MAGNETIC PULSATIONS OBSERVED ON BOARD GEOS-2 IN THE ULF RANGE DURING MULTIPLE MAGNETOPAUSE CROSSINGS

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ABSTRACT

During periods of large magnetic activity, GEOS-2 has experienced multiple magnetopause crossings. We describe the characteristics of the ULF waves which have been detected during two of these crossings, the 28th of august and the 29th of september 1978. For both events, the interplanetary magnetic field had a strong southward component. The most striking phenomenon which is observed is the existence of a very strong turbulence, the intensity of which, integrated between ∿ 0.3 and 10 Hz, may reach values as high as 10γ. This turbulence is restricted to a small transition region (∿ 500 km) at the border of the magnetopause, within the magnetosheath. Its role with respect to the reconnection phenomenon is discussed. Further in the magnetosheath, the ULF noise has a much lower intensity and the He^{++} ion seems to play a role in organizing the data.

Keywords : Magnetopause boundary, ULF waves, Low frequency turbulence, Magnetic reconnection, Helium ions.

1. INTRODUCTION

During periods of large magnetic activity (ΣKp_i ∿ 50), the European Geostationary Satellite GEOS-2 has experienced multiple magnetopause crossings in the morning or dayside sectors. We report here the peculiar characteristics of the ULF waves which were observed during these periods. The magnetopause has been studied with *in situ* spacecraft observations since a long time (Ref.2). First measurements of magnetic pulsations in the ULF range (0.2 < f < 5 Hz) were carried out onboard OGO-3 and -5 leading Heppner et al. (Ref.11) to contribute to the important work performed on the average position and shape of the magnetopause on the dayside (see for instance Ref. 19). As was already underlined (Ref. 15), the results which were obtained previously in this frequency range suffer from an insufficient sensitivity and from a lack of precise information on the spectral characteristics of the waves when they can be detected. But the precise knowledge of the spectral structure of the waves is essential for the understanding of their generation mechanisms. Furthermore it could also give us a better insight on the processes which are at the origin of the erosion of the dayside magnetospheric flux.

In Section 2, a brief description of the experiment itself and of the analysing method is given. In the following sections, we will give successively the characteristics of the waves detected in the different regions explored by the spacecraft. We will see (figure 1) that there exists a small region (which we call the magnetopause layer or, in brief, the magnetopause), where the ULF spectrum is characterized by very strong turbulence (Section 3). Further inside the magnetosheath, the ULF intensity has decreased and the residual noise shows a cut-off at the Helium (double charged) gyrofrequency (Section 4). Within the magnetosphere (Section 5) we observe the classical ULF signals (Ref. 15) which consist of Short Irregular Pulsations, magnetosonic modes, etc.. A brief discussion of these results will be given in Section 6. The importance, with respect to reconnection theories, of the existence of a very strong ULF turbulence within a thin magnetopause layer will be stressed.

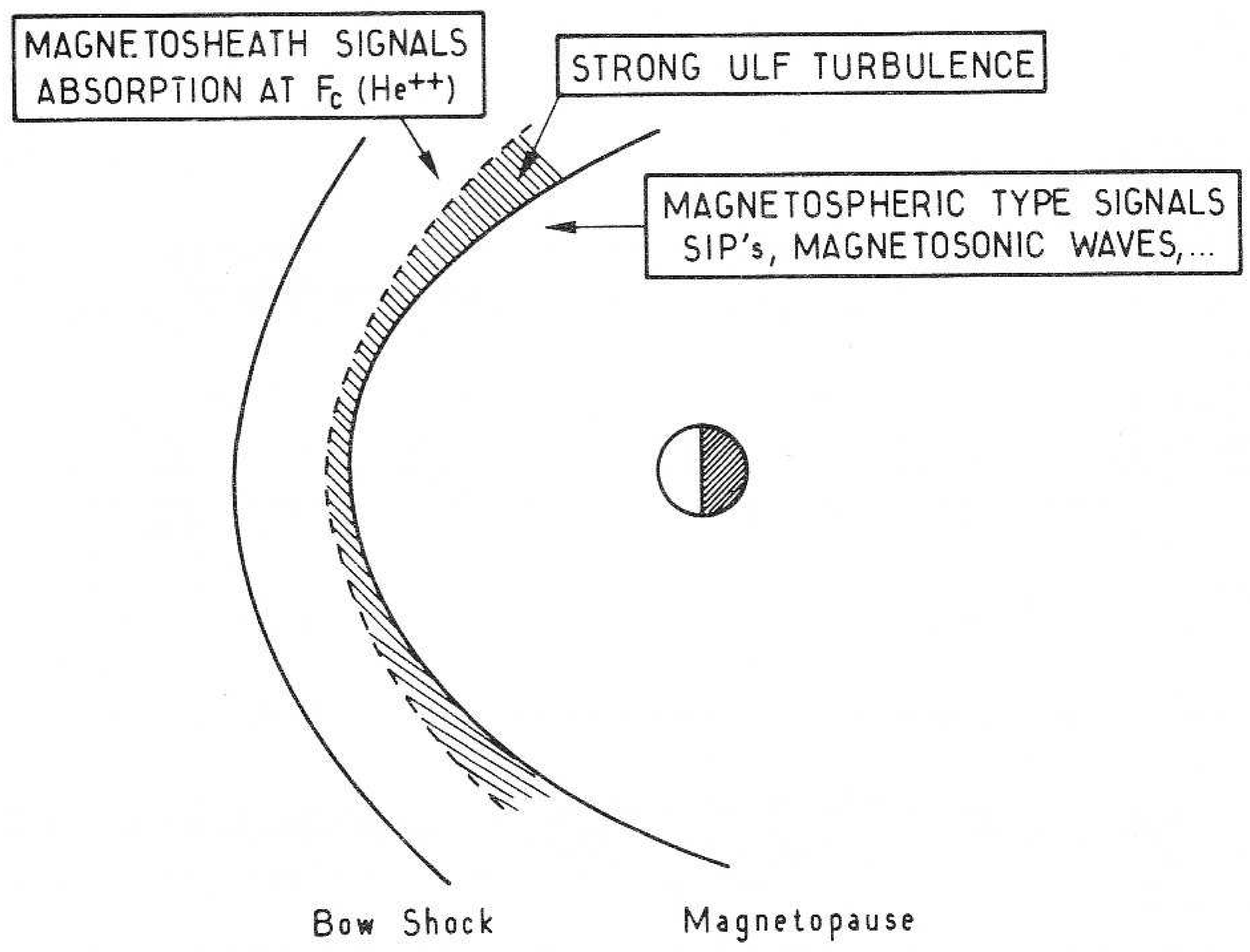

Figure 1. Schematic view of the different regions of the magnetopause, as defined by the characteristics of observed ULF waves.

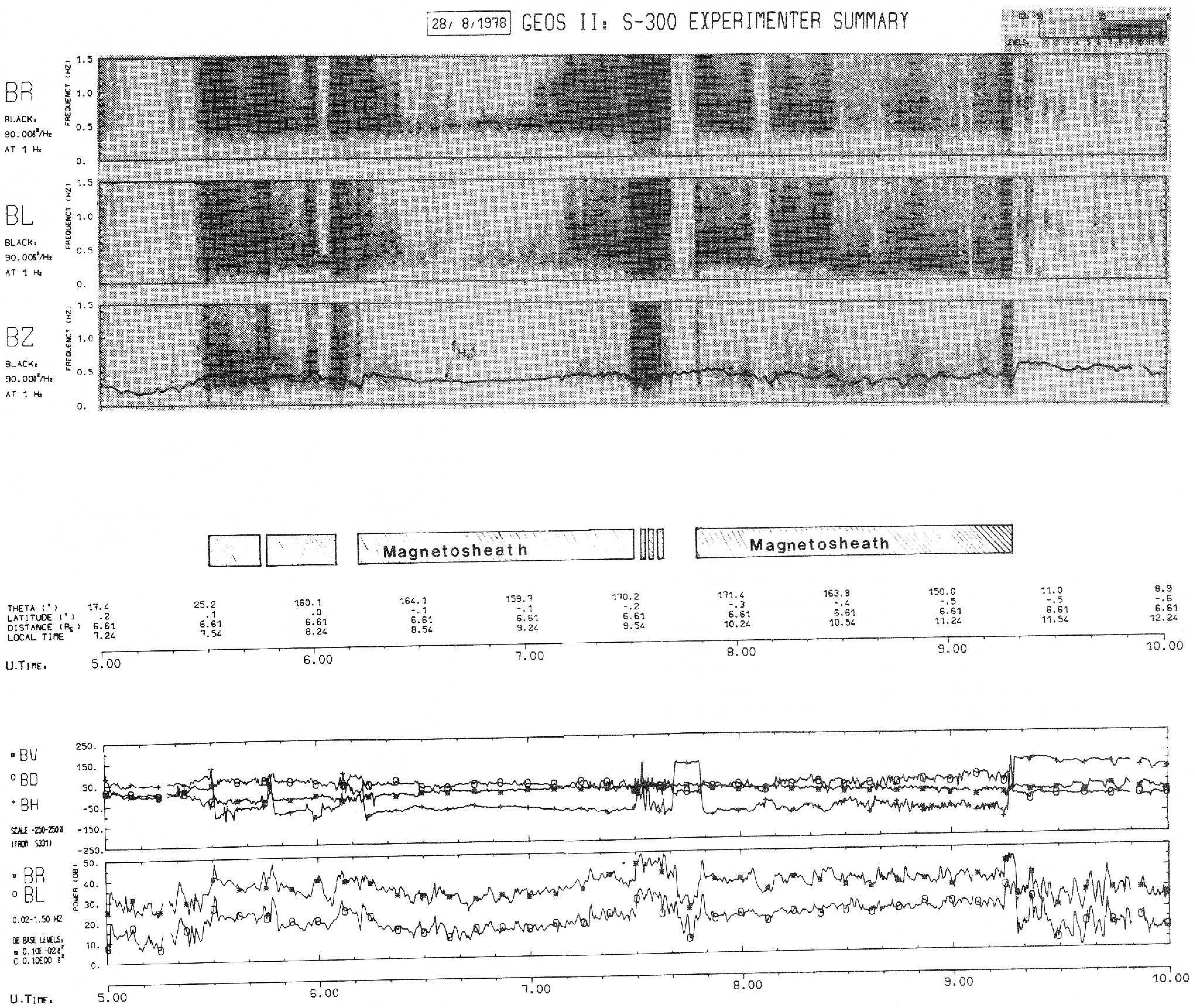

Figure 2. Grey scaling representation of the ULF waves in the frequency range 0.01 - 1.5 Hz is presented in the upper panels for the three components : B_z aligned along the spin axis; B_L and B_R, left and right hand modes in the plane perpendicular to it. In the magnetosheath these denominations must be inverted because the DC magnetic field has reversed its direction. Magnetopause crossings are defined by the inversion of the H component as seen on the fourth panel in which the three components of the DC magnetic field are represented. The bottom panels represents the time variation of the power integrated over 22s and 1.5 Hz for the B_L and B_R components. The 0dB level is equivalent to 10^{-1} γ^2 for B_L and 10^{-3} γ^2 for B_R.

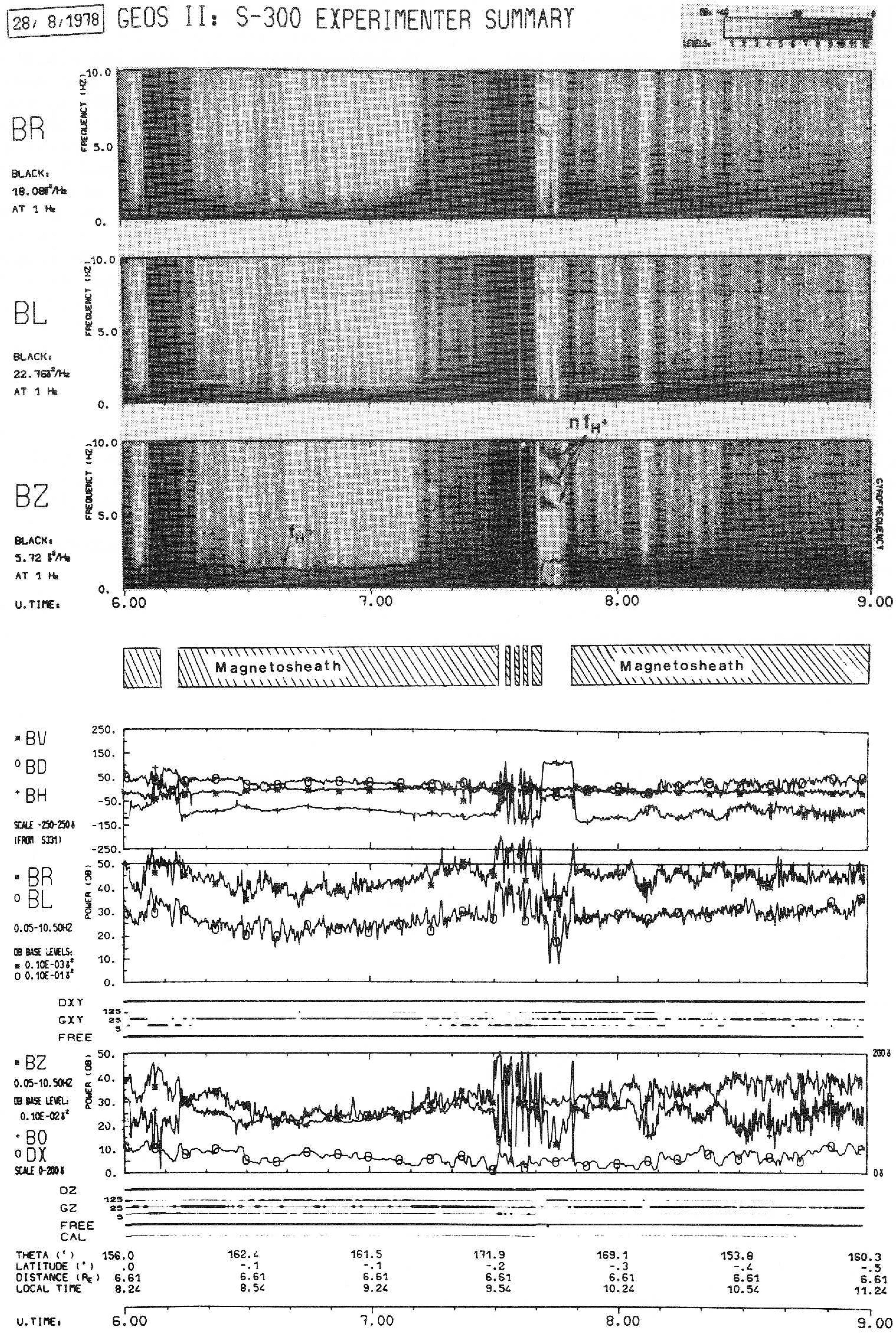

Figure 3. The August 28 event represented on extended time and frequency scales (up to 10 Hz). Same definitions as for Figure 2 except that another panel has been added at the bottom on which is plotted : B_Z, the power integrated over 22s and 10 Hz (0dB = $10^{-3}\ \gamma^2$), B_O, the DC total magnetic field (scale on the right from 0 to 200γ) and DX, the component of the DC magnetic field in the equatorial plane of the satellite (same scale). Note that during the very short incursion of GEOS-2 into the magnetosphere (between 07.41 and 07.49 UT) high harmonics of the proton gyrofrequency are observed.

2. ANALYSIS AND DISPLAYS

The magnetic sensors onboard GEOS cover the frequency range between 0.02 and 11.5 Hz. Three orthogonal components are detected. The component aligned with the spin axis is called B_z. The GEOS-2 orbit is such that the θ angle between the spin axis and the magnetic field is usually smaller than $\sim 20°$. The signal received on the two other components, in the plane perpendicular to the spin axis, is affected by the rotation of the satellite. In the antenna reference system, the energy is splitted into two parts at the frequency $f \pm f_s$ (f being the wave frequency and f_s the spin frequency) depending on the polarization. It is more convenient to consider a stationary frame of reference and to distinguish left (B_L) and right-handed (B_R) components. This splitting effect due to the spin can be removed by applying a complex Fourier Transform followed by a translation in frequency as was suggested by Kodera et al. (Ref. 13). Such a method is applied on a routine basis. The spectra (B_L, B_R, B_z) are computed over 512 points (i.e. 22 s. of signal , the sampling frequency being $\sim$ 23 Hz), and they are plotted as a grey scaled representation. Two frequency scales were retained, one between 0 and 1.5 Hz (see Figure 2) in order to study waves with a frequency below the proton gyrofrequency (in this case the helium (single charged) gyrofrequency is superimposed on the B_z signal as a continuous dark line); the second, between 0 and 10 Hz (see Figure 3), covering almost all the bandwidth of the sensors (in this case the proton gyrofrequency is plotted in the B_z panel). A complementary picture giving the integrated powers of the signal is also systematically generated (lower part of Figures 2, 3 and 5). A more detailed description of the analysing method can be found in Robert et al. (Ref. 17). On the lower part of the figure we have also plotted the component of the DC magnetic field in the VDH system and its intensity B_{o1} (Figure 2). Thus it is very easy to see which region the satellite is moving into. (In this representation, the VDH system is referred as a geographic frame in which V is vertical outward, D is eastward and H is the vector product V x D).

In order to obtain a more precise spectral shape of the turbulence observed during the magnetopause crossings, frequency spectra over 1024 points (44s) were also performed (see Figure 7).

3. ULF WAVES AT THE MAGNETOPAUSE CROSSING

One of the well-known magnetic signature of a magnetopause crossing consists of the sudden variation of the strength or of the orientation of the

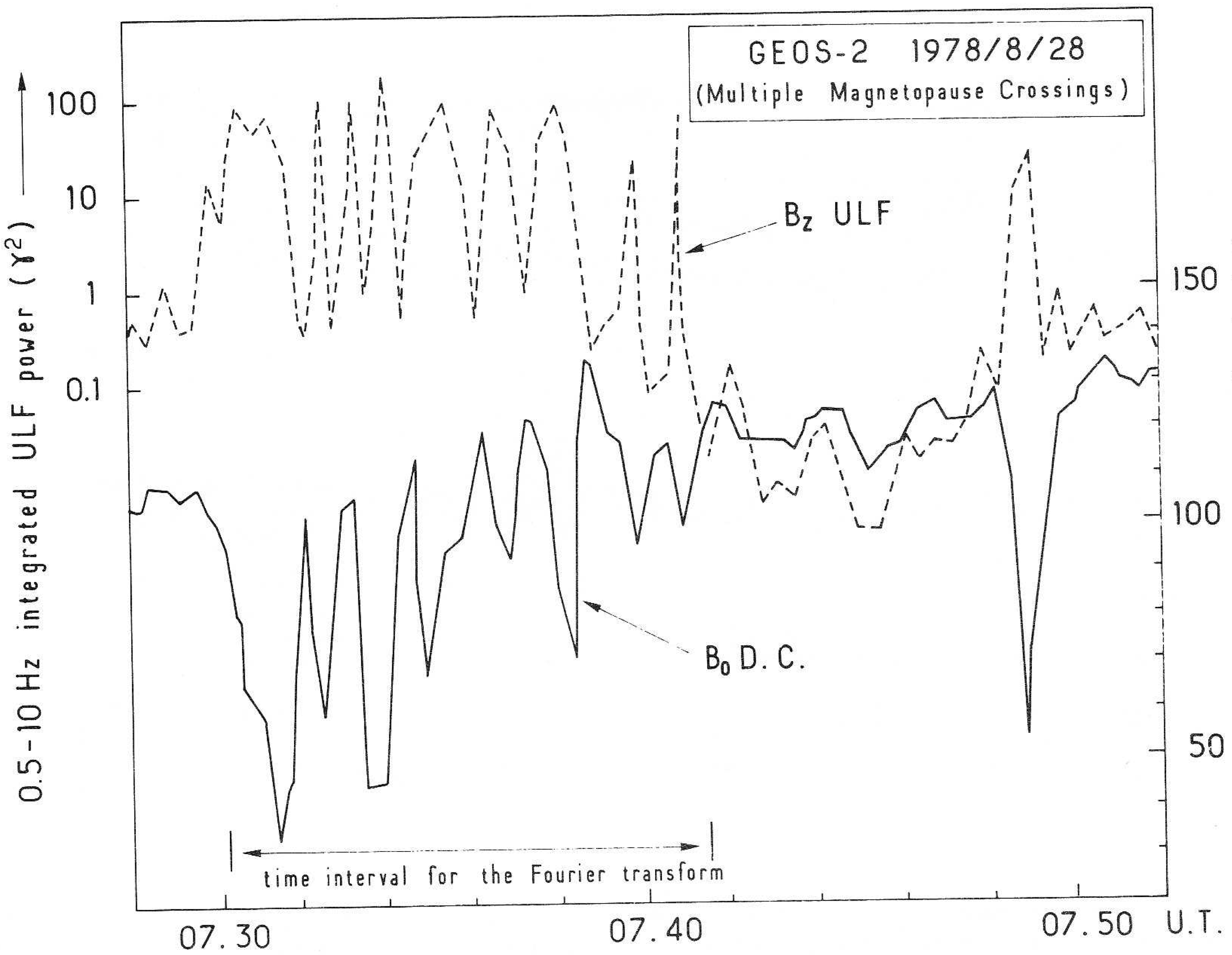

Figure 4. Oscillations of the magnetopause position, as detected by the total amplitude B_0 of the DC magnetic field, and associated changes in the ULF turbulence level B_z (integrated up to 10 Hz). Note the anticorrelation between these two quantities. Also represented the time interval over which a Fourier analysis of these two signals has been performed (see Figure 5).

H component of the DC magnetic field. When the interplanetary magnetic field (IMF) is directed southward, it is possible to detect without ambiguity magnetopause crossings. The θ angle which is of the order of 10 to 20° when the magnetic field is northward takes values around 160 - 170°. On some occasions such a behavior of H and θ were observed onboard GEOS-1 and GEOS-2. As a first step we have selected two especially interesting cases onboard GEOS-2, corresponding to very strong geomagnetic storms, namely August 28, 1978 and September 29, 1978.

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A first crossing occurred at 05.30 UT (07.54 LT). Just at that time a very strong turbulence is recorded on the three magnetic components in the ULF range (Figure 2). The spectrum covers a wide frequency range and extends probably well above 11 Hz, our maximum frequency (see Figure 3); the intensity is very large (b $\sim$ 10γ integrated between $\sim$ 0.3 and 11 Hz) and the polarization is linear (B_L and B_R have the same intensity (see the lower part of figures 2 and 3 and consider that the base levels (in dB) are different for B_L and B_R components : respectively 10^{-1} and 10^{-3} γ^2 on Figure 2 and 10^{-2} and 10^{-4} γ^2 on Figure 3. One observes systematically the same wide band waves for each magnetopause crossing, the period between 07.30 and 07.41 corresponding to multiple crossings. It is clear that each time GEOS-2 enters or leaves the magnetosheath, there is a strong ULF turbulence. But when the satellite stays for a long time deep inside the magnetosheath, the turbulence level has decreased (from 06.13 to 07.30 and from 07.49 to 09.15). The ULF turbulence seems therefore restricted to a narrow region within the magnetosheath, just at the border of the magnetopause. Obviously, with one satellite only, it is not possible to establish how deep the satellite has penetrated into the magnetosheath. But results obtained with the two ISEE spacecraft have shown that the size of the transition region which exists within the magnetosheath at the magnetopause boundary is of the order of 500 km when the Interplanetary Magnetic Field (IMF) is southward, and of the order of 1600 km when it is northward (Ref. 18). During the event we are studying, the magnetosheath B field is clearly southward ($-100\gamma < B_H < -50\gamma$). There is a good evidence that between 06.13 and 07.30 and between 07.49 and 09.15, GEOS-2 was much further in the magnetosheath than 500 km and we see that the noise has strongly diminished. The fact that there exists a narrow region in the vicinity of the magnetopause where the ULF turbulence is enhanced has been already reported on the basis of HEOS-2 measurements (Refs. 1, 7). (See also Refs. 5, 6). Our results extend these observations to lower frequencies where the turbulence is much stronger and they bring new information about the power spectra and polarization of these emissions.

During the time period from 07.30 to 07.41, GEOS-2 experienced multiple magnetopause crossings. This period has been studied in detail. On Figure 4 we have plotted the integrated power of the B_z component (from 0.05 Hz to 10.5 Hz) as a function of time, together with the amplitude B_o of the DC magnetic field. Although the sampling rate (22s) is too large to enable us to observe the zero field which should be associated with the neutral sheet crossing, it is clear that the amplitude of the ULF wave is larger when the DC magnetic field is lower : the ULF turbulence is very strong when we are at the center of the magnetopause current. We will comment on this point in the discussion Section.

It is also worth noticing that the magnetopause seems to present an oscillatory motion during this period. Similar motions were reported by Williams (Ref. 21) by using three-dimensional energetic ion distributions. We have computed the spectra of the oscillations of the total magnetic field B_o and of the envelope of the ULF signal (B_z component) (see Figure 5). The two

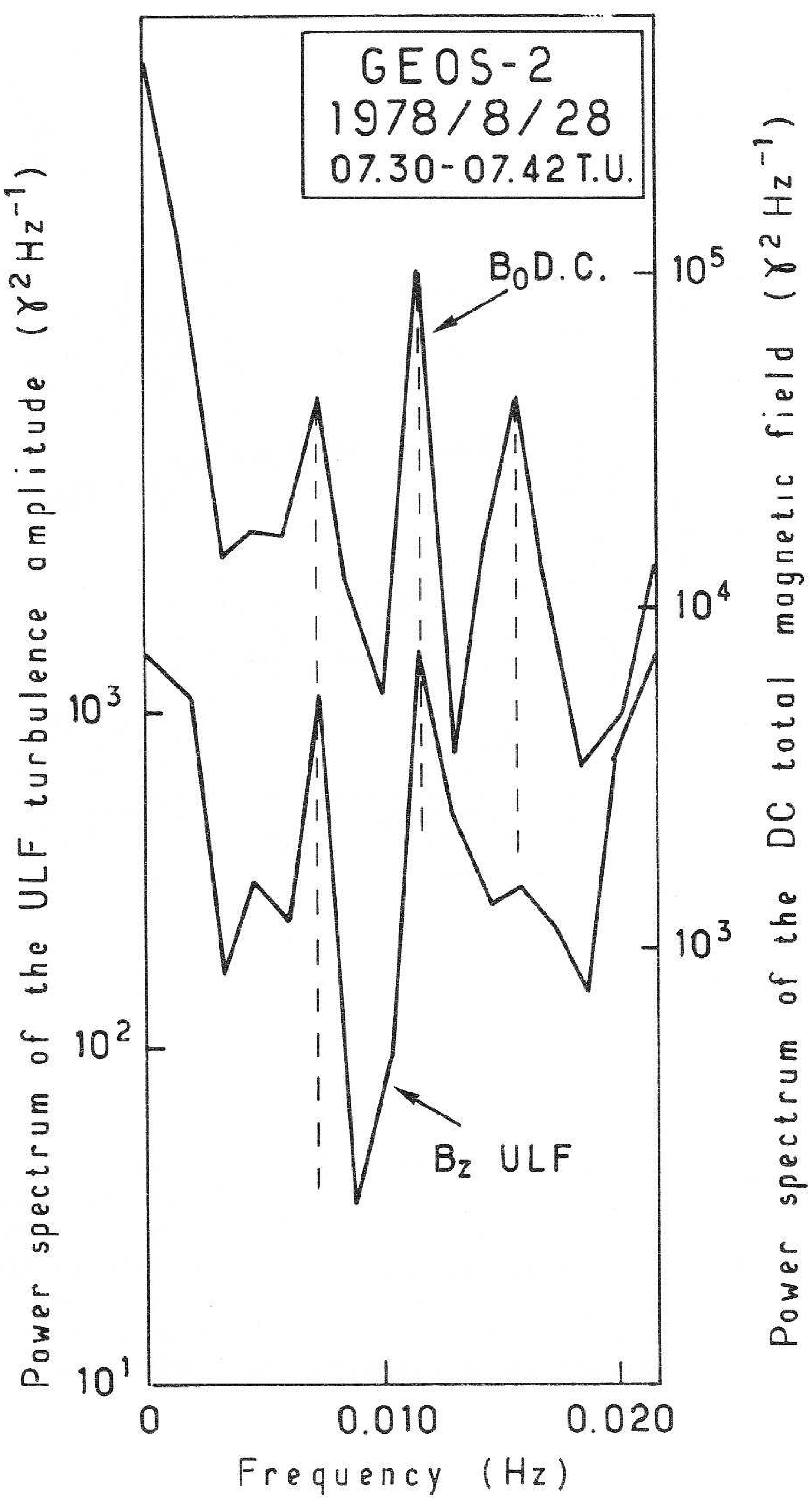

Figure 5. Power spectra of the oscillations of B_o and B_z between 07.30 and 07.44 UT. Spectral peaks occur in the Pc4-5 frequency range.

spectra present peaks at the same frequencies (around 10^{-2} Hz). This corresponds to periodicities of the order of 100s for the motion of the magnetopause. This value is in agreement with the results of Williams et al. (Ref. 22) who found

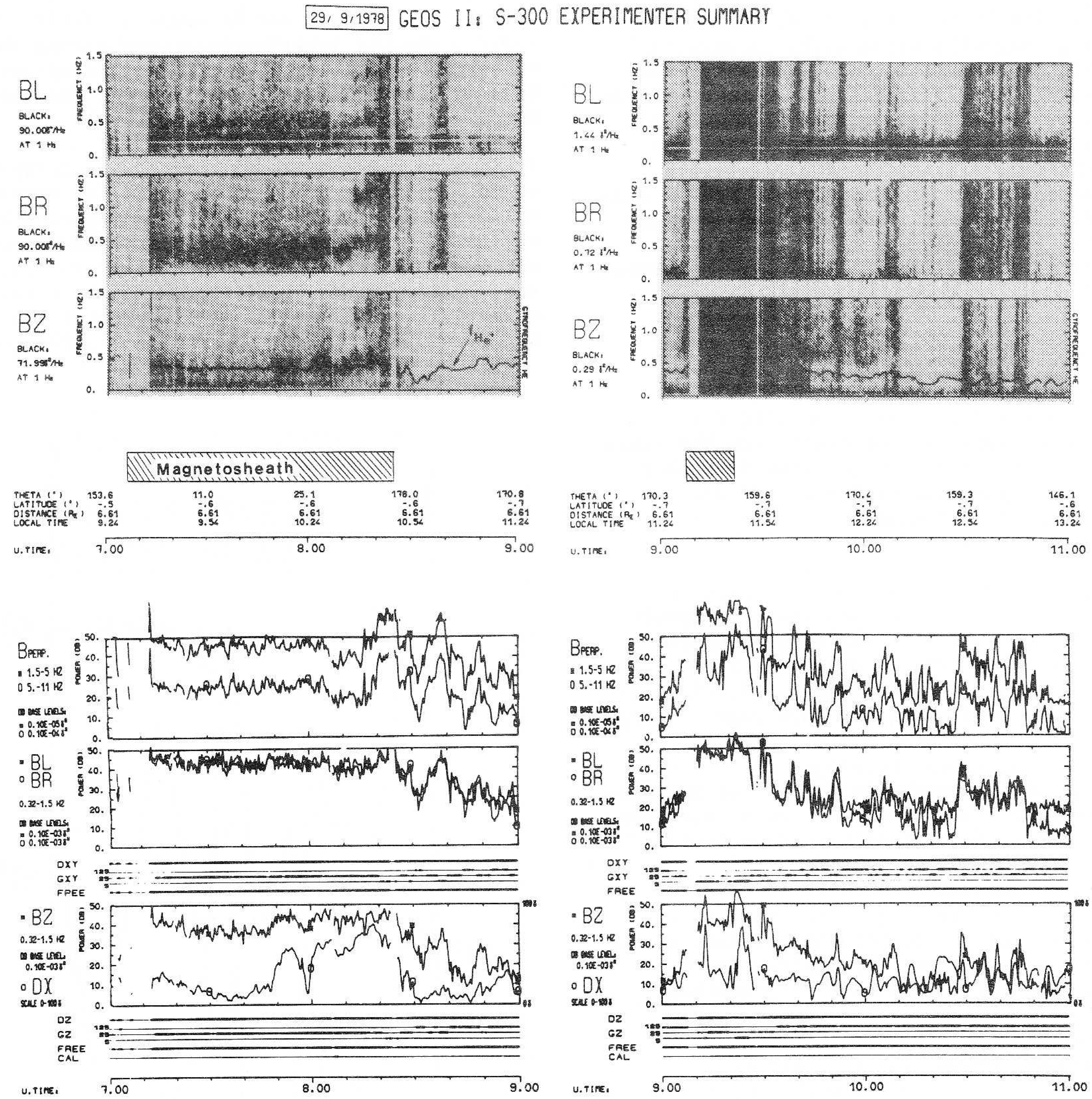

Figure 6. The September 29 event. Same definitions as for Figure 3 except that the fourth panel from the top corresponds to the power of the total perpendicular AC field, integrated between 1.5 and 5 Hz (X) and between 5 and 11 Hz (O). The OdB levels are respectively $10^{-5}\ \gamma^2$ and $10^{-6}\ \gamma^2$. For the right and left grey scale panels, the correspondence between the black level and the power spectral density is not the same, the maximum signals in both cases having approximately the same intensity but not the same grey scalings. Note also that at the 07.07, 08.23 and 09.28 magnetopause crossings the turbulence is so strong that the grey scaling has been overflown.

that "the dayside magnetopause motion is consistent with a large scale radial motion having a ∿ 10 minutes period plus simperimposed boundary waves with 90 - 150 seconds period". This could well be the manifestation of a Kelvin-Helmoltz instability, which is supposed to be at the origin of most of the Pc4-5 detected on the ground, and which apparently is still seen when GEOS-2 has left the magnetosheath, after 07.41 (see the fluctuations of the He^+ gyrofrequency on the third panel of Figure 2).

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For this event, there are some problems in the restitution of the VDH components of the magnetic field. But again the magnetosheath field is southward and the measurement of the θ angle between the spin axis and the magnetic field gives us fair indications about the times of crossing of the magnetopause. These occurred at 07.07; 08.23; 09.08 and ∿ 09.22 UT. Again a very strong turbulence (∿ 10 γ between 0.3 and 10 Hz) is observed at the magnetopause boundary, and again the noise level is much lower (20 to 30 dB) deep into the magnetosheath. Again the strong turbulence seems to be very linearly polarized, as evidenced in the second panel from the bottom of Figure 6 which corresponds to B_L and B_R integrated between 0.3 and 1.5 Hz).

4. WAVES IN THE MAGNETOSHEATH

ULF waves inside the magnetosheath are characterized not only by the fact that their intensity is much lower than in the magnetopause transition region, but also by the fact that the Helium ions, both singly and double charged, seem to organize the data.

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The negative value of the H component of the DC magnetic field during the long time intervals 05.30 - 05.45; 05.47 - 06.30; 06.13 - 07.30; 07.49 - 09.16 indicates that GEOS-2 is located within the magnetosheath during these periods (Figure 2). When the spacecraft is deep inside the magnetosheath (∿ 06.15 ∿ 07.15), a narrow band signal is seen, whose mean frequency is slightly above the He^+ gyrofrequency. A cut-off at the He^{++} gyrofrequency is also observed (not on the spectrograms but on detailed spectra taken at different times). This cut-off is mainly detected on the left hand mode, whereas the right hand mode is continuous through this frequency, as evidenced on a spectrum taken at 07.05 (Figure 7a).

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Again an intense signal (∿ 1γ) is observed in the vicinity of the He^+ gyrofrequency (from ∿ 07.12 to 08.23 UT), with a cut-off at the He^{++} gyrofrequency. At 08.05 UT, the signal suddenly changes; its intensity decreases and two bands are now clearly seen, one above and one below the He^{++} gyrofrequency (Figure 7b). The apparent polarization in the plane perpendicular to Z is linear ($B_R \approx B_L$) but in this case the θ angle between the DC magnetic field and the spin axis Z does not have a small value, so that the denomination left or right does not have a strict meaning.

From a detailed study of magnetospheric ULF signals detected onboard GEOS-1, Young et al. (Ref. 23) have shown that the He^+ ion play a dominant role in the generation and propagation of these waves. Because He^{++} is the dominant Z > 1 ion in the magnetosheath, it is not surprising that it could play there a similar role, although its temperature being higher, it will mainly absorb the waves and be at the origin of the cut-offs we observe. Emissions in the vicinity of the He^+ ion is an indication that these ions are also present in the magnetosheath. In fact, recent measurements made onboard PROGNOZ-7 (Ref. 14) show that both ions are present in the vicinity of the magnetopause, the He^{++}/He^+ ratio being larger inside the magnetosheath than outside.

5. WAVES INSIDE THE MAGNETOSPHERE

We will emphasize here observations whose importance lies in the fact that they are made in the vicinity of the magnetopause boundary or during a very disturbed period.

5.1. Within the magnetosphere (Figure 2 from 09.18 to 09.30 UT or Figure 6 from 09.40 to 10.05 UT) we clearly see "narrow" band emissions above the He^+ gyrofrequency. These signals have a much lower intensity (∿ 0.1 γ) than those detected in the magnetopause transition region or even in the magnetosheath. Their polarization and frequency characteristics are linked to the presence of He^+, as discussed by Young et al. (Ref. 23).

5.2. During the short incursion of GEOS-2 into the magnetosphere which occurred on august 28, between 07.41 and 07.49 UT, we see (Figure 3) the existence of multi-structures at harmonics of the proton gyrofrequency. Such emissions are often seen in the equatorial region of the magnetosphere, down to L values of the order of 5. They are presently interpreted as a coupling between the magnetosonic (cold plasma) mode and the electromagnetic ion cyclotron Bernstein waves. This coupling may be induced either by an azimuthally symmetric distribution function having a peak in the $v_\perp$ direction (Ref. 16). It is worth noting that such emissions are able to occur in the near vicinity of the magnetopause, thereby indicating that, in the equatorial plane at least, there is no marked difference in the plasma characteristics between regions very near to the magnetopause and regions much deeper inside the magnetosphere.

5.3. At 05.20 UT and after 09.40 UT the 28th of august (Figure 2), but mainly after 09.30 UT the 29th of september (Figure 6), strong (∿ 1γ) impulsive wide band noise occurs intermittently. These emissions, which are called Short Irregular Pulsations or SIP's, are related to substorms (Ref. 4). Although, when observed at ground stations, SIP's are mainly seen during the night, it is not unusual that onboard GEOS, they are seen during morning hours, in conjunction with their auroral precipitation events (Ref. 20). The two events which are studied here corresponding to a very disturbed period (Kp > 8), it is very likely that impulsive precipitation regions may extend to very late morning hours.

6. SUMMARY AND DISCUSSION

During the course of this study we have shown that there are two distinct regions within the magnetosheath, as far as the ULF waves are concerned : a magnetopause transition region, the width of which

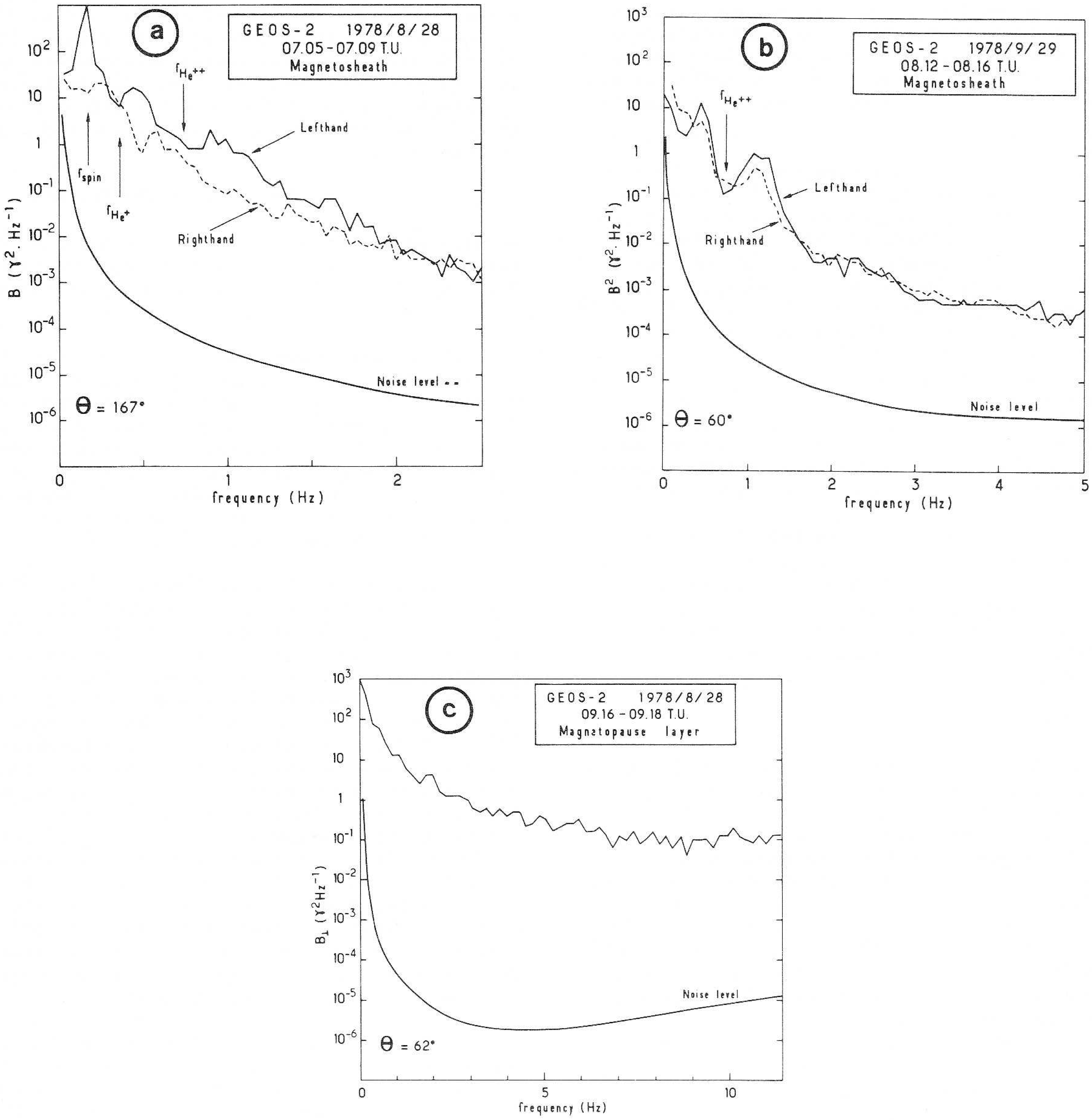

Figure 7. Examples of power spectra obtained in the magnetosheath (a and b) where an absorption at the He^{++} gyrofrequency is observable, and in the magnetopause (c) transition region where the spectrum is seen to decrease very slowly with frequency above $\sim$ 3 Hz. The "perpendicular" component of the AC magnetic field is plotted, but again this should not be considered as a true perpendicular power, the θ angle varying by more than 50° during the integration time.

cannot be defined with accuracy but which is of the order of 500 km, in which there exists a strong ULF turbulence, whose frequency spectrum extends well above 11 Hz; and the deep magnetosheath, in which the level of the turbulence is much lower and where absorption effects, due to the presence of He^{++} ions, are observed. As soon as the satellite reenters the magnetosphere, typical signals, characteristic of ULF magnetospheric emissions (narrow band, proton gyrofrequency harmonics, SIP's) are observed, indicating that, at least for these two events, an inner transition region does not seem to exist. The only exception to this is the September 29 event, between 09.22 and 09.31 UT, during which the strong ULF turbulence is still present (although decreasing in amplitude very rapidly). However, we know that for this date, there are difficulties in interpreting the magnetic field data and defining with accuracy the different times of magnetopause crossings.

The existence of strong ULF turbulence near the magnetopause, in a region of limited size within the magnetosheath, has been evidenced by other satellite results (Ref. 1, 5, 6, 7). Its interpretation may shed some light on the reconnection theories. On the other hand, its existence may be a clue to the reconnection energy loss problem. This problem has been raised by Heikkila (Ref. 8, 9, 10) on the basis of the absence of observations of the necessary proton temperature increase which should be a consequence of the reconnection energy dissipation.

For a magnetopause current density $j = \Delta B/\mu_o$ equal to 8×10^{-2} $A.m^{-1}$ (corresponding to a jump in the magnetic field $\Delta B = 100\gamma$ as observed in the two events discussed here), and for a magnetosheath electric field of the order of 0.2 $mV.m^{-1}$ (corresponding to a potential drop of 50 kV over 40 R_E), the dissipated power per unit area of magnetopause boundary is of the order of 1.5×10^{-5} $W.m^{-2}$. One of Heikkila's arguments, based on many HEOS-2 magnetopause crossings, is that such an energy dissipation implies a corresponding energy gain of magnetosheath protons of the order of 0.8 keV, which was never observed (although Fälthammar (Ref. 3) argued recently that the amount of energy increase per particle should not be so large and therefore would not possibly be detectable). The question we would like to raise here is : cannot the missing energy be found in the waves ?

We have seen that the turbulence level, integrated up to 11 Hz, is of the order of 10γ. Assuming an Alfven velocity of the order of 300 $km.s^{-1}$ ($N_e \sim 20$ cm^{-3}, $B \sim 50\gamma$), this corresponds to a power flux equal to $1.2 \times 10^{-5} W.m^{-2}$. The radiated power may be even larger if we admit that the spectrum extends higher up in frequency, at least to the lower hybrid resonance frequency (∿ 30 - 40 Hz), which seems very likely.

Therefore we see that the orders of magnitude of the power locally dissipated by the magnetopause current, in the presence of an East-West electric field, and of the power flux locally transported by the ULF waves are very similar. Obviously, the areas which are involved in both processes are not the same : the electromagnetic dissipation is evaluated per unit area of the magnetosphere boundary, whereas the wave power flux, which does not intrude into the magnetosphere, nor at large distances into the magnetosheath, escapes tangentially to the magnetopause. We have no present evidence that the ULF turbulence is observed on a sufficiently large region to balance the total electromagnetic power dissipation ($\sim 10^{11}$ W), which, in most calculations, is assumed to take place over an area of the order of $(15 \times 30)R_E{}^2$ (i.e. $\sim 1.8 \times 10^{16}$ m^2). Moreover, there is some recent experimental evidence that protons are indeed energized in the vicinity of the magnetopause, in the polar plasma mantle, thereby satisfying the energy balance equation (Ref. 12). However, it is not impossible that an appreciable fraction of the dissipated electromagnetic power is carried away from the reconnection region by ULF waves.

Another point which is worth mentioning with respect to the reconnection theories is that the ULF turbulence is so strong that it may be at the origin of the anomalous resistivity needed to maintain, in an otherwise collisionless plasma, the high electric field which drives the reconnection. As evidenced on Figure 4, the ULF turbulence is stronger when the DC magnetic field approaches the zero value, that is when GEOS-2 is just in the center region of the magnetopause current, where this current is stronger. There are different mechanisms by which wave turbulence may be induced by large currents. In the absence of a precise knowledge of the plasma characteristics in this very central region, it is impossible to comment on such mechanisms, but we can evaluate the relative importance of the particle and wave energy densities. Assuming a magnetosheath proton temperature of the order of 10^6 - 10^7 °K (10-100 eV), the particle energy density is of the order of 3×10^{-11} - 3×10^{-10} $J.m^{-3}$, i.e. of the same order of magnitude than the wave energy density ($\sim 4 \times 10^{-11}$ $J.m^{-3}$). In other words, we are near the strong turbulence limit. In this respect, it is worth noting that the power spectrum of the turbulence follows more or less the Kolmogorov law $P \propto k^{-5/3} \alpha\ f^{-5/3}$, the waves being not dispersed in this low frequency range ($\omega = kC_s$ or $\omega = kV_a$). Figure 7c shows a spectrum into the transition region, for which we have computed two regression lines $P \propto f^{-\beta}$, one between 0.55 and 3 Hz, the other between 3 and 11 Hz. In the low frequency range the power decreases rapidly ($\beta_1 = -2.5 \pm 0.3$) whereas in the higher frequency range it follows almost exactly the theoretical law ($\beta_2 = -1.8 \pm 0.2$).

We need more examples and more detailed studies of the properties of ULF waves (power spectra, flux, polarization, wave normal direction) in the magnetopause transition region to understand the exact contribution of these waves to the phenomena which occur inside this boundary layer.

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