COMPARISON OF ULF WAVES AT MAGNETOPAUSE CROSSINGS AT DIFFERENT LATITUDES, AS SEEN BY THE CLUSTER AND DOUBLE STAR STAFF EXPERIMENTS

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ABSTRACT

Strong ULF wave activity has been observed at magnetopause crossings since a long time. Those turbulent like waves are possibly one of the contributors to particle penetration from the Solar Wind to the Magnetosphere through the magnetopause.

STAFF Wave experiments onboard Cluster and Double Star TC1 spacecraft permit the comparison of those waves during coordinated crossings, at the same local time, but at different latitude, the TC1 Double Star orbit being nearly equatorial and the Cluster one polar. From a first analysis of simultaneous Cluster and DSP data sets in the first half of year 2004, 21 coordinated magnetopause crossings have been identified, i.e. within less than 3 hours, out of which 16 are within one hour time delay. Some characteristics of the ULF wave data in the vicinity of these crossings are compared, as wave power and frequency spectra power law. Similarities and differences are discussed at the light of solar wind parameters, latitude, local time or time delay between the crossings. These results first confirm the relation between the solar wind pressure and the ULF wave power. They indicate that in most of the cases, the wave power measured by Double Star is stronger than the one measured by the Cluster spacecraft., whereas no local time dependence has been found. If those first results were to be confirmed, it could imply a predominant role of the equatorial plane in the solar wind/ magnetosphere coupling via ULF wave turbulence, with no preference for the sub-solar region.

1. INTRODUCTION

The investigation of the physical processes by which mass and momentum are transferred through the magnetopause, from the solar wind to the magnetosphere, is one of the prime goals of both Cluster and DSP missions. Different models have been proposed, such as the reconnection model [1] or the Kelvin-Helmholtz instability [2, 3]. Also, there is evidence for localised flux tubes, known as Flux Transfer Events (FTEs), connecting the magnetosheath to the magnetosphere [4, 5]. These FTEs are viewed as remnants of reconnection events, but whether they are consequences of tearing [6], Kelvin-Helmholtz or other instability is still an open question. Different experimental studies have given the indication that the small-scale electromagnetic fluctuations, the amplitude of which is maximum at the magnetopause [7, 8, 9], were likely to play a significant role in these transfers, taking the place of collisions which do not exist in the medium. After some preliminary studies [10, 11], Belmont and Rezeau [12] have proposed a theoretical model, which shows how the electromagnetic turbulence present in the magnetosheath can couple with the boundary. According to this paper, when incident waves, supposed to propagate on the fast magnetosonic mode, impinge the magnetopause, they first convert to Alfvén waves. In the presence of a magnetic field rotation, these Alfvén waves can then be trapped in the boundary, so producing a local enhancement of the fluctuation level. The major consequence of this trapped small-scale turbulence should be to allow micro-reconnection through the magnetopause, possibly distributed all over the boundary. The role of the waves that are observed at the magnetopause and in its vicinity is one of the prime objectives of the STAFF experiment, both on Cluster and on Double Star.

Cluster observations up to now do not permit to choose between the different scenarios, but in fact show that the different processes are at work. Some observations [13] are consistent with fast collisonless reconnection, whereas [14 and 15] report on Cluster observations of FTEs. Different Cluster studies gave evidence of the presence of Kelvin-Helmholtz instability [16, 17 ,18]. A first Cluster magnetopause crossing case study [19] also shows that the magnetopause is the seat of surface waves, possibly due to Kelvin-Helmholtz instability. Superimposed on this large-scale instability are ULF/ELF fluctuations (0.1- ~100 Hz) that, as previously observed, maximise at the magnetopause crossing, but are also present both in the boundary layer and the magnetosheath.

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Thanks to the 4 Cluster spacecraft and to the use of the k-filtering method, it has been shown that the turbulence that is observed close to the magnetopause is at each frequency the superimposition of different modes at different k, due to Doppler effect. But contrary to the prediction, the mirror mode has been shown to be dominant, while other ULF/ELF waves are also present [20, 21, 22]. First Cluster data analysis with this method, in the very close vicinity of the magnetopause, show that there is some reflection of the waves at the magnetopause (Attié, private communication). One of the questions concerning the role of the ULF turbulence on mass and momentum transfer, is to evaluate in which region this is the most efficient. The comparison between DSP and Cluster data should say whether the low latitude and the noon or subsolar region are more favourable than high latitude, and/or morning and evening local times. The present paper gives the first results of such a study on a series of magnetopause crossings. The combination of Cluster and DSP TC1 orbits is particularly well suited to such a study. The TC1 spacecraft has its apogee at 13.3 Earth radii and an inclination of 28.5° whereas Cluster has a polar orbit with an apogee of 19.6 $R_{E,}$ both apogees being at the same local time. Then Cluster and DSP can cross the magnetopause at approximately the same time when the difference in the orbit periods makes it possible, at the same local time, but at different latitudes.

The next section describes briefly the data and how the coordinated magnetopause crossing data set is constructed by describing one of the events. Section 3 gives some statistical results of 4 months of Cluster/DSP comparisons, followed by a summary of this study.

2. THE DATA

To calculate the ULF magnetic wave power and frequency spectrum power law, we use wave form data from STAFF experiment (Spatio Temporal Analysis of Field Fluctuations) on both Cluster [23] and Double Star TC1 [24] spacecraft. The precise determination of the magnetopause crossing is done thanks to the Cluster and DSP magnetometer experiments FGM [25, 26]. The similarity of STAFF wave experiment on Cluster and DSP, does help making such comparisons. Unfortunately on DSP TC1, the STAFF antenna boom failed to deploy, which means interference from the spacecraft systems is very high. Even so, useful measurements can still be made, as described in [24] and will be shown later on. In particular the on board calibration permits to show that the measured magnetic fluctuations, when strong enough, are significant, having the same intensity on ground and in flight in spite of the interferences. For more details, see [24].

We have made a list of all DSP TC1 magnetopause crossings from the beginning of DSP scientific operation phase on 19th of February 2004 until DSP no longer crosses the magnetopause at the end of May 2004, as orbit plan evolves and apogee moves counter clock from about 13 to 06 UT. We have compared with the Cluster magnetopause crossings during the same period. Doing so we found 21 coordinated crossings, i.e. within less than 3 hours, out of which 16 crossings are done by both Cluster and TC1 within one hour delay or less. During this time period the four Cluster separation was about 200 km, thus for this study we consider the 4 spacecraft as a single point, as compared to the distance between DSP TC1 and Cluster

One example is given in Fig. 1 for the magnetopause crossings of February 22, 2004 between 19 and 21 UT. DSP data are on the left and Cluster on the right. Only data of Cluster 4 are shown, since the STAFF data from all Cluster spacecraft are very similar. DSP crosses the magnetopause at 19:33 UT during an outbound pass whereas Cluster crosses it at 20:10 UT during an inbound part of its orbit. In the two top panels are plotted the STAFF dynamic spectra of the Bz component (parallel to the spin axis) from 0.1 to 12.5 Hz and the integrated power for this component from 1.5 to 10 Hz. The suppression of the low frequencies, eliminating strong interferences on DSP, makes the integrated powers more comparable between the 2 spacecraft. One can see that the natural signal is quite above the interference level. In the bottom two panels are plotted the magnetic field modulus and the elevation theta angle calculated from the FGM magnetometer Prime Parameter Data (PPD), for DSP and Cluster. The

2004 February 22

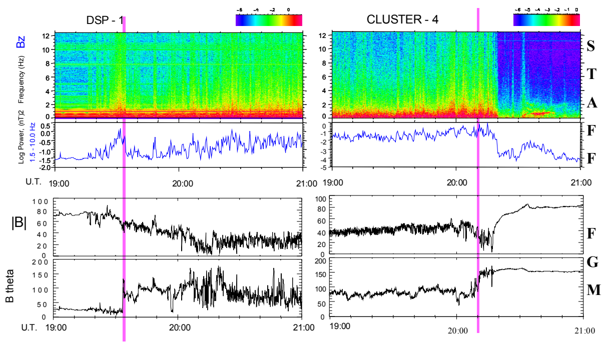

Fig. 1. Magnetopause crossing by DSP and Cluster during their outbound and inbound pass respectively, on 22 February 2004, indicated by a violet line. STAFF dynamic spectra data are shown in the top panel, below which are plotted the integrated power in the 1.5-10 Hz frequency range. At the bottom, modulus and elevation of the magnetic field from the FGM PPD are plotted (after Cornilleau-Wehrlin et al, 2005).

time of the estimated magnetopause crossing is given by a pink line. Cluster probably travels through the boundary layer between 20:10 and 20:20 UT. Fig. 2 gives the orbit of Cluster and DSP TC1 in the Y,X and

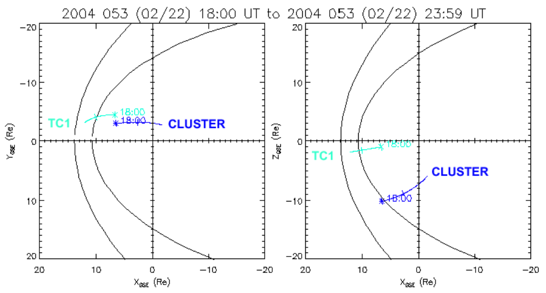

Fig. 2. Orbits of DSP TCI (outbound) and Cluster (inbound) for 22 February 2004 from 18 to 24 UT in the X,Y and X,Z GSE plans. Asterisks correspond to 18 UT (after Cornilleau-Wehrlin et al, 2005).

Z,X GSE planes from 18 to 24 UT. The asterisk is for 18 UT and the bar for 21 UT. Whereas the spacecraft are close in local time, they are separated in latitude by 54 degrees (see Table 2). We have usedthe Sibeck model [27] to evaluate the magnetopause sub-solar point, i.e. its position in the Earth-Sun direction, using the spacecraft coordinates given in table 2. The result is very similar for both crossings, 9.7 and 9.4 Earth radii, consistent with a stable interplanetary medium for the preceding time interval. This stability of the magnetopause during the 40 minutes that separate the two crossings permits the comparison of the wave observations for these two crossings by DSP and Cluster respectively.

Table 2. Positions of Cluster and DSP TC1 on February 22, 2004 at the time they cross the magnetopause. D_Sibeck is the location of the magnetopause sub-solar point estimated with the Sibeck model [27].

	DSP TC1	CLUSTER
Magnetopause crossing time (UT)	19:30	20:10
X (R_E)	8.6	3.7
Y (R_E)	4.3	3.2
Z (R_E)	1.4	9.4
R / R_E	9.8	10.6
D_Sibeck (R_E)	9.7	9.4
Latitude	8	62
Local Time	12:30	12:30

Fig. 3 gives the power spectra for both Cluster 1 and DSP in the magnetosheath, the closest possible to the magnetopause crossing, in order to integrate over 40 seconds. The 3 components are given in the spacecraft reference frame, which is not far from GSE, plus the total magnetic power. Cluster spectra are in black and DSP ones in red. On DSP, to eliminate the strongest interferences, frequencies below 2 Hz have been filtered. In the Bx and By components interferences around 8 and 10 Hz are clearly visible, whereas on Bz it is clean. From these data, one can see that a comparison of DSP and Cluster Bz components is meaningful: the spectra follow a power law, with a similar exponent of ~ - 2.6 at both places, -whereas the intensity is higher on DSP, at low latitude, by an order of magnitude.

Thus in what follows we will use for the comparison between DSP and Cluster the wave power at 2 Hz, either on Bz or the total power, and for the power law a fit only to the Bz component between 2 and 6 Hz.

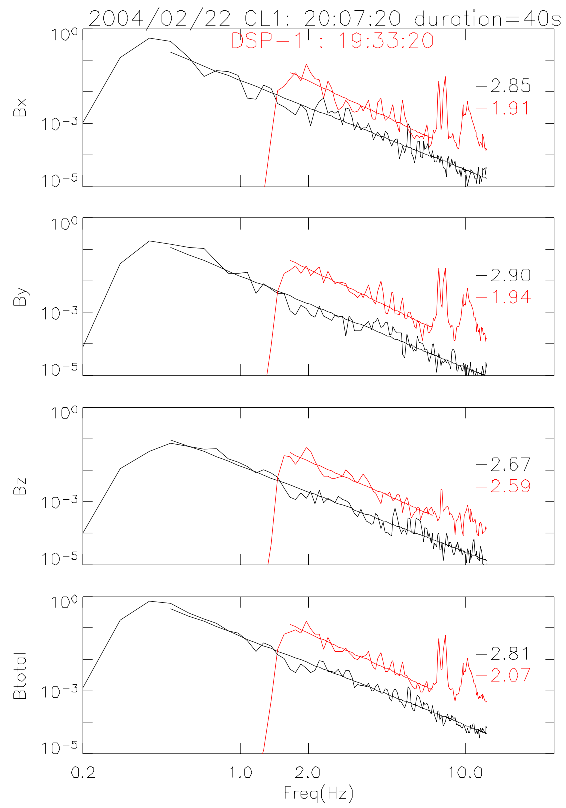

Fig. 3. Integrated power over 40 seconds of ULF waves in the magnetosheath for the event shown in Fig. 1, the closest possible to the magnetopause; the 3 components in GSE and the total wave power are plotted, for DSP (in red) and Cluster (in black). To avoid interferences, DSP data are filtered below 2 Hz and the fit to a power law (straight lines), is stopped at 6 Hz. The exponents of the power law are given at the right-hand side of each panel On Bz component, the cleanest one, the power law is similar for both spacecraft, but the power is stronger for DSP, than observed by Cluster. (after Cornilleau-Wehrlin et al, 2005).

In this case study we have found that the power is stronger by an order of magnitude at low latitude (DSP) than at high latitude (Cluste, 60 degrees), whereas the power law is the same at both locations. The similar values of the sub-solar point determined by the Sibeck model [27] for both magnetopause crossings, which is consistent with stable interplanetary conditions, make the comparison results reliable

In order to confirm or infirm this case study results we have constructed a small data base with the 21 events identified between February and May 2004.

For each event we have looked at the time delay between the 2 crossings and, when possible, the interplanetary conditions, calculated the sub-solar points, as explained above, for DSP and Cluster, calculated the wave power and compared it at 2 Hz and evaluated the power law on Bz between 2 and 6 Hz.

Some results of the analysis of this small data set are given in the next section.

3. THE FIRST STATISTICAL RESULTS

As already mentioned, between 21-02-2004 and 22-05-2004 there are 21 coordinated magnetopause crossings, i.e. within less than 3 hours, out of which 16 are within one hour time delay.

To be convinced of the quality of our data set in spite of the level of interferences, we looked at the variation of the Bz component wave power at 2 Hz on DSP TC1 the closest possible to the magnetopause in the magnetosheath, as a function of the sub-solar point. This is shown in Fig. 4. Clearly the wave power decreases as the sub-solar point increases, which is a significant result : the strongest is the solar wind pressure, the more intense are the ULF waves.

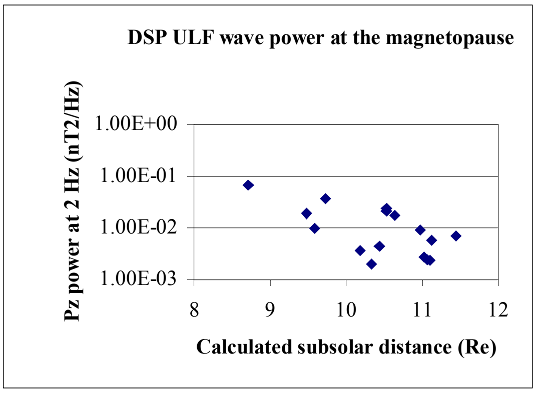

Fig. 4. DSP ULF wave power, at 2 Hz on the bz component to avoid interferences effects, as a function of the magnetopause subsolar point.

Being sure to have a valuable data set, we can go back to the Cluster-DSP comparisons.

Fig. 5 gives the total wave power at 2 Hz as measured at coordinated magnetopause crossings. The power at DSP is plotted as a function of the power at Cluster for a given event. Most of the time, the power is stronger at DSP, which is at low latitude (about 7 ° +/- 1), than at Cluster which is at much higher latitude (40°< λ < 60°, depending on the date of year or local time). Nevertheless in some cases the power is stronger at Cluster. We will go back on this later on. Another point

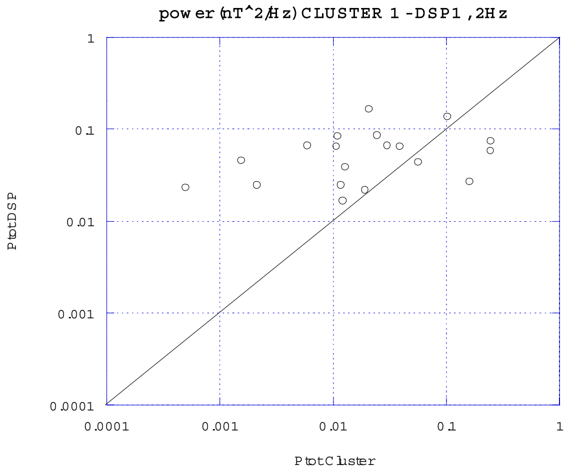

Fig. 5. For each coordinated magnetopause crossing the total power at 2 Hz measured on DSP is plotted as a function of the one measured at Cluster. The black line corresponds to an equal value at both places. Most of the time the intensity at DSP (low latitude) is higher than at Cluster at high latitude.

that we have looked at is the influence of the local time on the ULF power. The 2 curves shown in Fig. 6, give DSP and Cluster total ULF power measured at 2 Hz as a function of Local Time at the time of the coordinated magnetopause crossings. The comparison of each couple of points of course gives the results of Fig. 5, i.e. that most of the time the power is stronger at low latitude, as measured by DSP, than at high latitude (Cluster). The new information given by Fig. 6 is that there seems to be no local time dependence on the level of the wave activity, which is different from some expectations.

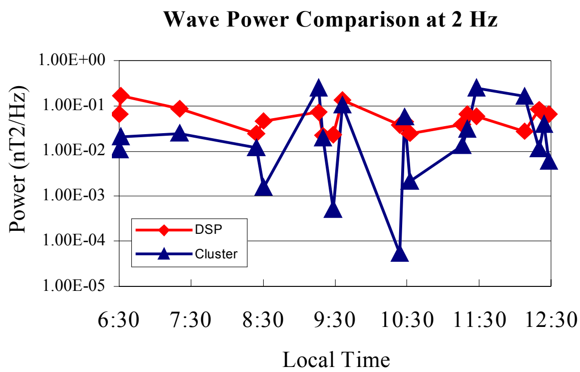

Fig. 6. ULF wave total power at 2 Hz as a function of local time, for DSP (red lozenges) and Cluster (black triangles). There is no maximum at noon, the power is most of the time higher at DSP (low latitude).

Lets go back to the few events for which the power seen by Cluster is higher than the one seen by DSP. Looking at increasing local time, the first such event at about 09:15 LT occurs on April 10, 2004. DSP first crosses the magnetopause during an outbound pass at 20:10 UT, whereas Cluster, also during an outbound pass crosses the magnetopause at 21:00 UT. An interplanetary shock seen at ACE at 19:30, should have reached the Earth bow shock in the meantime at about 20:25 UT, and thus compressed the magnetosphere. This is consistent with the sub-solar point distances deduced from the position of DSP and Cluster at the time of the crossings that are 10.3 and 7.5 R_E respectively. Then we find again that one of the determinant factor is the solar wind pressure which is translated in term of the magnetopause sub-solar distance. For the 2 other events around 11:30 and 12:00 LT, the delay between the 2 crossings is more than 2 hours and the solar wind activity is varying.

We have also compared the power law at the 2 places for the set of events. For the reasons mentioned above, the fits to a power law of the ULF wave power spectra have been limited to the Bz component, between 2 and 6 Hz. The result is given in Fig. 7. For this comparison we have a more restricted data set, to be sure to avoid possible interferences effects. There is no correspondence between the events for which the power law is smaller at Cluster than at DSP and the events for which the power is stronger at Cluster (Fig. 5). It is difficult at this stage of the study to conclude on this aspect. Many different parameters can contribute to the different behaviour of the power law, and one should not forget that the important domain for the consideration of power laws, specially in the perspective of turbulence, is the k domain, which is accessible to Cluster and not to DSP.

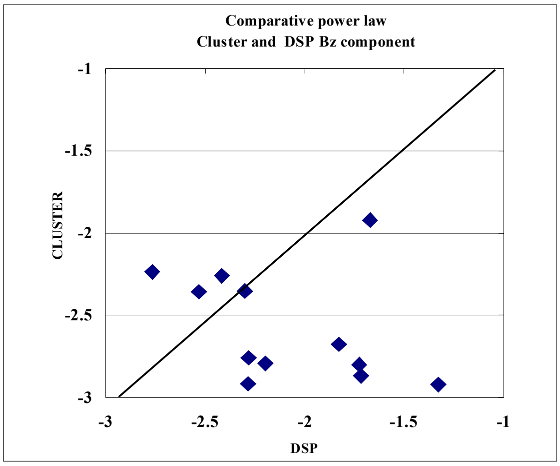

Fig. 7. Comparison of the power law coefficient determined at Cluster as a function of the one determined at DSP. The coefficients are deduced from a fit to the power spectra of the Bz components in the 2 to 6 Hz frequency range.

4. SUMMARY AND PERSPECTIVES

We have compared DSP and Cluster ULF waves from STAFF experiments on both missions at magnetopause crossings. During the time period 21-02-2004 and 22-05-2004 we have found 21 coordinated magnetopause crossings, i.e. with less than 3 hours, 16 of which were experienced by both spacecraft in less than one hour delay. We here consider Cluster as one point is space, the 4 satellites being separated by about 200 km at that time whereas the distance between DSP and Cluster is at the scale of at least one R_E. One of the advantages of this comparative study rely in the fact that both orbits have their apogees at the same local time, DSP being close to the equator whereas Cluster has a polar orbit and crosses the magnetopause at high latitude, specially around noon.

We have shown on a case study that despite the presence of interferences on DSP data due to the STAFF boom being stacked under the spacecraft, the DSP data are valuable for such a comparison. Statistical results for DSP data alone show that the ULF wave power at the magnetopause increases when the solar wind pressure increases, reflected by the shortening of the magnetopause subsolar distance.

The comparison of both data set at coordinated crossings shows that most of the time the power is higher at low latitude (DSP) than at high latitude, at a given local time. This is true when the solar wind conditions are stable and the sub-solar point doesn't move between the 2 crossings and when moreover the 2 crossings occur within less than one hour. Conversely, there is an example for which the sub-solar point has moved by 3 R_E between DSP and Cluster magnetopause crossings. This is due to the arrival of an interplanetary shock at the Earth in the mean time. For this example, the intensity of the ULF waves at Cluster is higher than at DSP.

The influence of the local time has been looked at, and it is found that in the vicinity of the equatorial plane, the intensity, at least between 06:30 and 12:30 LT, doesn't show a local time dependence.

Some comparison of the power law has been done. The power law coefficients seem to be lower at DSP than at Cluster, but this has to be confirmed on more events.

The above results may indicate that the low latitude magnetopause is a more favorable region for ULF waves to play a role in the penetration of Solar Wind origin particles into the magnetosphere. Another important parameter regarding the ULF wave power level is the solar wind pressure. Conversely, there is apparently no local time dependence on the ULF wave amplitude. These results are first ones and constitute only a small piece of the puzzle to reconstruct in order to understand the formation and role of turbulent ULF waves at the magnetopause.

Acknowledgements

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