GSE coordinates and each spacecraft is identified by a referenced colour (Rumba=blue, Salsa=red, Samba=green, Tango=black).

Those FGM data also show a rapid magnetopause transition: before 09:20 we
Figure 6: Ion distribution recorded by the CIS instrument on 17 March 2001
Figure 7: Three components of the FGM magnetic field in GSE coordinates on 17 March 2001 (Rumba=blue, Salsa=red, Samba=green, Tango=black)
can see the Earth’s dipole magnetic field with its relatively flat components, and then a sudden increase in all the field components indicate the magnetopause crossing between 09:21 and 09:22. Once in the magnetosheath, the field became more variable and fluctuating, as expected. This rotation of the magnetic field and the increase in the magnitude is a typical signature of a magnetopause crossing.

The fluctuations seen just after the magnetopause crossing on the FGM data encourages us to look at the STAFF experiment data which are represented on Figure 8. The four panels on the top of the figure are spectrograms (one for each spacecraft) representing the magnetic fluctuations of $B_z$ in GSE below 12 Hz.

The previous studies of these regions have shown that the behavior of the low frequency waves changes radically at the crossing: the level of turbulence is low in the magnetosphere, high in the magnetosheath and even higher right on the magnetopause (Rezeau et al., 1989). Thus, remembering the crossed regions identified on the PEACE and CIS data, we clearly see on those STAFF data that the spacecraft are located in the magnetosphere before 09:20 and they cross the magnetopause around that time to enter the magnetosheath. Furthermore, as on the FGM data, we can notice a higher level of turbulence just after having encountered the magnetopause and lasting for about five minutes, from 09:21 to 09:26. Looking back to the particle data, we can indeed see higher energies and density on the PEACE data from 09:21 to 09:27 and at the same time, more important fluctuations on the density and the velocity recorded by CIS, turning back to a less turbulent state after 09:27. This disturbed boundary layer found in the outer side of the magnetopause is due to the turbulent motion of the particles coming across the boundary.

We now concentrate on the few minutes corresponding to the magnetopause crossing and we will focus on the variations of the different particle moments recorded by the PEACE experiment on board Tango: density, velocity and temperature. All those parameters are shown on Figure 9.

With those particle moments recorded by PEACE we find back the signatures seen on Figure 5, with high temperatures, low densities in the magnetosphere, and a reversal of those values in the magnetosheath. On the temperature panel, we first see a negative gradient between 09:20:26 and 09:21:16 and then a dramatic decrease in a time shorter than the instrument resolution (4 seconds). Looking at the top panel, we notice a gradient with a density raising by a factor 20 in about 20 seconds. The panel showing the velocity is very helpful for the identification of the boundary, because we can clearly see the sharp increase in the electron speed due to the
Figure 8: Colour Spectrogram of the STAFF data on 17 March 2001
Figure 9: Density, velocity, temperature recorded by PEACE (spacecraft #4) on 17 March 2001
currents $j$ flowing along the magnetopause.

The high-resolution of the PEACE instrument allows us to determine the thickness of the magnetopause. From the observation of Figures 7 and 9, we can say that the magnetopause crossing lasts for about 25 seconds (plus or minus 4 seconds due to the experiment resolution), from 09:21:16 to 09:21:41.

If we try to deduce the magnetopause thickness from the multiplication of those 25 seconds elapsed during the crossing of the boundary by the spacecraft radial speed (for example $v_x = 2.13 \text{ km.s}^{-1}$ for Samba at that time), we find a thickness of about 50 km.

In order to test the valuability of this result, we calculate the ions Larmor radius in the magnetosheath and in the magnetosphere, which is given by:

$$\rho_L = \frac{mv_{\perp}}{qB} = \frac{\sqrt{2mE}}{qB}$$

From the CIS and FGM data, $E$ and $B$ will respectively be taken equal to 200 eV ($3.2 \times 10^{-17} \text{ J}$) and 17 nT in the magnetosheath. Those values lead to a Larmor radius of about 120 km (for comparison, we calculated a Larmor radius of about 760 km in the magnetosphere, taking 10 keV for the ions energy and 19 nT for the magnetic field magnitude).

However, Russell (1990) and Kivelson (1995) explain that typically the thickness of the magnetopause is equivalent to many thermal ion gyro radii, and thus our result implies that the magnetopause thickness calculated previously is not plausible. This inconsistent value proves that there is an additional process that must be taken in account. The first assumption is the eventual motion of the magnetopause that could have come in the direction of the spacecraft during the crossing of the boundary. Thus we need to estimate the speed of this magnetopause motion in order to evaluate its thickness.

### 3.3 Magnetopause thickness

The distance between the four spacecraft and the time difference between their respective magnetopause crossing will allow us to estimate this speed and thus, the boundary thickness.

In order to obtain this difference, let us redraw the Bz component of the magnetic
field recorded by the four CLUSTER spacecraft during the time interval from 09:20 to 09:23 (Figure 11). We measured a difference of about 4 to 8 seconds between all the satellites which is approximately the time resolution of the instrument. The evaluation is thus unprecise and we chose the two most distant spacecraft (see Figure 10), Samba and Tango. We find a time difference of (8 ± 4) seconds. Assuming that the magnetopause thickness is nearly radial at this latitude (see Figure 12), we calculate the distance between Samba and Tango in GSE coordinates and find $R_3 - R_4 \approx 450\text{km}$.

Those values for the distance between spacecraft and the time spent by the magnetopause to travel from one to the other leads to the following magnetopause velocity: $37\text{km.s}^{-1} < v_{MP} < 112\text{km.s}^{-1}$.

The range of velocity values is quite large due to the fact that the spacecraft are not very distant and that we have a four seconds resolution on the data, which is of course not enough when the measured time is about 8 seconds! Moreover, only the lower edge of the velocity range seems to be realistic, according to the range of values currently met in the literature for the boundary velocity (it is quite variable, but most of the time between about 3 to over 40 km.s$^{-1}$). Nevertheless, those values allows us to estimate the magnetopause thickness, in multiplying it by the time elapsed in the magnetopause crossing (25 ± 4 seconds) and in adding the component due to the radial spacecraft speed (taken equal to 2 km.s$^{-1}$).

<table>
<thead>
<tr>
<th>Magnetopause velocity</th>
<th>Distance covered by the magnetopause</th>
<th>Distance covered by the spacecraft</th>
<th>Magnetopause thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>37 km/s</td>
<td>925±148 km</td>
<td>50 km</td>
<td>975±148 km</td>
</tr>
<tr>
<td>112 km/s</td>
<td>2800±448 km</td>
<td>50 km</td>
<td>2850±448 km</td>
</tr>
</tbody>
</table>

Once again, only the lower values are realistic and close to the typical range found for the magnetopause thickness (between 400 and 1000 km, with values reaching exceptionally 1800 km), and regarding to the relatively low values of the solar wind pressure and speed, it is not astonishing to have it expended and reaching the upper values of its thickness.

Relying on this value of 37 km.s$^{-1}$ for the magnetopause velocity, we can also estimate the thickness of the boundary layer encountered just after the magnetopause.
Figure 10: Sketch showing CLUSTER II spacecraft location in the GSE x-z plane on the 17 March 2001 around 09:20.
Figure 11: Bz component of the magnetic field recorded by FGM between 09:20 and 09:23 on 17 March 2001 (Rumba=blue, Salsa=red, Samba=green, Tango=black)
Figure 12: Magnetopause model and spacecraft position in GSE coordinates on 17 March 2001. The arrow indicates the direction from the center of the GSE coordinates system to the spacecraft position, which is nearly the normal to the magnetopause at that point. The distance from the center is indicated on the x-axis, from 0 to 14 Re
crossing and seen on the data for about 6 minutes. Thus, this layer which represents a region with higher turbulence on all the particle moments and magnetic field components would be approximately 14000 km long, that is $\sim 2.2 R_e$.

### 3.4 Discussion

To conclude with this particular day, we can say that despite the uncertainties on the results found for the magnetopause velocity and thickness, it raises the fact that the magnetopause motion must be taken in account while doing such estimations. We can wonder about the origins of this motion, and it would seem natural to say that the magnetic field and plasma variations in the magnetosheath could induce magnetopause motion. To have access to those variations, we need to review the satellite observations made in the solar wind that day.

**ACE interplanetary data**  Upstream solar wind and IMF conditions during the interval discussed here were measured using the Advanced Composition Explorer (ACE) spacecraft. On 17 March 2001, ACE was located in the solar wind at GSE coordinates $(X,Y,Z) = (+226.3,-36.5,-0.63) R_E$. The propagation delay between field signatures appearing at the spacecraft and their arrival at the subsolar magnetopause must be calculated. An idea of the result is obtained in dividing the distance between ACE and the magnetopause over the solar wind speed.

On the 17th of March, taking a solar wind density $n \approx 2.5 \ cm^{-3}$ and speed $V \sim 290 \ km.s^{-1}$, the magnetopause position is about $R_{MP} = 14.4 \ R_E$, which gives a delay of 1 hour and 18 minutes.

This estimate is not very satisfying because the solar wind does not have a constant speed along his way from the sun down to the ionosphere. To make a careful estimate of the propagation delay between fields observed at the spacecraft and the arrival of their first effects on the magnetopause, two different components must be considered. The first one is the propagation time in the solar wind between arrival at the spacecraft and arrival at the subsolar bow shock, and the second one is the frozen-in transit time across the subsolar magnetosheath.

Regarding to those considerations, Fasel (1994) established the following equation giving the time in minutes between the IMF conditions observed at the satellite
and when the information is transmitted to the magnetopause:

$$T_{lag} = \frac{3060}{V_{SW}} - \frac{x_{bs-sat}}{V_{SW}} \times 106$$

where 3060 and 106 are the conversion factors needed to put the appropriate times into minutes, since the solar wind speed $V_{SW}$ is in kilometers per second and the distance between the bow shock and the satellite $x_{bs-sat}$ is given in $R_E$.

The problem is that Fasel assumed the bow shock to be located at a constant distance of 14.6 $R_E$, based on Fairfield studies (1971). Using more recent results, for example the empirical study by Peredo et al. (1995), we can parametrize the subsolar shock location in taking into account the solar wind parameters. From a comprehensive analysis of observed shock locations these authors found that the subsolar shock is typically located at a distance which is larger than that of the subsolar magnetopause by a factor of 1.46:

$$R_{BS} = \frac{17.6}{p(nPa)^{1/6}} = \frac{162}{[n(cm^{-3})V^2(km.s^{-1})]^{1/6}}R_E$$

We had a magnetopause situated at a distance of 14.4 $R_E$, thus $R_{BS} \approx 21$ $R_E$. Using Eq. 5, the time for the information to reach the magnetopause is then:

$$T_{lag} \approx 85 \text{ min}$$

The ACE magnetometer data (Figure 13) have been lagged by this interval for comparison with CLUSTER observations near the magnetopause.

In looking at those ACE data, we can conclude that around the period of interest the magnetic field was relatively stable, with $B_x$ values of about 4.5 nT, $B_y$ values around 1 nT and $B_z$ values between 0 and 2 nT. To finish with those ACE data we can say that the solar wind pressure curve, which is not represented here, was quite flat with a mean value of 1 nPa.

It appears now from the observation of the calm conditions in the interplanetary magnetic field and solar wind recorded by ACE on the 17th of March that there could be another origin for the magnetopause motion. We can think about some other causes, for example surface waves, magnetospheric activity... Concerning the surface waves, Rezeau et al. (2001) showed that the magnetopause is not a plane at the scale of the CLUSTER tetrahedron ($\sim 700$ km) and that the structures at the
Figure 13: IMF in GSE coordinates measured by ACE on 17 March 2001. ACE was situated at GSE coordinates (X,Y,Z) = (+226.3,-36.5,-0.63) Re and data are lagged by 85 min.
boundary could be related with the Kelvin-Helmholtz instability. Further studies must be performed to reach a global understanding of the processes involved.
4 Discussion

In this part, we will introduce data recorded during more perturbated days, the 14th of February 2001, with multiple magnetopause crossings and probably FTEs, and the 2nd of February 2001, with a very soft magnetopause crossing and a mixing of plasma from different magnetospheric regions.

4.1 February 14th 2001: multiple crossings of the magnetopause

We present now on Figure 14 the PEACE data recorded by the four CLUSTER spacecraft on 14 February 2001 (from top to bottom: Rumba, Salsa, Samba and Tango), on which we can see several signatures looking like magnetopause crossings, around 09:45, 09:54, 09:59, 10:04, 10:17 and 10:33. We may wonder why so many signatures are seen on the particle data, and what is the real nature of those phenomena.

We also show the electron moments recorded by PEACE at the same period of time on Figure 15. The magnetopause crossings have approximately the same signature as seen on the 17 March data, with an increase in the density clearly identifiable for all the selected times and a decrease in the temperature. On the velocity panel, the signatures are not as clear as on the other panels because this parameter varies very rapidly and thus the first four crossings are not really recognizable, as the last crossing which was yet easily identifiable on the other parameters.

This last point concerning the less identifiable signatures on the first crossings is interesting because this particular day has already been studied in a paper submitted by Wild et al. (2001), in which they observe Cluster FGM data and explain that the first four signatures seen could be FTE signatures. We have redrawn those FGM data in boundary normal coordinate system on Figure 16, indicating the time of the different identified events as follows: red lines for FTE, yellow line for the magnetopause boundary layer crossing, and green lines for magnetopause crossings.

The problem comes from the fact that, contrary to the results exposed in section 1.3.4 concerning the FTE, we do not find a mixing of the two populations (electrons coming from the magnetosheath and magnetosphere) on at least two of the FTE signatures, the first one at 09:45 and the last one at 10:04. This could be explained by the fact that the spacecraft would be distant from the reconnection point or
Figure 14: CLUSTER spectrogram recorded by the PEACE instrument (low-energy range) on 14 February 2001
Figure 15: Density, velocity, temperature recorded by PEACE (spacecraft #1) on 14 February 2001
Figure 16: FGM data in boundary normal coordinate system recorded by Rumba on 14 February 2001 (from Wild et al., 2001), with red, yellow and green lines indicating respectively the FTE, the boundary layer and the magnetopause crossings.
outside the flux tube. Indeed, we do not see the more energetic particles from the magnetosphere. Moreover, we should have a bipolar variation of the $N$ component of the magnetic field, that is a positive and later a negative value of $B_N$, whereas we observe that during the first FTE at 09:45, $B_N$ is always negative. This could also be explained by the fact that the normal to the magnetopause is a mean value calculated with a minimum variance method on a too long period of time and thus the $B_N$ origin would be shifted. By the way, all those comments make us wonder if those signatures are real FTEs or just magnetopause crossings. To say so, we can look at the conditions in the interplanetary medium observed during that day by the ACE spacecraft. To take in account the delay due to the distant spacecraft position, we use the propagation delay calculated by Wild as being equal to $\sim 55$ minutes, so that we will be able to compare the variations in the solar wind density and speed and in the IMF with the signature appearance on the FGM data. Thus, the ACE data have been lagged by 55 minutes and drawn on Figure 17 with the top three panels representing the three magnetic field components in GSE coordinate system, and the two bottom panels representing the solar wind density and speed.

Those perturbated ACE data indicate that the IMF and solar wind were very unstable on the 14th of February and thus, those changing conditions could affect the magnetopause position in such a way that the boundary could swing back and forth around the spacecraft position and thus make them record multiple crossings. We would need further studies to identify without any doubt the nature of the signatures seen on PEACE and FGM that day, but we have seen once again that the magnetopause was not a stable boundary but a constantly changing one.

4.2 February 2nd 2001: plasma mixing

Another interesting day is the 2nd of February 2001, during which we do not see any clear transition between the magnetosphere and magnetosheath, as for the 17th of March, but a mixing of those two populations which stands for a very soft transition between the two magnetosphere regions, and lasting for nearly two hours. This soft transition is clearly seen on the Cluster Quicklook plot (Figure 18), and specially on the CIS panel.

We have also drawn the electrons density and temperature recorded by PEACE between 13:00 and 16:00(Figure 19), showing very different profiles compared to those
Figure 17: Interplanetary magnetic field in GSE coordinates and solar wind proton density and speed recorded by ACE on 14 February 2001 (data lagged by 55 min.)
Figure 18: Quicklook Plot showing different parameters recorded by the Cluster instruments on 02 February 2001
of the 17th of March on which we had a sharp transition at the magnetopause crossing.

On the temperature panel we can see a quite important, fluctuating and negative gradient in the magnetosheath until 14:16, but we do not find again a brutal decrease in the temperatures. On the density panel, we can also see a fluctuating curve but this time constantly increasing by a factor 10 on the period of time from 13:00 to 16:00. Once again there are no clear peak on the density and we realize now that it is quite difficult to compare those data with the sharp magnetopause crossing we had previously, and that it is even harder to define a time period during which the crossing happened.
Figure 19: Electrons density and temperature recorded by PEACE on the 2\textsuperscript{nd} of February 2001 between 13:00 and 16:00
5 Conclusion

In the present work, we have studied the first CLUSTER II data and specially during the periods when magnetopause crossings happened. The first assessment we can make is that those magnetopause crossings can be very different one from another.

We have observed a very sharp crossing on the 17th of March 2001, with clear signatures on the different CLUSTER experiments, whereas we have a very soft one recorded on the 2nd of February 2001, with no clear transition representing the magnetopause. Between those two opposite cases, we observed quite sharp but multiple crossings on the 14th of February 2001, with changing solar wind and IMF conditions.

Despite those differences between the observed magnetopause crossings, it comes out that some parameters appear to be invariant characteristics of those crossings. First, on the particle data, we find a transition (sometimes sharp and sometimes soft) between the hot magnetopause populations and the less energetic but more dense magnetosheath populations. Second, when looking at the magnetic field data, we find again a transition between the field turbulence level which is higher in the magnetosheath than in the magnetosphere, and we always observe an increase in the magnetic field strength right at the magnetopause crossing.

With those typical signatures, it seems like if it is easy to identify such boundary crossings, but we have also pointed out that other phenomena could be understood as magnetopause crossings, like the FTE seen on the 14th of February records. We have also demonstrated that the magnetopause is not the simple two-dimension fixed layer sometimes described in the theoretical models, but that it was constantly in motion even in relatively calm conditions regarding to the IMF and solar wind parameters.

Finally, we can say that the magnetopause can be very difficult to identify and even sometimes to characterize as being a real boundary between two different regions. Further studies will be needed in order to reach a global comprehension of the magnetosphere’s boundary dynamics.
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