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L. Rezeau, G. Belmont, N. Cornilleau-Wehrin, F. Reberac, Cyril Briand. Spectral law and polarization properties of the low-frequency waves at the magnetopause. *Geophysical Research Letters*, 1999, 26 (6), pp.651-654. 10.1029/1999GL900060 . hal-00408119

**HAL Id: hal-00408119**

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Submitted on 3 Sep 2020

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## Spectral law and polarization properties of the low-frequency waves at the magnetopause

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**Abstract.** The magnetic fluctuations, at the magnetopause and in the adjacent magnetosheath, exhibit power law spectra which are very reminiscent of turbulent spectra. In prospect of future modelizations of such a turbulence, new information is brought about the experimental properties of these fluctuations. The power laws spectra previously obtained in the ULF range are shown to hold also in VLF, up to the lower hybrid frequency. Concerning the polarization, 1) the direction with respect to the static magnetic field is shown to be dominantly perpendicular at low frequencies, consistently with Shear Alfvén modes in this range, and 2) no right-hand sense of rotation can be evidenced at frequencies higher than the proton gyrofrequency, although one could expect the fast magnetosonic mode to be dominant in this range. The physical implications of this last observation for the non linear effects at work in the turbulence are briefly discussed.

### Introduction

The magnetic fluctuations related to the solar wind-magnetosphere coupling have been studied for almost twenty years. It is now well known that the level of these fluctuations is high in the magnetosheath, with a sharp maximum at the magnetopause [Labelle and Treumann, 1988]. Early experiments had already shown on a few examples that these fluctuations have a monotonous spectrum [Gurnett *et al.*, 1979]. These authors used the search-coil magnetometer of ISEE which allows to explore the frequencies higher than 5.6 Hz [Anderson *et al.*, 1982]. A systematic study has been performed afterwards in the Ultra-Low-Frequency range using the GEOS 2 spacecraft [Rezeau *et al.*, 1989]. It showed that these spectra have a  $f^{-\alpha}$  law and that spectra in the magnetosheath plasma adjacent to the magnetopause have similar power law, except that the level is lower and the slope steeper in the magnetosheath than at the magnetopause: on average  $\alpha \approx 2.5$  at the magnetopause and in the boundary layer,  $\alpha \approx 2.8$  in the magnetosheath. Some features of the observations have now a likely explanation: as magnetic turbulence is permanently observed in the magnetosheath (presumably generated at the bow shock), it seems that the high amplitude magnetopause fluctuations can be due to an amplification of these magnetosheath waves when propagating across the magnetopause [Belmont *et al.*, 1995, Johnson and Cheng, 1997, De Keyser *et al.*, 1998]. Apart from this explanation, the alternate possibility remains that local instabilities could occur at the boundary [Tsurutani *et al.*, 1998]: even if this interpretation appears less appropriate for explaining a permanent feature, it is true that different kinds of instabilities may occur frequently at the magnetopause since many parameters do exhibit shears or gradients there. For the sake of interpreting the data in terms of turbulence theories (even if those theories

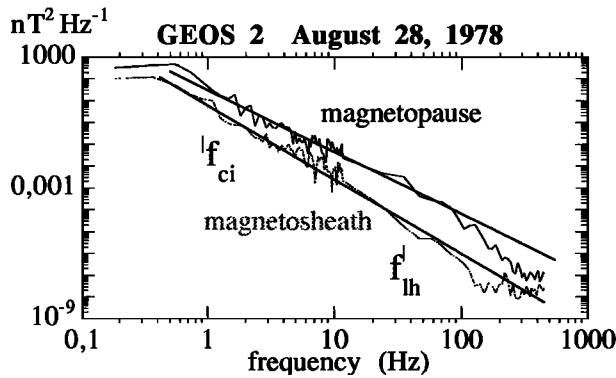
do not exist hitherto for such media and such frequencies), wave number spectra are generally needed. A major difficulty, in magnetospheric studies, comes from the nature of the observations: data recorded with a single spacecraft yield time series and therefore frequency spectra, and it is *a priori* difficult to deduce wavenumber spectra from them, except if the Taylor « frozen-in flow » approximation was valid, i.e. if the flow velocity was much larger than all the wave propagation velocities. This is verified in the solar wind, where the bulk velocity is much larger than the Alfvén velocity, allowing for several turbulence analysis [e.g. Matthaeus and Goldstein, 1982, Tu and Marsch, 1995], but it is not in the magnetosheath or in the magnetosphere. The only solution to the problem is to make multipoint measurements in the turbulent regions. This is going to be done in a near future with CLUSTER. The data from four spacecraft are not sufficient *a priori* to compute a full wavenumber spectrum, but they will allow to remove a large part of the spatio-temporal ambiguity [Pinçon and Lefeuvre, 1992]. Awaiting for this project, some more information can be obtained from the one-point measurements, since some features of the spectra had not yet been investigated in the past, especially the study of a possible polarization of the fluctuations.

### Spectral Laws

In this section, a particular case is analyzed to stress some important characteristics of the frequency spectra. Figure 1 shows the spectra from GEOS 2 data (day August 28, 1978) for two different times. The most intense one corresponds to a magnetopause crossing, the other one to the adjacent magnetosheath. A difference in the frequency resolution can be seen around 11 Hz: it corresponds to a change in on-board processing: below 11 Hz is the ULF part of the experiment (time sampling = 0.043 s, spectrum computed on 5.5 s), above 11 Hz is the ELF part (time sampling = 0.000671 s, spectrum computed on 0.086 s). The first interesting property is the fact that both spectra can be accurately fitted by a power law over a large frequency range, extending approximately from the proton gyrofrequency to the lower hybrid frequency. Below the proton gyrofrequency, a change of tendency is observed but, due to the effects of the spacecraft spin frequency, the experiment does not allow to explore low enough frequencies to analyze this change quantitatively. Above 50 or 100 Hz the spectra begin to decrease much more steeply and reach the noise level around 200 Hz. In this high frequency range, the magnetopause spectrum can be fitted by a power law with an index approximately equal to 5 (the accuracy is bad due to the small number of values on which the fit is performed). This result extends what was obtained on the basis of ULF data only [Rezeau *et al.*, 1989]: the power law of the spectra is valid above the gyrofrequency up to a frequency around 100 Hz which has the order of magnitude of the lower hybrid frequency. The second interesting property is the difference in the spectral indices for the two regions:  $\alpha \approx 2.8$  in the magnetopause,  $\alpha \approx 3.4$  in the magnetosheath. Both values are much larger than the 5/3 value of hydrodynamics [Kolmogorov, 1941] or the 3/2 value of

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Paper number 1999GL900060.  
0094-8276/99/1999GL900060\$05.00



**Figure 1.** Total spectral density of the fluctuations in the magnetopause (5:44:25) and in the magnetosheath immediately after (5:44:31). The power fits are performed between 0.6 and 100 Hz for both spectra. The  $|$  indicate the value of the characteristic frequencies of the medium (gyrofrequency and lower hybrid frequency) for the two periods of time, below the curves for the lowest one and above for the other one.

MHD [Kraichnan, 1965], and their difference can bring an important experimental constraint for future theories, for the nature of the non linear effects as well as for the localization of the sources.

### Discussion of the Doppler effect

Before discussing the possible existence of non-linear effects to explain the power law spectra, the role of Doppler broadening has to be addressed. As noticed in the previous section, the Doppler effect might be present since the plasma in the magnetosheath has a significant bulk velocity [Paschmann *et al.*, 1978]. For a given frequency and wavenumber, the Doppler shift is known to be equal to  $kV\cos(k,V)$ . An exact calculation of this quantity is of course not possible since we do not measure the wavenumber, but an estimation of  $k$  and  $V$  can be done to estimate the Doppler shift. The plasma velocity is usually measured by plasma instruments, unfortunately for the day when most magnetopause crossings were observed on GEOS 2 (August 28, 1978), no velocity measurement was available. An estimate of this velocity can nevertheless be obtained using a magnetosheath model [Spreiter *et al.*, 1968] and the solar wind data [King, 1983]: the values range from 70  $\text{kms}^{-1}$  at 11:00 LT to 240  $\text{kms}^{-1}$  at 8:00 LT. This order of magnitude is consistent with the observations made by the plasma instrument onboard other spacecraft, such ISEE or AMPTE, which give values in the range 100-200  $\text{kms}^{-1}$  [Paschmann *et al.*, 1978, Paschmann *et al.*, 1993, Phan *et al.*, 1994]. As the solar wind velocity was higher on that day than usually (it allowed the magnetopause to reach the geostationary orbit where GEOS 2 was), the obtained value of 240  $\text{kms}^{-1}$  is not surprising. Assuming a linear propagation, the waves can be described by Alfvén waves or fast magnetosonic waves, with a phase velocity of the order of the Alfvén velocity, around 250  $\text{kms}^{-1}$ . Thus the Doppler shift is equal to  $fV/v_\phi\cos(k,V) \approx f\cos(k,V)$ , which is smaller or equal to  $f$ , depending on the angle between the wavenumber and the velocity which is not known. Although this result is far from quantitative, it is important since it implies that the whole shape of the spectra cannot be due to the Doppler broadening of a very low frequency emission; the fluctuations must have a spectrum similar to the observed spectrum, extending up to high frequencies, possibly broadened by a factor 2 (at the maximum) by the Doppler effect. There is another confirmation of this result: if the Doppler effect was dominant in the shape of the spectrum, a strong effect of local time could be expected, with a Doppler ef-

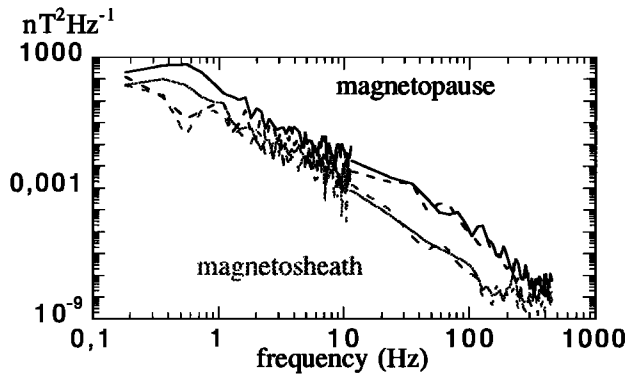
fect decreasing with decreasing flow velocity, that is from the flanks of the magnetopause towards the nose. The fact that the GEOS 2 spacecraft performed a sampling of the magnetopause over a wide local time range allows to discuss that point: from 8 to 13 LT, the observed spectral laws are the same ( $f^{-\alpha}$ ). The only noticeable feature is a weak decrease of the spectral index (less than 10% and for only one component). This study, performed on the ULF part of the spectra, confirms that the Doppler broadening has a minor contribution in the shape of the spectra.

This conclusion means that it is meaningful to discuss the role of non-linear effects to explain the shape of the spectra, as in hydrodynamic turbulence theory. In this context, the  $k^{-\alpha}$  laws are due to strong non-linear interactions between successive scales [Kolmogorov, 1941, Frisch, 1995]. It is not clear in our case that such strong non-linear effects are present. The fact that the magnetic fluctuations are only 15% of the static magnetic field would rather mean that weak non-linear coupling is happening [Rezeau *et al.*, 1986]. This justifies the search for the properties of the linear modes in the turbulence, since it is likely that it can be described in terms of linear modes weakly coupled by non-linear effects.

### Identification of linear modes

The properties of the linear modes in low frequency range are quite well-known, especially under the assumptions that the frequency is negligible with respect to the proton gyrofrequency (MHD range) and that the temperature is low ( $\beta \ll 1$ ): three modes can exist, the shear Alfvén mode, and the two magnetosonic modes, fast and slow [Quémada, 1968]. Nevertheless realistic conditions at the magnetopause must be taken into account: the  $\beta$  is not low and, furthermore, the ion temperature is higher than the electron temperature which makes the slow mode completely absorbed (unless it is forced) [Belmont and Rezeau, 1987]. The main features of the remaining two modes are the following: the fast mode propagates at frequencies higher than the proton gyrofrequency as well as lower, it is a compressive mode, which means that the magnetic perturbation can have a component parallel to the static magnetic field and it has a right-hand side polarization with respect to the magnetic field; on the contrary the Alfvén mode is limited to frequencies below the gyrofrequency (without Doppler shift) and has a polarization perpendicular to the static magnetic field. These characteristics can be obtained by analytical calculations under various approximations [Hasegawa and Uberoi, 1982, Belmont and Rezeau, 1987], or they can be computed with a numerical program as WHAMP [Rönmark, 1982], solving the dispersion relation in a fully kinetic plasma. One advantage of the kinetic calculation is to take into full account the ion gyrofrequency and gyroradius effects; nevertheless, one must keep in mind that the wavelengths approaching the magnetopause thickness (which is of the same order of magnitude as the ion gyroradius) cannot be compared meaningfully with the homogeneous results provided by the program.

With the above results, the interpretation of the magnetopause fluctuations can *a priori* be anticipated: above the proton gyrofrequency they must propagate on fast mode, below there are two possibilities which could be disentangled by their polarization. It is therefore interesting to study the polarization. Generally speaking, the reference to a "static magnetic field" in a highly inhomogeneous region as the magnetopause is problematic; nevertheless, at the time considered on Figure 1 the spacecraft made a small entry in the magnetopause and never completely reached the magnetospheric side of the boundary; so that the rotation of the static magnetic field was not a full rotation and considering the polarization relative to the magnetic field is not meaningless. Figure 2 shows the parallel and perpendicular components of the fluctuations for the same times as



**Figure 2.** Comparison of the parallel (dashed line) and perpendicular (continuous) components of the fluctuations, relative to the average magnetic field. The ULF spectra are computed over 11 seconds to increase the resolution. The time periods are the same as in Figure 1. The ELF spectra are still computed over 86 ms and averaged afterwards.

in Figure 1. It is clear that there is a change in the polarization around the gyrofrequency, the perpendicular component being dominant below it, whereas both components get similar values above. This indicates that shear Alfvén mode is most certainly present at low frequencies. This observation is consistent with the results of *Anderson et al.* [1991] on AMPTE data: they interpreted the low frequency part of the spectrum as ElectroMagnetic Ion Cyclotron waves which is the name they give to the non-MHD part of the shear Alfvén mode.

### Sense of rotation of the fluctuations

The rotation sense of the waves is an additional indication to interpret the observations. Figure 3 shows the foreseen "rotation parameter" for both propagation modes:

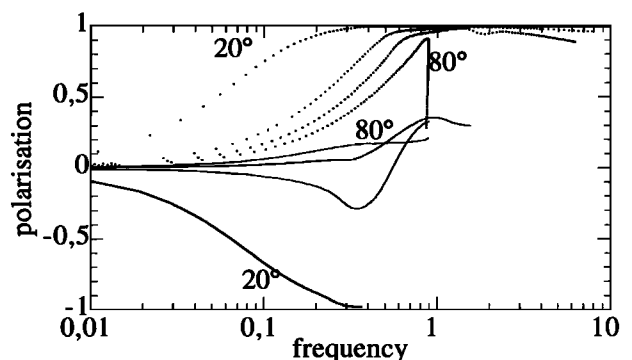
$$R = \frac{2 \operatorname{Im}(b_x b_y^*)}{|b_x|^2 + |b_y|^2} \text{ where } b_x \text{ and } b_y \text{ are the components of magnetic perturbation perpendicular to the static magnetic field. } R \text{ is equal to 1 for a right polarized wave, -1 for a left polarized wave, and 0 for a linearly polarized wave. It is computed with the WHAMP program run in the same conditions as the experimental ones (as far as possible), that is } B = 80 \text{ nT, } n = 50 \text{ cm}^{-3}, T_e = 40 \text{ eV, } T_i = 300 \text{ eV (measured by } \textit{Rodgers et al} [1984] \text{ around 5:36 on the same day). Apart from the very low frequencies or the quasi-perpendicular propagation, the fast mode appears to be a right polarized wave, whereas the shear Alfvén mode is left polarized for small propagation angles, but can change polarization above a given angle. This result obtained in a high } \beta \text{ case (} \beta \approx 1) \text{ is similar to the result obtained by } \textit{Belmont and Rezeau} [1987] \text{ for a low } \beta \text{ plasma. It shows that the rotation sense is not a good test to decide between the two modes below the proton gyrofrequency but that, above the proton gyrofrequency the observed polarization should be right-handed, which can be tested on data.}$$

Figure 4 (top panels) shows the ratio  $R$  calculated for the spectra shown on Figures 1 and 2. Below the proton gyrofrequency (1 Hz), no preferential sense of rotation comes out, which could be foreseen from the above theoretical analysis since two different modes (right and left-handed) can be present simultaneously in this range. But nothing comes out either above the gyrofrequency, which seems to contradict the existence of the only fast mode in this frequency range. Before accepting this result as a physical one, several checks have been performed since the determination of the sense of rotation

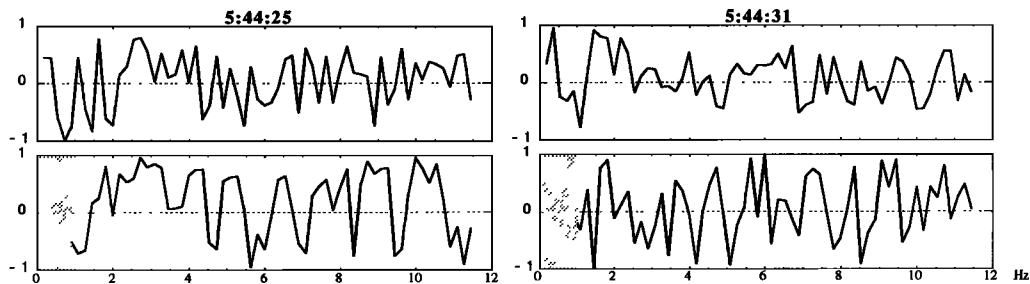
grounds upon the phase of the Fourier components and that this information can easily be polluted by inadequate data handling. First, we have analyzed magnetosheath samples instead of magnetopause crossings since, when the "static" magnetic field  $B_0$  varies too quickly within the analysis sample, the plane "perpendicular" to  $B_0$  cannot be defined properly. The search coil itself is not in question since in other regions of the magnetosphere polarized waves were identified [*Perraut et al.*, 1979]. The main difference with the cases presented earlier could lie in the spectral law: when intense low frequencies are present, a detailed study of simulated signals has shown that the phase of the high frequency components can be lost if no care is taken [*Reberac*, 1998]. To keep the phase information in the high frequency range, the low part of the spectrum has to be taken off by a moving average filtering, and an appropriate tapering for avoiding all side effects (a  $\sin^2$  function for instance). With all these precautions, the sense of rotation of a simulated signal can be restored, but, as shown on Figure 4 (bottom panels), no sense of rotation can be seen on the data: the values of  $R$  seem to be randomly distributed. This means that left and right handed waves are superimposed, but not that the polarization is linear (in that case,  $R$  would be equal to 0). As a final remark it can be noticed that the Doppler effect, discussed in the previous section, cannot explain the loss of polarization: if the Doppler shift is at most equal to the frequency itself, the low frequency left handed polarization can leak up to twice the proton gyrofrequency, but not much higher and the polarization should come out for higher frequencies. One must then yield to the evidence that there is no right-handed polarization in the part of the spectrum where the linear theory anticipates it. The consequence is that most likely non-linear effects have to be taken into account.

**Summary and discussion of the possible nonlinear effects**

It has been shown that the spectral laws observed at the magnetopause and in the adjacent magnetosheath are not mainly due to Doppler effect. As the flow velocity is of the same order of magnitude as the Alfvén velocity, the Doppler shift can be expected to be, at worse, equal to the frequency itself. In fact, it is likely to be smaller since the medium characteristic frequencies are visible in the spectra (a change of polarization is observed at the proton gyrofrequency). The attempt of identifying the linear modes properties in the data is only partially successful: the enhancement of the component perpendicular to the magnetic field below the proton gyrofrequency is an indication of the presence of shear Alfvén waves in that range. On the



**Figure 3.** Polarization of the fast mode (dotted line) and the shear Alfvén mode (solid line) for different propagation angle: 20°, 45°, 60° and 80°. The horizontal line is the ratio frequency/gyrofrequency.



**Figure 4.** Polarization ratio computed on the data shown on Figure 1 and 2. The left row is for the magnetopause spectrum, the right one for the magnetosheath spectrum. The top panels show the data without filtering or tapering, the bottom panels are obtained after moving average (over 1 second) filtering and tapering by a  $\sin^3$  function.

other hand, above this frequency, the fast compressional mode is expected to be the only possible mode of propagation; it is characterized by a right-handed polarization. A detailed study has been performed to prove that this sense of rotation is not present in the data. It then leads to the conclusion that the fast mode is not recognizable in the higher part of the spectrum.

The observation of power law spectra, as well as the apparent disagreement between the observed sense of rotation and that predicted by linear theory, seem to imply that nonlinear effects are at work. Are these observations consistent with "strong" or "weak" turbulence schemes? "Strong" turbulence involving coherent structures should probably induce both a power law spectrum and a loss of all the properties of the linear modes, in particular the polarization. But it does not seem likely that the ratio  $\delta B/B$  (around 15 %) can be consistent with such an interpretation. This moderate value should rather imply a "weak" turbulence interpretation where the different frequencies are only related to each other through some "wave coupling". Such an interpretation could also lead to power law spectra [Zakharov, 1984], but a priori, it should also keep the main features of the linear modes, in particular their polarisation. In this context, the absence of a definite sense of rotation above the gyrofrequency could not be explained as long as the usual right-handed fast mode remains the only mode existing in this range. As a matter of fact, it is known that a bi-fluid or Hall-MHD theory does provide a continuation of the Shear Alfvén mode above the gyrofrequency [see e.g. Formisano and Kennel, 1969]; but this "intermediate" mode is most generally ruled out for the reason that, from more complete kinetic calculations, it appears to be heavily damped in a homogeneous linear medium. We suggest that it could be the role of the weak non linear effects to force this -usually damped- mode by coupling it with the strong lower frequency fluctuations. This is the subject of future studies.

**Acknowledgments.** The authors thank K. Rönmark for the WHAMP program and T. Oscarsson for fruitful discussion. The data analysis of GEOS data is supported by CNES, the French space agency.

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(Received: October 27, 1998; revised: December 21, 1998; accepted: January 14, 1999)