Structure and Dynamics of the Earth's Magnetopause

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ABSTRACT

Theoretical modelling of the magnetopause structure and dynamics is an important activity of the Belgian Institute for Space Aeronomy. This paper focuses on (1) the local structure of the magnetopause, its equilibrium state and the conditions required to maintain this state, (2) on validation of theory from observations made onboard ISEE 1 & 2 and AMPTE/IRM satellites, (3) on theoretical attempts to interpret transient phenomena observed near the magnetopause by Interball-Tail and Magion-4 satellites, and (4) on modelling the plasma wave distribution in the vicinity of the magnetopause in preparation of the forthcoming CLUSTER II mission.

KEYWORDS

Magnetopause, tangential discontinuities, percolation, transient events, plasma waves.

INTRODUCTION

The magnetopause is the current boundary layer separating cold ($\approx$100 eV) dense ($\approx$30 cm^{-3}) plasmas on magnetosheath magnetic field lines from hot ($\approx$1 keV) tenuous ($\approx$0.3 cm^{-3}) plasmas on magnetospheric field lines. It is a highly dynamic layer, which may result in the transfer of solar wind across this boundary[1]. Study of the fine structure and dynamics of the magnetopause current layer is an established matter of research at the Belgian Institute for Space Aeronomy. It is recognized that this study is of fundamental importance in understanding the entry processes of solar wind into the magnetosphere. In order to identify these entry processes it is first necessary to build a realistic equilibrium model of the magnetopause, then to perturb this equilibrium in response to solar wind variations. The simplest equilibrium state of the magnetopause is that of a one-dimensional tangential discontinuity (TD) of finite thickness within which the magnetic field rotates from an arbitrary interplanetary direction to the magnetospheric direction. In this approach the magnetopause is an impermeable boundary since there is no magnetic connection between the solar wind plasma and the magnetosphere. The RDKK (Roth-De Keyser-Kuznetsova) model developed at the Belgian Institute for Space Aeronomy is a TD kinetic model. It has the unique feature to take into account simultaneous large shears in magnetic field (>90°) and plasma flow, a characteristic often oberved across TDs in space plasmas that no other previous TD model in the litterature was able to reproduce[2].

Large-scale, adiabatic electromagnetic perturbations in the form of periodic variations are frequently observed at the magnetospheric boundary[3]. We first summarize the results we obtained when these perturbations are superposed on our equilibrium model of the magnetopause structure. The most interesting conclusion of this study is that thresholds exist for the formation of stochastic "percolated" magnetic filaments allowing transfer of solar wind into the magnetosphere[4-6].

In this paper we also focus on the electron density observed at the subsolar magnetopause by the ISEE 1 & 2 pair of satellites in the case of high magnetic shear and show that the RDKK equilibrium model is able to validate these observations[7]. The RDKK kinetic model[2] is clearly the most appropriate one to tackle the problem of the existence of equilibrium configurations when large shears in magnetic field and plasma flow supported by two other ISEE 1 and 2 dayside magnetopause crossings for which high time resolution electron density data were available[7].

CONDITIONS FOR TD EQUILIBRIUM

The effect of velocity variations across a tangential discontinuity has serious implications for the Earth's magnetopause. Using the RDKK model[2] and assuming an empirical model of the solar wind flow around the magnetopause based on satellite observations, De Keyser and Roth[8-10] were able to predict which regions on the magnetopause correspond to equilibrium configurations for a given magnetic field rotation. These regions are indicated in figure 2 by shading on a plot of the dayside magnetopause for different angles of the magnetic field rotation.

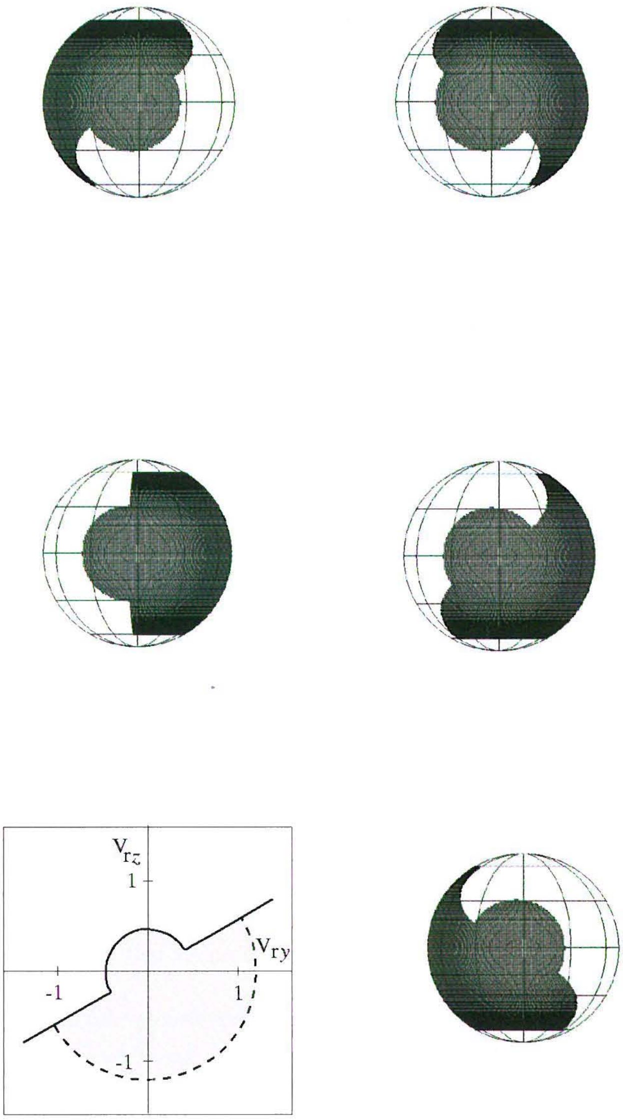

Figure 2: Given a typical velocity jump domain (bottom left) and assuming that the magnetosheath plasma is streaming radially away from the stagnation point, it is possible to predict where the dayside magnetopause may be in TD equilibrium for a given magnetic field rotation angle. The stagnation point is at its typical location 5° dawnward from the subsolar point, and the dipole tilt angle is zero. The shaded regions correspond to magnetic field rotation angles of +180° and +90° (top left-right), 0° and -90° (middle left-right) and -180° (bottom right) (from reference 10).

The following interesting results were found: (a) any magnetic field rotation is allowed near the stagnation point. This region of the magnetopause surface can therefore be in a state of tangential discontinuity equilibrium whatever the angle of magnetic field rotation; (b) there is a tendency for large positive rotations to occur predominantly in the northern hemisphere, while large negative rotations are expected predominantly in the southern hemisphere; (c) small positive and negative rotations, i.e., less than 90°, are only possible on the dusk side; (d) no low magnetic shear (less than 90°) equilibrium seems possible at the dawn side.

In figure 3 (from reference 11), these theoretical predictions are verified using data from 45 crossings of the dayside magnetopause obtained by the AMPTE/IRM satellite.

Especially the sense-of-rotation difference of the magnetic field between northern and southern hemispheres is important. This has been a debated subject since early studies based on Explorer 12 observations in 1968. As far as we know, only a theoretical analysis for wide crossings of the rotational discontinuity type is available to explain such a difference; our result for tangential discontinuities constitutes a nice complement.

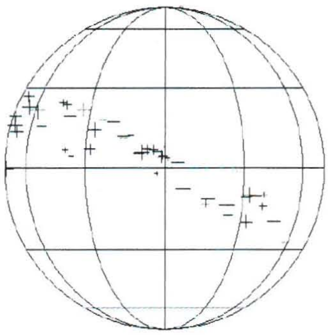

Figure 3: GSM map of AMPTE/IRM magnetopause crossings with the observed magnetic field rotation. A + symbol indicates a positive (clockwise) rotation, a - symbol a negative (counter-clockwise) rotation sense; the symbol size is proportional to the rotation angle. Note the dominant presence of large positive rotations north of the dawn side equator and the absence of low shear dawn side crossings (except for a case of questionable TD nature). Near the stagnation point and at the dusk side both rotation senses are observed (from reference 11).

IMPULSIVE TRANSPORT OF SOLAR WIND

There is a long-standing controversy regarding impulsive penetration of solar wind plasma into the magnetosphere and the other solar-wind magnetosphere coupling mechanisms[1]. Several international meetings were organized in the period 1994-1999 in the hope of quantifying the specific importance of the different solar wind/magnetosphere interaction mechanisms. At the Chapman Conference on *The Physics of the Magnetopause* (San Diego, USA, 1994) an invited talk on the subject was given by Roth[12]. In 1996 a three-year project called *Source and Loss Processes of Magnetospheric Plasma* was selected by the International Space Science Institute (ISSI) in Bern as the first in the field of solar terrestrial physics. This ISSI study project focused on the inner and outer boundaries of the magnetosphere in an effort to quantify the significance of the various proposed source and loss processes for magnetospheric plasmas. The Belgian Institute for Space Aeronomy contributed to that project and discussed the role of impulsive penetration of solar wind plasma through the magnetopause as a plausible source of magnetospheric plasma (see reference 1, pages 263--270). Recent and important developments on the theory of impulsive penetration are presented elsewhere in this book[13].

TRANSIENT PHENOMENA AT THE DUSK SIDE

Interball-Tail and Magion-4 are part of the Russian multi-satellite Interball mission. They were launched in August 1995 into essentially the same highly elliptical orbit with a period of 95 h, an apogee of 200,000 km, and an inclination of 62.9°.

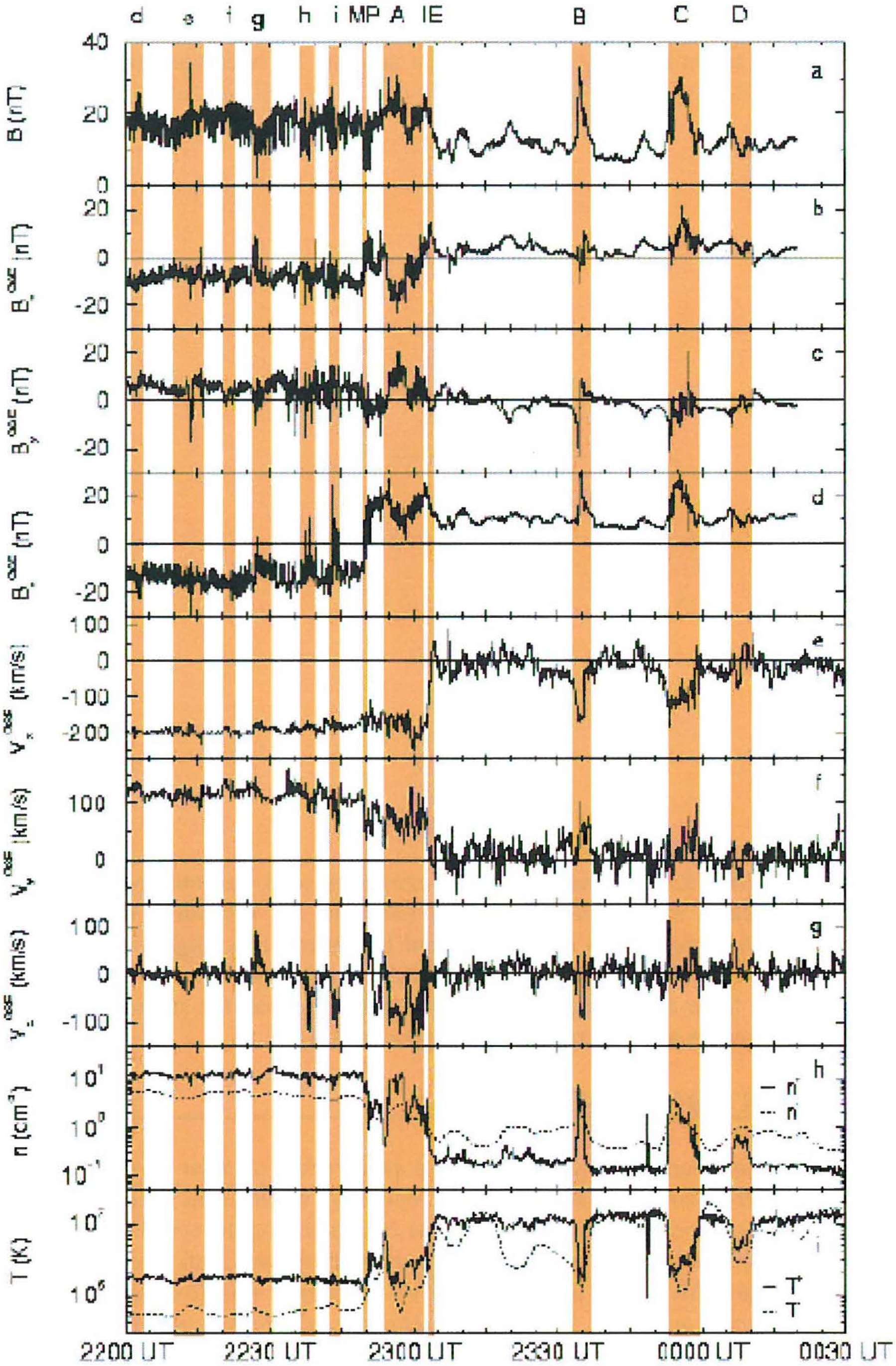

Figure 4: February 15--16, 1996 dusk side inbound crossing of the magnetopause by Interball-Tail (from reference 15).

Figure 4 shows Interball-Tail data obtained between 22:00 UT, February 15, and 00:30 UT, February 16, 1996: (a-d) the magnetic field magnitude and its GSE components, (e-g) the GSE ion velocity components, (h) the ion and electron densities n^+ and n^-, and (i) the ion and electron temperatures T^+ and T^-. The magnetopause crossing (labeled ``MP" in figure 4) occurs near 22:50 UT and is identified by the large magnetic field rotation. This MP crossing is followed by four distinct transients, labeled A, B, C, and D. The main velocity change does not occur at the magnetopause, but after transient A, at about 23:03 UT, coincident with the transition to magnetospheric density, corresponding to the LLBL inner edge (IE). There are also smaller transients, labeled d, e, f, g, h and i, before the magnetopause crossing, characterized by temporary rotations of the magnetic field.

In one study[14] transients A, B, C, and D were shown to correspond to a new class of Flux Transfer Event (FTE) called DMTE for *Disconnected Magnetosheath Transfer Event*. DMTEs are thought to be the result of localized sporadic reconnection: magnetosheath plasma blobs disconnect from the magnetopause, propagate and dissipate into the magnetosphere.

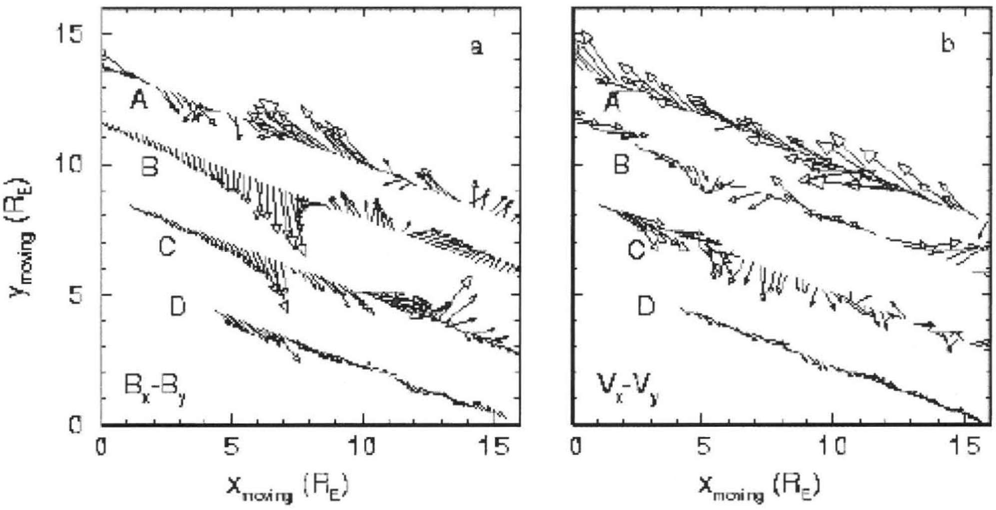

Figure 5: Flux rope topology suggested by juxtaposing data obtained from the four consecutive transients A, B, C, and D: projections of (a) magnetic field and (b) velocity vectors onto the *xy* plane of a reference frame that is oriented like the GSE frame but that moves with a velocity intermediate between the magnetosheath and the magnetospheric plasma flow. The offsets between the trajectories for each transient were chosen arbitrarly. The vectors for different transients do not have a common scale; this figure is meant to illustrate only their orientation (from reference 15).

Another study[15] made at the Belgian Institute for Space Aeronomy, in collaboration with the Space Science Institute (Moscow, Russia) and the Charles University (Prague, Czech Republic) investigated other possible interpretations: are the transients observed in figure 4 the signature of tailward traveling waves or are they the manifestation of magnetosheath plasma penetration into the magnetosphere? In revisiting the February 15-16, 1996 dusk side magnetopause crossing the authors of this study found strong evidence for magnetic field and flow vortices near the magnetospheric boundary (see figure 5) and hence for the existence of flux tubes with helicoidal field lines; such structures can be associated with both interpretations. However, the cross-correlation between the dual satellite observations and the apparent periodicity strongly suggest a Kelvin-Helmholtz surface wave, although other interpretations are not impossible.

PLASMA WAVES AT THE MAGNETOPAUSE

In the framework of the Cluster II mission the Belgian Institute of Space Aeronomy (BISA) participates in the experiment teams STAFF [Spatio-Temporal Analysis of Field Fluctuations; Principal Investigator is N. Cornilleau-Wehrlin (CETP/UVSQ, Vélizy, France), BISA Co-Investigator: M. Roth] and WHISPER [Waves of HIgh frequency and Sounder for Probing of Electron density by Relaxation; Principal Investigator is P. Décréau (LPCE and Université d'Orléans, Orléans, France), BISA Co-Investigator: J. Lemaire]. The participation in WHISPER is described elsewhere in this book[22].

The objective of the STAFF wave experiment is to assess the role that plasma waves play in affecting and controlling the physical processes by which mass, momentum, and energy are transferred through the magnetopause, from the solar wind to the magnetosphere[23]. Many experiments aboard single spacecraft have shown that a very high level of fluctuations is observed in all frequency ranges during magnetopause crossings. The question of the origin of these fluctuations has seldom been addressed in the literature. Two different hypotheses are generally considered: either they are due to local instabilities of the current layer, or they are generated in the magnetosheath and are amplified at the magnetopause[24,23]. Modelling the plasma wave distribution in the vicinity of the magnetopause will help to test the second hypothesis.

A study of the propagation of ultra-low frequency electromagnetic waves at the magnetopause using a linear magnetohydrodynamic (MHD) description[16] was made at the Belgian Institute for Space Aeronomy, in collaboration with "le Centre d'Etude des Environnements Terrestre et Planétaires (Vélizy, France)". Even though the mass flux across the magnetopause turns out to be zero, there may very well be an energy flux into the magnetosphere. Figure 6 shows the wave amplitudes (maximum and minimum modulus of the magnetic field, left frames) and the time-averaged energy flux (right frames) as a function of the distance to the center of the magnetopause (in km). The magnetosphere is to the left, the magnetosheath to the right of the magnetopause. They found different solution classes. Class 1: a non-vanishing perturbation intensity in the magnetosphere indicates transmission, while the energy flux remains constant as the incident flux equals the transmitted flux plus the reflected one. In the reference frame adopted here, a negative flux indicates energy transfer from the magnetosheath to the magnetosphere. Class 2: the wave does not penetrate into the magnetosphere and is completely reflected, resulting in a net zero energy flux. Class 3: similar to class 2 but now resonant amplification (infinite wave amplitude) occurs at 1 or 2 points inside the magnetopause; resonant absorption implies a jump in the energy flux profile. Class 4: reflection, transmission and resonant amplification occur simultaneously; again, the energy flux is discontinuous at the resonant points.

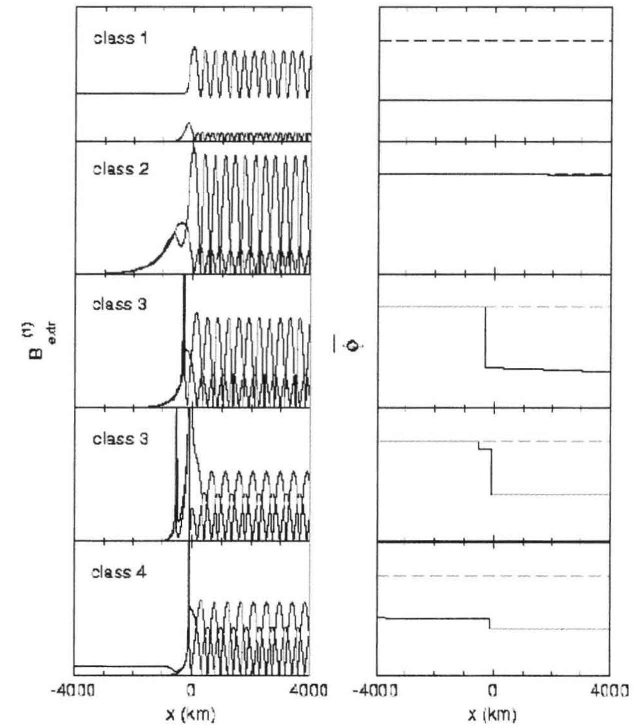

Figure 6: Representative solutions for the zero magnetic shear magnetopause in the warm plasma case. The figures plot the maximum and minimum values of the modulus of (left) $B^{(1)}$ (in arbitrary units) and (right) the time-averaged energy flux φ (in arbitray units; zero flux corresponds to the dashed horizontal line) as a function of the distance to the center of the magnetopause (in km). The magnetosphere is to the left and the magnetosheath is to the right of the magnetopause. See text for the description of the different solutions (from reference 16).

In a subsequent study by De Keyser the linear magnetohydrodynamic response of the magnetopause to pressure pulses and broadband magnetosheath fluctuations has been computed[18]. The tail flank magnetopause is known to be subject to magnetosheath pressure variations, and may possibly develop a Kelvin-Helmholz instability.

De Keyser has also examined the effect of low-frequency long-wavelength perturbations induced by magnetosheath waves on the flank magnetopause and on the plasma sheet and the plasma sheet boundary layer[17]. He found that a certain fraction of the energy input contained in the magnetosheath waves can cross the magnetopause and can be transported to and locally dissipated in the plasma sheet boundary layer.

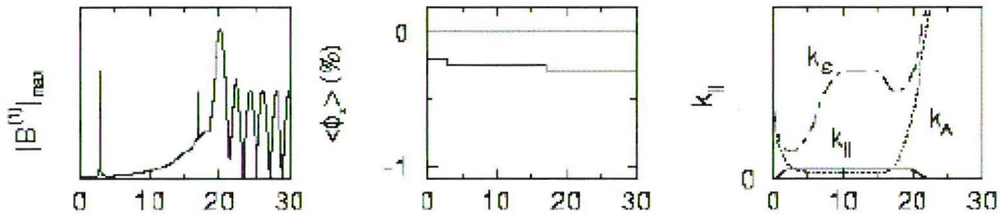

Figure 7: Wave solution for a frequency of 10mHz, a tangential wavelength of $24R_E$ (earth radii) and a tail magnetic field orientation from dusk to dawn. The time-averaged energy flux $<\Phi_x>$ (right panel) is normalized to the energy flux carried by the incident wave (from reference 17).

Figure 7 shows the propagation of an incident magnetosheath wave (the magnetosheath is on the right of the figure) across the magnetopause (near x=20 R_E), through the lobe, and across the plasmasheet boundary up to the central plasma sheet (at x=0 R_E). Part of this wave is reflected at the magnetopause. Part of the wave is resonantly absorbed at the magnetopause, as shown by the singularity in the wave amplitude (left panel) and the jump in the energy flux profile (right panel). Although the wave is evanescent in the tail lobe, it still has a non-zero amplitude by the time it reaches the plasmasheet boundary layer, where resonant absorption can occur again (peak in wave amplitude, jump in energy flux). At these sites of resonance, wave energy is converted from the imposed compressional waves to Alfvén waves (as in this example) or to slow mode waves. The jumps in the energy flux indicate how much of the energy carried by the wave is dissipated in the resonant layer. In this example both Alfvén resonances are responsible for diverting only 0.04 % of the incident wave energy.

CONCLUSIONS

Kinetic models developed at the Belgian Institute for Space Aeronomy can clarify under which conditions the magnetopause may be in a state of TD equilibrium. In this review we have shown that these models are well validated from satellite observations. The dynamics of the magnetopause is under the control of solar wind parameters. There are a number of processes that may lead to transfer of solar wind plasma across the magnetopause. Transients observed near the magnetopause are hard to interpret, although observations made by dual satellites may shed some light on the processes responsible of their occurrence. The high-resolution multi-point in situ measurements made by the armada of CLUSTER II satellites are needed to assess the importance of these processes. Plasma waves play also a role in affecting and controlling the energy transport from the magnetosheath to the magnetosphere. The STAFF and WHISPER experiments on the CLUSTER II mission will help characterize the plasma wave distribution in the vicinity of the magnetopause. In addition, the WHISPER experiment has the capability to measure the absolute value of the total density in four points and will therefore provide more precise information about the structure and velocity of transients observed in the solar wind and magnetosheath regions as well as during magnetopause crossings.

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