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## Power of magnetopause low-frequency waves: A statistical study

D. Attié,<sup>1</sup> L. Rezeau,<sup>2</sup> G. Belmont,<sup>1</sup> N. Cornilleau-Wehrin,<sup>1</sup> and E. Lucek<sup>3</sup>

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[1] ULF fluctuations at the Earth magnetopause have been the subject of a long-standing interest because of their noticeable amplitude and their potential role in plasma penetration through the magnetosphere boundary. Some information on the nature of these fluctuations has already been provided thanks to GEOS and ISEE, and more recently Cluster, case studies and from a few statistical studies on magnetopause crossings. Here we present a new statistical study concerning the power of the ultralow frequency fluctuations based on the data of the Cluster-STAFF experiment. New insight in the properties of turbulence is obtained, because of the orbit of the Cluster spacecraft, which gives access to regions far from the subsolar point. The correlation of the wave power with solar wind and magnetosheath properties indicates that these fluctuations are controlled and possibly driven by external sources. Its correlation with the magnetopause properties (namely the magnetic shear angle) provides an indication of an amplification process at the boundary.

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### 1. Introduction

[2] A high level of magnetic fluctuations in the ULF range is generally present in the magnetosheath. The power in the same frequency range is observed to be much lower in the magnetosphere and often presents a maximum at the magnetopause crossing itself [Rezeau *et al.*, 1989; Labelle and Treumann, 1988]. A precise knowledge of these fluctuations is needed in order to understand their origin and their role in processes at the magnetopause, including the question of plasma penetration into the magnetosphere.

[3] This paper presents a statistical study of the wave power in the magnetopause region and of its correlation with local and external parameters. As the waves are necessary actors of all the mechanisms envisaged in the literature for explaining the magnetopause transfers, the results presented are expected to be useful in the future to put constraints on the models and discriminate between them. The aim of the paper is limited to the study of the wave power and does not investigate the nature of the waves neither the mechanisms of transfer they can provide. Let us however briefly review, in introduction, what are these possible mechanisms and why all of them demand waves.

[4] From its very definition, magnetic reconnection is strictly necessary to explain the transfer of magnetic flux through the magnetopause (hereafter MP). When this phenomenon is present, the particle penetration follows, even if, in the absence of magnetic flux penetration, this penetration

alone could be explained by plain cross-field diffusion (but it is a slower process). Over many years, various models have been proposed to explain the transfers from solar wind to magnetosphere. Because the plasma is collisionless, the crucial role played by the waves is a common feature to all the models regardless of the mechanism proposed; diffusion or reconnection, and independent of the way of modeling the waves: via a self-consistent calculation or via some assumed “anomalous” transport coefficients. Apart from the first stationary models, most of the classical scenarios have implied large-scale instabilities of the tearing type, i.e., assumed that the boundary is a stationary tangential equilibrium, which is locally unstable at some places. These scenarios imply dissipation of the magnetic energy around X points, the dissipation having first been assumed resistive (possibly because of some “anomalous resistivity” related to microturbulence), and more recently “collisionless” (see for instance GEM challenge [Birn *et al.*, 2001]). An alternative to these “spontaneous” models are the models of “driven” reconnection, which have also been investigated for long: in these models, the X point vicinity is no more considered as a closed system but some external energy input is allowed (through the boundary conditions in numerical experiments). In most papers, this energy input has been associated with laminar and stationary flows, which lead the boundary to an instable state, so keeping the theories close to the spontaneous models. In view of the strong ULF turbulence present in the magnetosheath (hereafter MSH), one can suspect that reconnection is more likely to be forced by these turbulent-like magnetic fluctuations. Driving the reconnection process by such non stationary external conditions, in the absence of any instability, has been investigated much more rarely. One can consider that the models of “impulsive penetration” [Echim and Lemaire, 2000] belong to this category, even though the authors present

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them rather as “alternatives to reconnection.” As the mechanism actually implies flux penetration, one should rather consider them as reconnection models, which are alternatives to the spontaneous ones (and to the classical driven ones). The model of *Belmont and Rezeau* [2001] (hereafter BR01) also belongs to this category: the behavior of monochromatic MHD waves is investigated as they propagate from the MSH toward the magnetosphere across the MP boundary. The wave power maximum observed at the boundary can be interpreted in BR01 as a propagation effect in the rotating magnetic field, which induces the trapping of a back-streaming Alfvén wave created by wave coupling in the density gradient. BR01 also shows that this process creates small-scale variations in the plasma, which might be sufficient to break the ideal MHD assumption and trigger reconnection. As this behavior is strongly dependent on the rotation of the d-c magnetic field across the MP, we shall look here for possible correlation between this shear angle and fluctuation level [*Rezeau and Belmont*, 2001].

[5] Many spacecraft have already observed the magnetopause and some could investigate the lowest part of the magnetic spectra, typically below the ion gyrofrequency, in the frequency range traditionally known as ULF. Some of these spacecraft were in the equatorial region (GEOS 2, ISEE 1 and 2), some at high latitude (HEOS, POLAR, INTERBALL). POLAR and INTERBALL had search coils that allowed measuring the magnetic components of waves [*Lakhina and Tsurutani*, 1999]. With its polar orbit, extending to 19.6 Earth radii and its broadband wave instruments (0.1 Hz to 4 kHz for the STAFF instrument), Cluster allows to make a new exploration of the magnetopause, far from the subsolar point, at high latitudes or on morning or evening sides of the magnetosphere. Case studies have already provided a quite valuable set of information on the nature and the localization of the waves in the MSH and at the MP [*Lacombe et al.*, 1995; *Denton et al.*, 1995; *Song et al.*, 1992]. Preliminary results obtained from the first Cluster MP crossings have shown that the peak in wave amplitude is clearly right in the boundary, and that the waves present a rather parallel propagation with a shear Alfvén type polarization [*Rezeau et al.*, 2001]. In the adjacent MSH, the k-filtering technique applied to the Cluster data has confirmed recently, on a case study, the existence of important mirror mode waves [*Sahraoui et al.*, 2003].

[6] Statistical studies have been performed mainly from the ISEE equatorial database [*Rezeau et al.*, 1992; *Song et al.*, 1993]. The primary goal of the present paper is to use the Cluster database to get further statistical information on the amplitude of the fluctuations and to look for indications upon their causes and consequences. A set of crossings have been selected, between July 2001 and June 2003. Each crossing is identified using the magnetic field variation from the FGM data [*Balogh et al.*, 2001] and the electron density variations as estimated from WHISPER [*Décroux et al.*, 1997] or EFW [*Gustafsson et al.*, 1997] data. The selection was made using the wave data only: a description of each case with more physical parameters would be interesting but would restrict the study to the use of a much smaller database. The energy density of the magnetic fluctuations is calculated from the STAFF data [*Cornilleau-Wehrin et al.*, 1997, 2003] in the range 0.35–10 Hz. In section 2, we will explain using a case study the way that we determine

the wave energy density from these data. We will then present the statistical results in sections 3 and 4, and discuss the physical implications in section 5.

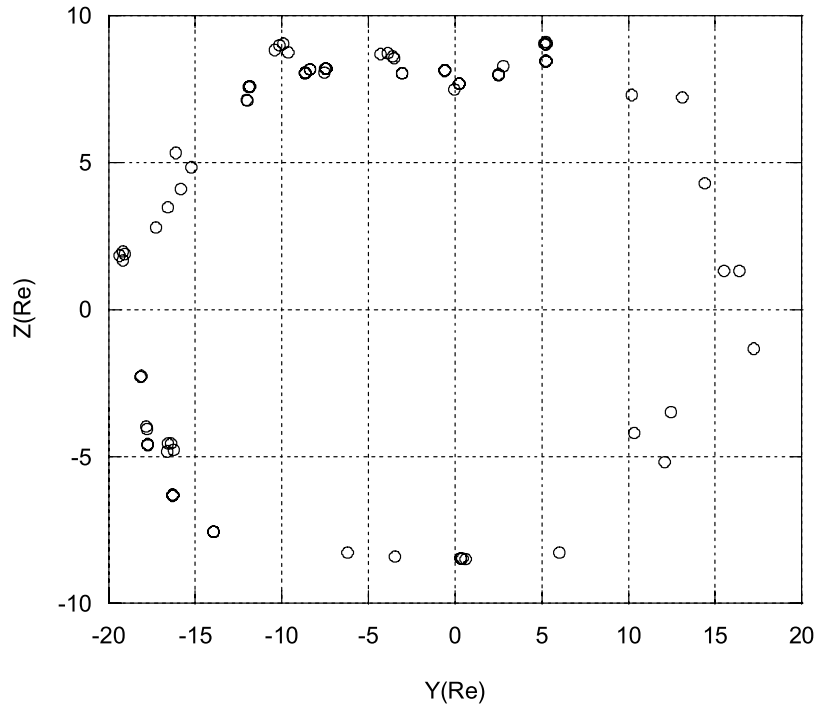
## 2. Data Processing and Statistics

[7] In this statistical study we used a subset of Cluster MP crossings observed between July 2001 and June 2003 selected on the basis of two criteria. The first limits the latitude of the crossings to be less than  $70^\circ$ . At higher latitudes the crossings often occur in the cusp or its vicinity where the plasma is likely to have different characteristics [*Grisson et al.*, 2005]: a high level of fluctuation (on both the MSH and magnetospheric side) and solar wind penetration make the physics quite different in these regions as compared to the day-side MP. The second condition is that the magnetosphere and the MSH are clearly identifiable: we have only selected cases in which the satellites stay in the MSH for a time at least a factor of two longer than the duration of the crossing itself. This condition is necessary in order to be able to compare the fluctuation levels at the MP and in the adjacent MSH. This condition leads to the exclusion of around half of the crossings and in particular many multiple crossings. Because of Cluster orbit, the MP crossings take place either on the dayside at high latitudes, or at low latitude on the flanks, the low-latitude crossings being less frequent, at least during the first years of the mission we are concerned with. We tried to avoid such a biased sampling by retaining as many crossings as possible in May and June 2003, when they were at low latitude. Figure 1 shows how the crossings are distributed in the YZ (GSE frame) plane and clearly shows that the observations made by Cluster are all far from the subsolar point. The statistics cover 43 MP crossings by the four spacecraft. The magnetic shear often appears to be quite different on the 4 spacecraft even if the separation distance is small. The 4 spacecraft are therefore treated independently. Taking into account the fact that the data are not always suitable for analysis on all 4 spacecraft, the final data set contains 130 events.

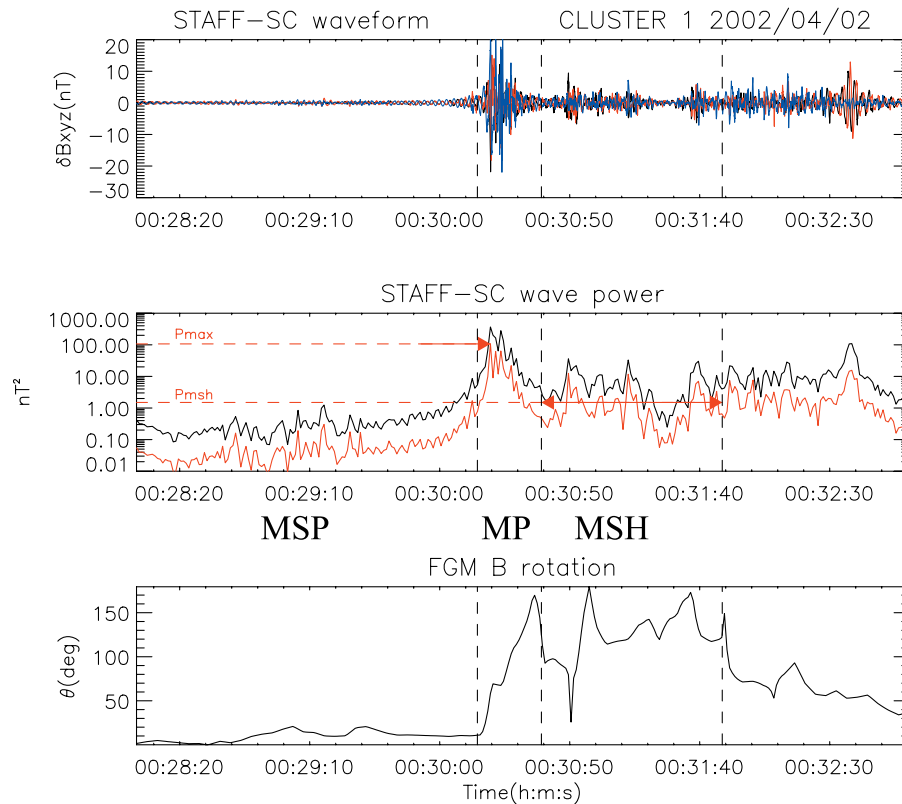
### 2.1. Crossing Identification

[8] The DC magnetic field data used for the crossing identification are the FGM prime parameters (4 s resolution). The density gradient is determined from WHISPER data in passive mode. Occasionally, in particular when the duration of crossing is shorter than 4 s, the FGM high-resolution data are used and the density gradient is located by using the spacecraft potential provided by EFW.

[9] For analyzing each crossing at each spacecraft we had to accurately determine the location of the MP current layer. For this purpose, we mainly used the rotation parameter, which is calculated as follows: we first perform a minimum variance analysis of the DC magnetic field. The rotation angle  $\theta$  is then the angle in the MP plane (intermediary-maximum variance direction) between  $\mathbf{B}(t)$  and the initial vector  $\mathbf{B}_0$  at the beginning of the interval. Using this one-dimensional parameter the MP crossing is easily determined, for example see Figure 2 (bottom), between the two first dashed lines. A small return back into the magnetosphere is observed at 00.3:50.



**Figure 1.** Positions of magnetopause crossings by Cluster on the YZ plane (GSE frame) for the studied data set: 130 crossings, for the time period July 2001–June 2003.



**Figure 2.** (top) Cluster STAFF, waveform  $\delta B$  (0.35–10 Hz) on the three components in a fixed frame (red, black and blue). (middle) Comparison between the 2 calculation methods of the magnetic fluctuations energy density with Cluster STAFF data. In black:  $\langle \delta B^2 \rangle$ . In red:  $P = \langle (\delta B - \langle \delta B \rangle)^2 \rangle$ . (bottom) Cluster FGM, rotation angle  $\theta$  of  $\mathbf{B}$  with respect to the initial vector  $\mathbf{B}_0$ .  $P_{\max}$  is the peak energy density at the MP.  $P_{\text{msh}}$  is the mean energy density in the adjacent magnetosheath.



## 2.2. Wave Energy Density Calculation

[10] The energy density of the ULF fluctuations is obtained from the waveform  $\delta\mathbf{B}(t)$  provided by the STAFF experiment. The search coils are not a priori sensitive to the DC magnetic field but, because of the rotation of the spacecraft, the two components that are in the spin plane actually measure the projection of the DC field in the spin plane at the spin frequency (0.25 Hz). To avoid any difference between the three components, the signal has therefore been filtered with a low-frequency cutoff equal to 0.35 Hz (Figure 2, top).

[11] Once the signal is filtered to exclude power at frequencies below 0.35 Hz, the fluctuation energy density that we used is not simply  $\langle\delta\mathbf{B}^2\rangle$  because this value would have mixed the “waves,” which we are looking for, with a contribution of the MP field gradient. If this gradient is seen, for instance, as a Heaviside function superimposed on the signal, it is clear that its  $1/f^2$  spectrum can pollute the genuine waves. Typically, the waves are polluted when the duration of crossing is less than 3 s: when it is larger, the gradient has no significant effect because of the 0.35 Hz cutoff frequency. In order to reduce in any case the effect of the gradient, we use the following method: the wave energy density is calculated in successive 1-s long windows, after windowing with a  $\cos^3[\omega(t - t_0)]$  function to reduce edge effects. The energy density is then calculated from this windowed signal  $\delta\mathbf{B}_s$ , after subtracting its mean value:  $P = \langle(\delta\mathbf{B}_s - \langle\delta\mathbf{B}_s\rangle)^2\rangle$ . As illustrated in Figure 2 (middle), this method gives results with a better contrast between the different regions (red curve), but with an overall form not significantly different from  $\langle\delta\mathbf{B}^2\rangle$  (black curve). Using this method we consider the integration of the energy density over a wide bandwidth [0.35–10 Hz], the higher limit being the limit of the waveform filter used for the normal bitrate mode which is used most of the time. This choice is expected to provide a trustable proxy for the global ULF wave activity: the spectrum is far from monochromatic and can generally be fitted by a power law above a frequency around the proton gyrofrequency; a “knee” is sometimes observed around this frequency [Song *et al.*, 1993], but it is well inside the frequency range. It must be noted that, because of the Doppler effect [Sahraoui *et al.*, 2003] the proton gyrofrequency has no precise signification with respect to the frequencies observed in the spacecraft frame. The bottom panel presents the time evolution of the shear angle, and shows that the peak in the power of the magnetic fluctuations is observed right on the MP gradient, between 00:30:00 and 00:30:20 TU. This peak energy density is about 10 times higher than the average level in the adjacent MSH. The reentry into the magnetosphere at 00:30:50 is clearly associated with a simultaneous decrease in the wave energy density.

[12] Finally, we will sometimes use normalized energies  $P^* = P/\langle B^2\rangle$  instead of the plain wave energies  $P$ , because the relative perturbations  $\delta\mathbf{B}/B$  can be better indicators for characterizing the wave activity than  $\delta\mathbf{B}$  itself. A previous statistical study performed on ISEE data [Rezeau *et al.*, 1992] has already shown that the nonnormalized energy density of the fluctuations at the MP directly depends on the compression of the magnetosphere, and therefore on the value of the DC magnetic field. This basic effect will have

to be distinguished from the others. For determining the enhancement of the waves coming from the MSH at the MP, it is necessary to compare the level measured at the MP with the level observed in the nearby MSH. Therefore we can define three quantities:

[13] 1.  $P_{\text{mp}}$  is the average fluctuation energy density over the crossing, i.e., calculated using the entire time interval when the shear angle varies (results not presented here).

[14] 2.  $P_{\text{max}}$  is the maximum energy density in this interval. (We don’t investigate the exact location of the maximum inside the current layer, neither its normal extension inside and outside the layer.)

[15] 3.  $P_{\text{msh}}$  is the average energy density in the adjacent MSH, calculated over an interval as long as  $\theta$  remains stable. These determinations are not calculated through an automatic procedure but after a visual inspection of each case. “Adjacent MSH” is a time-based designation here: it is indeed difficult to know the position and velocity of the boundary compared to the position and trajectory of the spacecraft. This information would need a fully detailed case study involving the 4 spacecraft, which would have been a huge work for a statistical study involving 130 crossings.

[16] In summary, in what follows for the statistical study, we will use the energy densities  $P_{\text{max}}$  and  $P_{\text{msh}}$  defined in their respective regions as  $P = \langle(\delta\mathbf{B}_s - \langle\delta\mathbf{B}_s\rangle)^2\rangle$ , and the corresponding normalized values  $P_{\text{max}}^* = P_{\text{max}}/\langle B^2\rangle$  and  $P_{\text{msh}}^* = P_{\text{msh}}/\langle B^2\rangle$ .

## 3. Test of the External Source Assumption

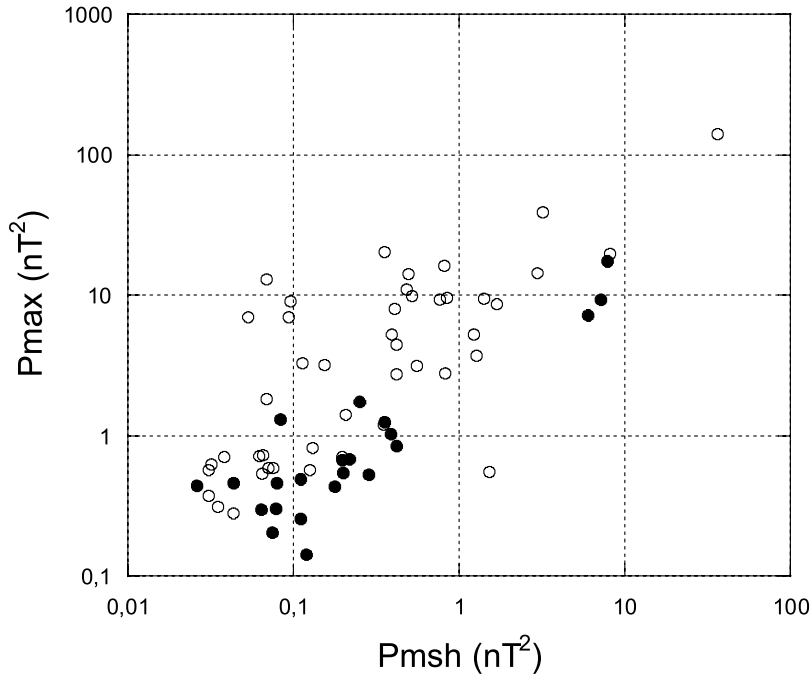
[17] The high level of fluctuations at the MP may be due to local causes, such as instabilities of the boundary itself, and/or driven from outside. We present here two statistical results to test the external source assumption. The first one relates the wave energy density at the MP to the wave energy density in the adjacent MSH; the second relates the MSH energy density to the solar wind properties.

### 3.1. Correlation MP/MSH

[18] In Figure 3 we present the correlation between the peak energy density  $P_{\text{max}}$  at the MP and the average fluctuation energy density  $P_{\text{msh}}$  in the nearby MSH as defined above. A good correlation appears between the two turbulence levels, together with a clear enhancement in the peak wave energy density with respect to the MSH averaged one. Since the level of MSH turbulence cannot be a consequence of that at the MP, this correlation is a clear indication that the level of turbulence at the MP is controlled by the wave power in the MSH. The correlation is still clearer when looking separately to the subsets of points that correspond to large rotations of the magnetic field (empty circles for  $\theta > 70^\circ$ ) and to small rotations (filled circles for  $\theta < 70^\circ$ ). This means that the shear angle is another important parameter which controls the MP fluctuation level. It will be studied in section 4. On the opposite, there is no significant correlation between the “amplification ratio”  $P_{\text{max}}/P_{\text{msh}}$  and the solar wind pressure (result not presented).

### 3.2. Correlation MSH/Solar Wind

[19] Previous results [Rezeau *et al.*, 1992], obtained from ISEE data, have shown that the amplitude of ULF magnetic



**Figure 3.** Cluster STAFF data. Relation between the peak energy density at the magnetopause and the average energy density in the adjacent magnetosheath. One point by crossing. An approximate power law relates  $P_{\max}^*$  to  $P_{\text{msh}}^*$ , but the correlation is clearer when distinguishing large and small rotations, the power being larger for larger rotations: open circles correspond to rotations of more than  $70^\circ$ , and black circles correspond to rotations of less than  $70^\circ$ . For the definitions of  $P_{\max}$  and  $P_{\text{msh}}$ , see Figure 2.

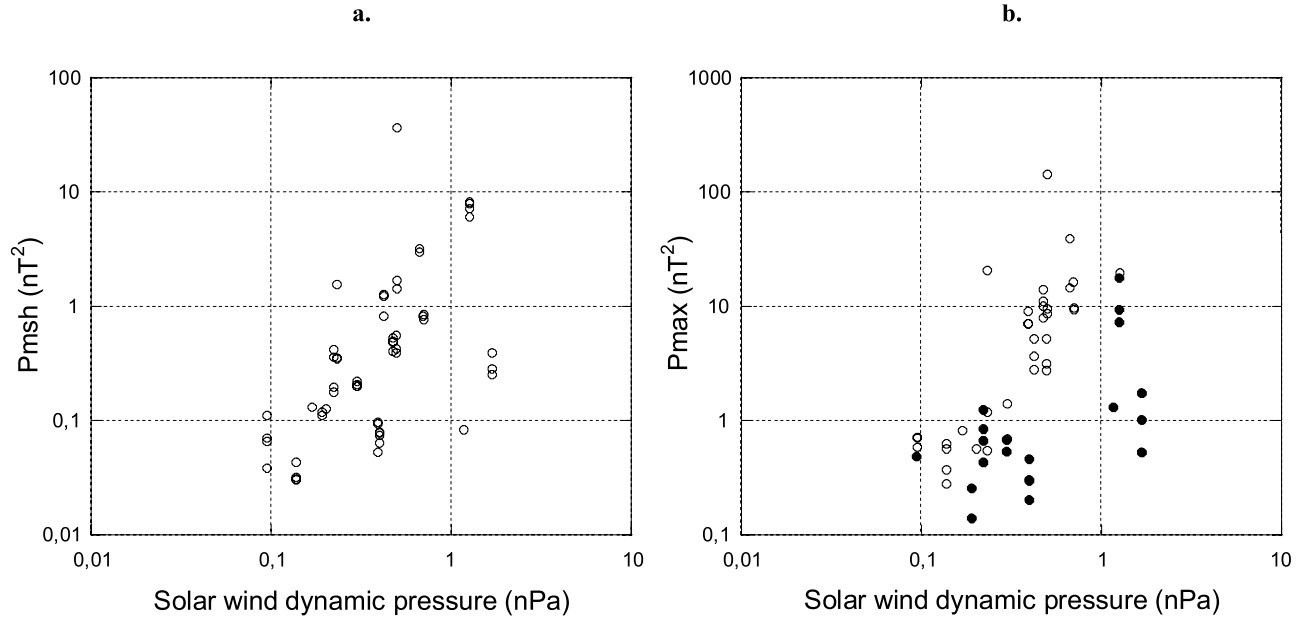
fluctuations observed at the MP increases when the MP-Earth distance decreases. The crossings within the sample were localized at the dayside MP at low latitude, near the subsolar point, and it was suggested that the level of magnetic fluctuations actually depends on the compression of the MP, i.e., on the upstream solar wind plasma pressure. As the Cluster observations are not localized near the subsolar point, the distance of observation with respect to the Earth is not a so good proxy of the compression of the magnetosphere. We therefore check directly the correlation of the ULF power with the dynamic pressure of the solar wind, measured upstream by the ACE spacecraft. For each crossing, the corresponding solar wind plasma dynamic pressure was calculated from ACE data, taking into account the propagation delay (using the solar wind velocity) between ACE and Cluster. Figure 4a shows that the average power of the fluctuations in the adjacent MSH indeed increases when the upstream solar wind dynamic pressure increases. Once again, this correlation is partly blurred by the role of the shear angle at MP and it becomes still clearer when distinguishing small and large rotations (full and empty circles). On Figure 4b, one can check that the increase of the MP fluctuations with solar wind pressure also corresponds to an increase in the level of fluctuations in the MSH. This effect, as already noticed in previous papers, comes through the magnetic compression of the MSH: it mainly disappears when the fluctuations are normalized to the local magnetic pressure (correlations not presented here). These results indicate that the level of fluctuations at the MP is controlled by the level in the adjacent MSH, which is in turn controlled by the solar wind properties. In the view of a driven

reconnection scenario, this behavior can be understood as the means by which the compression of the magnetosphere by the SW favors the plasma penetration through the MP.

### 3.3. Role of the Bow Shock

[20] The solar wind doesn't interact directly with the magnetopause: the flow first encounters the bow shock ahead of the magnetosphere. The angle  $\theta_{\text{BN}}$  between the interplanetary magnetic field and the shock normal is known to be a crucial parameter for the properties of the turbulence observed downstream; the level of turbulence, just downstream of a shock, is higher when the shock is quasi-parallel ( $\theta_{\text{BN}} < 45^\circ$ ) than when it is quasi-perpendicular ( $\theta_{\text{BN}} > 45^\circ$ ) [Formisano, 1977] at least for high enough Mach number. It seems therefore significant to look for correlations between the level of turbulence observed at the MP and the type of shock that is upstream. We tried in several ways to identify such a correlation, but no clear result emerged from these attempts. This negative result may mean that the nature of the shock is not the dominant effect. The level of turbulence might for instance depend on both  $\theta_{\text{BN}}$  and Mach number, high-latitude shock crossings tending to have lower Mach number than those nearer the equator. It could also be argued that the dominant turbulence due to quasi-parallel shocks may be in a frequency range smaller than the range under study.

[21] The absence of a significant correlation between  $\theta_{\text{BN}}$  and the turbulent power at the MP can finally be due to the technical difficulties to achieve such studies: far from the subsolar point, it is actually difficult to know where is the section of the shock that is upstream of the observed MP



**Figure 4.** Influence of the solar wind pressure: (left) Average energy density in the magnetosheath adjacent to the magnetopause (Cluster/STAFF) as a function of the solar wind dynamic pressure (ACE data). (right) Maximum energy density of magnetic fluctuations at the magnetopause  $P_{\max}$  as a function of the solar wind dynamic pressure.

and temporal effects cannot be fully disregarded. To overcome this difficulty, we tried to use the angle  $\theta_{\text{BR}}$  between the Earth-spacecraft vector  $\mathbf{R}$  and the interplanetary magnetic field (measured upstream by the ACE spacecraft) as a crude, but instantaneous, proxy of  $\theta_{\text{BN}}$ , but no better correlation emerged. More refined correlations can also be attempted using models of flow propagation in the MSH; as in work by *Shevryev et al.* [2006, and references therein].

[22] Another technical difficulty is that, when the magnetopause is observed in the front region (as reported in the ISEE statistics), an increase of the pressure is directly related to an Earthward motion of the boundary. On the other hand when the observation takes place far from the front region, the relation is much more complex because the MP does not move as a solid body, and so the global shape of the magnetopause is likely to be modified by the pressure increase.

[23] The correlation between the ULF fluctuations at the MP and in the solar wind would also deserve a study, but it has not been performed hitherto. It may be the subject of future work.

#### 4. Role of the Magnetic Shear in the MP Plane

[24] In BR01, a fast magnetosonic mode wave approaching the magnetopause from the MSH is converted into an Alfvén wave at the density gradient of the boundary. Then the Alfvén wave propagates backward toward the MSH. At the point where the magnetic DC field  $\mathbf{B}$  becomes perpendicular to the wave vector, the wave is no longer able to propagate. The Alfvén wave is therefore trapped in the boundary, which could explain the observed increase in the wave power. As long as the incident wave vectors are more or less randomly distributed, the trapping is likely to have more effect when the rotation of the  $\mathbf{B}$  field is larger. If this

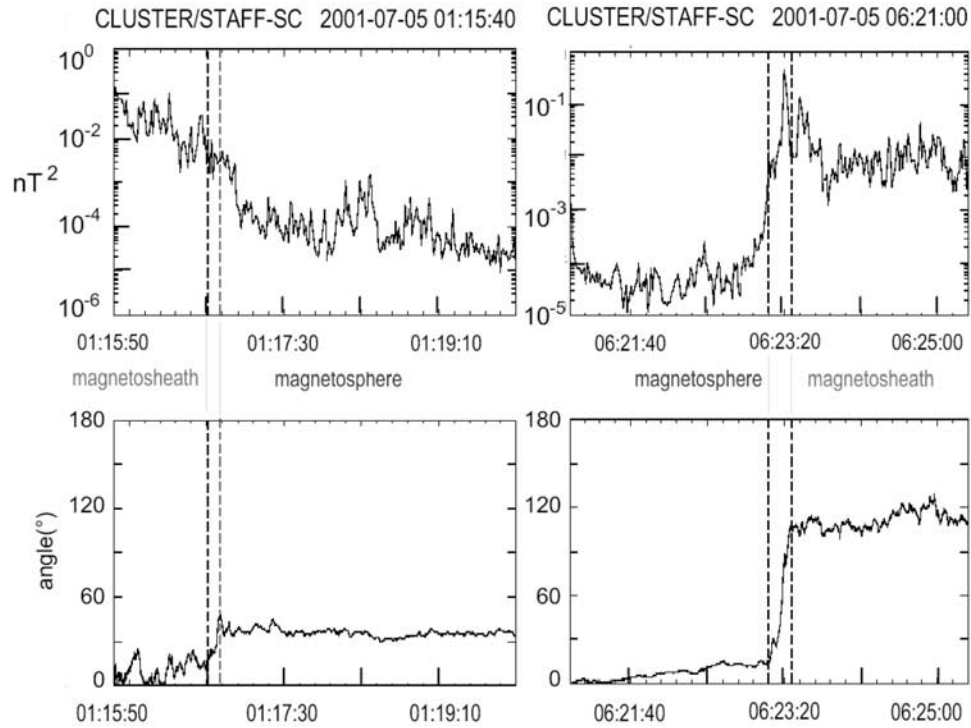
model, or a similar one, applies at the MP, it shows that the shear angle can, in some scenarios, play a role in the amplification of the fluctuations at the boundary. It is therefore quite useful to look for such signatures in the data. In order to get rid of the preceding effect of control of the fluctuation level by the MSH magnetic compression, we will use in this section normalized energy densities  $P^* = P/\langle B^2 \rangle$ . We present here two case studies and two statistical results: the first result relates the normalized peak energy density  $P_{\max}^*$  at the MP and the  $\theta$  angle. The second relates the enhancement ratio  $P_{\max}^*/P_{\text{msh}}^*$  to the value of  $\theta$ .

##### 4.1. Examples

[25] Before going to the main statistical results hereafter, let us present two typical examples that provide a good illustration of the property under study. Two cases are illustrated in Figure 5. In the first one (left column), the rotation angle is weak (around  $10^\circ$ ) and no noticeable enhancement is observed in the fluctuation energy density. In the second case (right column), the rotation angle is large (around  $100^\circ$ ) and there is a clear maximum in the fluctuation energy density at the MP crossing. The second case is quite similar to the case presented from Cluster spacecraft in work by *Rezeau et al.* [2001]. The striking difference observed between the two cases tends to indicate that the behavior of the waves at the MP indeed depends on the rotation angle. We shall now try to settle this result on a statistical basis and show that it is generic and not due to coincidental variations of the plasma parameters (These exemplary cases do not belong to the statistics, but they are nevertheless quite typical).

##### 4.2. Correlation Between $P_{\max}^*$ and $\theta$

[26] In Figure 6, it appears that the normalized maximum energy density in the MP transition  $P_{\max}^*$  is strongly corre-



**Figure 5.** (bottom left) Magnetopause crossings (dashed lines) with a low rotation of  $\mathbf{B}$  (FGM); (top left) the wave energy density profile (STAFF-SC) show no amplification. (bottom right) In the high rotation case, the wave energy density profile show a strong amplification compared to (top right) the mean level in the magnetosheath.

lated with the rotation angle  $\theta$ . This result is consistent with the result obtained by *Song et al.* [1993] who have shown that the power at the MP is higher when the Interplanetary Magnetic Field is South than when it is North since the local rotation angle is related to the IMF cone angle (the correlation is not simple, it depends on the location on the magnetopause but one can expect the local rotation angle to be small when IMF is North and large when it is South). This result proves that the magnetic shear angle indeed plays a crucial role, as in BR01, in the interaction process of the incident low-frequency fluctuations with the boundary. This result may still result from two different effects:  $P_{\max}^*$  may increase via an increase of the incoming fluctuation energy density  $P_{\text{msh}}^*$  or via an increase of the amplification mechanism  $P_{\max}^*/P_{\text{msh}}^*$ . The first parameter ( $P_{\text{msh}}^*$ ) is indeed not clearly correlated with  $\theta$  (result not presented here). This is confirmed by the study of the second one.

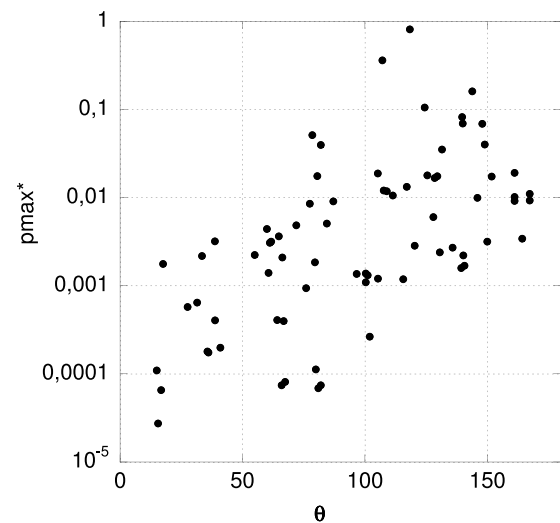
#### 4.3. Correlation Between $P_{\max}^*/P_{\text{msh}}^*$ and $\theta$

[27] In Figure 7, it is quite clear that a correlation exists between the amplification parameter  $P_{\max}^*/P_{\text{msh}}^*$  and the rotation angle  $\theta$ . For a low magnetic shear, the amplification process described above is not efficient, and the fluctuation energy density inside the boundary just decays to reach the magnetospheric level without any amplification. This can explain the few points where  $P_{\max}^*/P_{\text{msh}}^*$  is slightly less than 1. This result shows that the role of the magnetic shear is fundamental, not only for the absolute level of the fluctuations, but also for the amplification factor. Traditionally the magnetic shear is understood as a driver of a local instability, but the correlation between the MSH incident energy

and the wave energy at the MP seems in better agreement with the idea of an amplification of waves from one to the other.

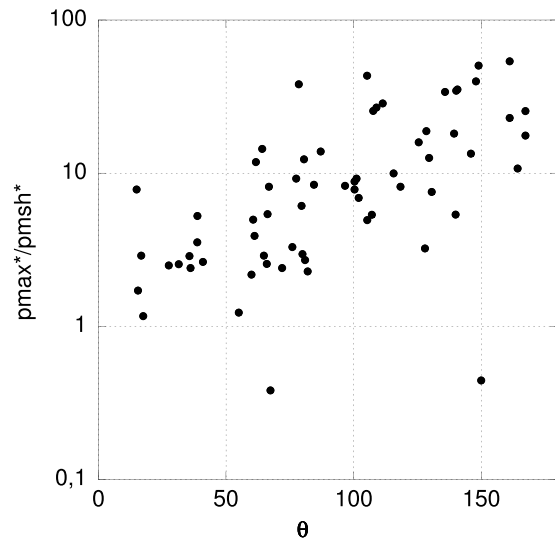
## 5. Conclusion

[28] The present study reinforces the idea that the ULF waves observed at the MP have an external source of



**Figure 6.** Cluster: relation between the  $\mathbf{B}$  shear angle  $\theta$  at the magnetopause crossing (FGM) and the normalized peak energy density (STAFF)  $P_{\max}^* = P_{\max}/\langle \mathbf{B}^2 \rangle$ . One point by crossing.





**Figure 7.** Cluster: relation between the  $\mathbf{B}$  shear angle  $\theta$  (FGM) at the magnetopause crossing and the dimensionless amplification parameter defined as  $P_{\max}^*/P_{\text{msh}}^*$  (STAFF).

energy. It has been shown that the level of fluctuations at the MP is greater for higher solar wind pressure and that this correlation persists even when the fluctuation level is normalized to the DC magnetic field, allowing us to remove the effect of the direct compression of the magnetosphere under conditions of higher ram pressure. Considering that the energy comes to the MP from the MSH, and that the plasma is collisionless, the most natural means for this transfer are waves. The nature and the characteristics of the MSH ULF waves could not be properly diagnosed until recently, because of the intrinsic mixing of turbulence and the difficulty of estimating the Doppler effect, but the multipoint measurements of Cluster now begins to provide trustable results. Cluster data have been used to show that Doppler-shifted “mirror modes” play an important role in explaining the observed fluctuations in the magnetosheath [Sahraoui et al., 2003, 2006]. These authors have demonstrated, in a case study, that a mirror mode, which has a zero frequency in the plasma frame, was observed at high frequencies because of Doppler effect. Comparable results had already been reported for long from monospacecraft data in cases of quasi-monochromatic fluctuations (see for instance Tsurutani et al. [1982], Lacombe et al. [1992], or Song et al. [1992]); nevertheless, the departure from a zero frequency was most often attributed to “drift mirror modes,” (the “drift” being due to the current in a background inhomogeneous pressure) rather than to plain Doppler shift (because of the motion of the measurement sensor relative to the plasma). The existence of such various modes anyway shows that the simple idea suggested in BR01 (where the incident ULF waves were supposed to be “fast modes”) that the shear angle may play a role in the wave amplification at the MP, needs to be revisited to take into account the more complex reality observed by Cluster. The statistics presented here indeed clearly show the key role played by the rotation of the magnetic field in the boundary, which is consistent with the wave trapping in the MP that

was found in this model. This result will have to be taken into account in any new model of the turbulence/boundary interaction.

[29] The spatial distribution in latitude and local time of the MP wave energy density does not lead to clear correlations with the wave energy density at the MP or with that in the adjacent MSH. As the observations of MP crossings by Cluster, due to its trajectory, are all far from the subsolar point, it seems possible that the convection by the flow along the MP, over quite long distances, may blur these effects. A study of simultaneous MP crossings involving Cluster and Double-Star Program should clarify this point: the equatorial spacecraft TC1 of DSP (launched in 2004) crosses the dayside MP close to the equatorial plane at the same local time as Cluster, at least its first year of operation. TC1 carries on board the spare model of the Cluster STAFF experiment allowing us to perform the same type of analysis as presented here [Cornilleau-Wehrin et al., 2005]. This is the subject of another study.

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