Latitude and local time dependence of ULF wave power at the magnetopause: A Cluster–Double Star study

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[1] Strong ULF wave activity has been observed at magnetopause crossings over 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. Spatio Temporal Analysis of Field Fluctuations wave experiments onboard Cluster and Double Star TC1 spacecraft permit the comparison of those waves during quasi-simultaneous magnetopause crossings, some being at the same local time but at different latitude, the TC1 Double Star orbit being nearly equatorial and the Cluster orbit being polar. From a survey of the first half of year 2004 and beginning of 2005 data, 23 coordinated magnetopause crossings have been identified, out of which 11 are at the same local time, for which the wave power density has been calculated. No clear dependence in local time has been found; in particular, the wave power density is not stronger at noon in the vicinity of the subsolar point than at other local times, the morning hour data showing more dispersed values than afternoon ones. For most of the events occurring at the same local time, the wave power density measured by Double Star (at low latitude) is stronger than the one measured by the Cluster spacecraft (at much higher latitude). 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 subsolar region.

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1. Introduction

[2] 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 Double Star Program (DSP) missions. Different models have been proposed, some based on cross field diffusion of the plasma, but most implying reconnection, i.e., associated with magnetic flux transfers [e.g., *Sonnerup*, 1980]. There is indeed experimental evidence for localized flux tubes, known as flux transfer events (FTEs), connecting the magnetosheath to the magnetosphere [*Russell and Elphic*, 1979; *Farrugia et al.*, 1987], which are viewed as remnants of transient reconnection phenomena. Whether the reconnection phenomena at the origin of FTEs are due to tearing instability [*Bhattacharjee et al.*, 1999], or to any other instability of the boundary or whether they are directly driven by incident perturbations (e.g., "impulsive penetration") is still an open question. The Kelvin-Helmholtz instability [*Pu and Kivelson*, 1983; *Belmont and Chanteur*, 1989] is by itself able to cause momentum transfers through the magnetopause, even in absence of particle penetration; it can be also indirectly responsible for particle penetration by driving the boundary toward an unstable state favorable to reconnection secondary instabilities.

[3] Different experimental studies have given the indication that the small-scale electromagnetic fluctuations, the amplitude of which is maximum at the magnetopause [*Perraut et al.*, 1979; *Rezeau et al.*, 1989; *Tsurutani et al.*, 1989], 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 [*Belmont et al.*, 1995; *De Keyser et al.*, 1999], *Belmont and Rezeau* [2001] have proposed a theoretical model, which shows how the electromagnetic turbulence present in the magnetosheath can couple with the boundary. According to their 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

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boundary, thus producing a local enhancement of the fluctuation level. The major consequence of this trapped small-scale turbulence should be to allow microreconnection 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 Spatio Temporal Analysis of Field Fluctuations (STAFF) experiment, both on Cluster and on Double Star equatorial probe TC1 (called hereafter DSP or DSP TC1).

[4] Cluster observations up to now do not permit to choose between the different scenarios, but seem actually to show that the different processes can be at work. Some observations [*Vaivads et al.*, 2004; *Khotyaintsev et al.*, 2004; *Retinò et al.*, 2006] appear consistent with the ''Petschek''-type models of stationary fast collisionless reconnection, whereas *Owen et al.* [2001] and *Robert et al.* [2002] report on Cluster observations of FTEs, therefore rather implying transient reconnection events. Different Cluster studies gave evidence of the presence of surface waves, possibly due to Kelvin-Helmholtz instability [*Gustafsson et al.*, 2001; *Rezeau et al.*, 2001; *Owen et al.*, 2004; *Hasegawa et al.*, 2004]. Superimposed on this large-scale instability are ULF/ELF fluctuations (0.1 to ~100 Hz) that, as previously observed, maximize at the magnetopause (MP) crossing but are also present both in the boundary layer and the magnetosheath (MSH).

[5] Thanks to the four 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 wave vectors, due to Doppler effect: the plasma velocity in the magnetosheath is typically ~100 km/s with respect to the spacecraft (which have in turn a velocity of ~3 km/s with respect to a terrestrial frame). But contrary to the prediction, the mirror mode has been shown to be dominant, while other ULF/ELF waves are also present [*Sahraoui et al.*, 2003, 2004; *Walker et al.*, 2004, *Tjulin et al.*, 2005]. A preliminary Cluster data analysis with this method in the magnetosheath, in the very close vicinity of the magnetopause, shows that there is some reflection of the waves at the magnetopause (D. Attié, private communication, 2004). *Attié et al.* [2008] have performed a statistical study relying on 130 magnetopause crossings undergone by the Cluster fleet during the time period July 2001 June 2003. This work clearly shows the key role played by the rotation of the magnetic field in the boundary, which is consistent with the wave trapping in the magnetopause that was found in the Belmont and Rezeau model: the wave power density increases with the magnetic field rotation angle. In order to separate the role of the magnetic field rotation from other possible causes of amplification, these authors have normalized the wave power density at the magnetopause to the one measured in the adjacent magnetosheath, and the effect persists. The other outcome of this statistical study is the role of the solar wind pressure on the ULF wave power density. It has been shown that the level of fluctuations at the magnetopause 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 removing the effect of the direct compression of the magnetosphere under conditions of higher ram pressure. This reinforces the idea that the ULF waves observed at the MP have an external source of energy. *Attié et al.* [2008] report that the analysis of the MP wave energy density as a function of latitude and local time, with the same data set, does not lead to any clear correlations with those parameters. As the observations of MP crossings by Cluster, due to its trajectory, have all been up to now 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. 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 is more favorable 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 for the first years of operation. Then Cluster and DSP can cross the magnetopause at approximately the same universal time when the difference in the orbit periods makes it possible, at approximately the same local time, but at different latitudes. The DSP orbit duration is one third of the Cluster one.

[6] The next section describes briefly the data and how the coordinated magnetopause crossing data set is constructed, starting from a case study. Section 3 gives some statistical results of Cluster/DSP comparisons during years 2004 and 2005, followed by conclusion and a summary of this study.

2. The Data

[7] To calculate the ULF magnetic wave power density we use wave form data from the STAFF experiment on both Cluster [*Cornilleau-Wehrlin et al.*, 2003] and Double Star TC1 [*Cornilleau-Wehrlin et al.*, 2005] spacecraft. The precise determination of the magnetopause crossing is done thanks to the Cluster and DSP magnetometer experiments (fluxgate magnetometer, FGM) [*Balogh et al.*, 1997; *Carr et al.*, 2005]. The similarity of the STAFF wave experiments on Cluster and DSP does help such comparisons to be made. Unfortunately, on DSP TC1, the STAFF antenna boom failed to deploy, which means interference from the spacecraft systems is very high. There are different sources of interferences. The first obvious ones come from the position of the antennas being stacked below the spacecraft. The interferences are payload and spacecraft mode of operation dependence, thus varying often. There are also interferences due to the solar panels. These ones are solar aspect angle-dependent, especially when the solar panels are intermittently shadowed by the FGM boom, and are at harmonics of the spin frequency. That is why corrections to the attitude of the spin axis to make it perpendicular to the ecliptic plane, to the extent possible, have been performed to reduce this source of interferences. Such corrections of attitude have been done twice, on 17 February 2004 and on 13 July 2004. Just after the correction of attitude the data have much less interferences and then data quality

degrades progressively until the next maneuver, due to the natural evolution of the spacecraft attitude. Unfortunately, the third correction of attitude maneuver planned for 15 November 2004 could not be performed as the Attitude Control Computer failed after the big storm at the beginning of November 2004. Nevertheless the natural evolution of the position of the spin axis with time permits to have cleanest data during winter 2004–2005 and spring 2005. These interferences are mainly in the spin plane, at harmonics of the spin frequency (0.25 Hz). Even so, useful measurements can still be made, as described by *Cornilleau-Wehrlin et al.* [2005], as will be shown later. In particular, the on board calibration permits to demonstrate 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 *Cornilleau-Wehrlin et al.* [2005], in particular their Figure 4. As explained above, the level of interference varies with time. Apart from the eclipse period, when DSP is in the tail, during which STAFF data are very clean, the better quality data happen to be in winter-spring time period, when DSP apogee is on the dayside and is then favorable for the magnetopause crossing [*Cornilleau-Wehrlin et al.*, 2005].

[8] We have made a list of all DSP TC1 magnetopause crossings from the beginning of DSP scientific operation phase on 19 February 2004 until DSP no longer crosses the magnetopause at the end of May 2004, as orbit plane evolves and apogee moves counter clock from about 1300 to 0600 universal time (UT). In order to cover afternoon local times we also looked at crossings in late December 2004 and beginning of year 2005, the DSP apogee ranging from 1800 to 1300 local time (LT). Extending to further years would make the study less significant as there is a drift between the respective local time of apogees of Cluster and DSP TC1. We have compared the time of DSP magnetopause crossings with those of Cluster during these two time intervals. The first crossing of the magnetopause by DSP in December 2004 occurs on 16 December; combining the data quality criteria and the simultaneous occurrence of MP crossing by both DSP and Cluster gives the first event on 15 January 2005. Doing so, for the overall period we found 23 coordinated crossings, i.e., within about 3 h or less in universal time, out of which 11 crossings are undergone by both Cluster and TC1 with about 1 h or less in local time separation. If we had been more strict on time intervals, the data set would have been very small, only 15 crossings are done by DSP and Cluster within 1 h time delay. We have restricted the interval in local time to one hour, as it is one of the purposes of the study to look at the evolution of the ULF wave power at the magnetopause as a function of the local time of the crossing, together with the influence of the latitude. For the 11 events considered as being at the same LT (average LT ±30 min), 10 correspond to crossings by both spacecraft within less than 65 min, a time delay of 3 h occurring only for one event, rather stable as the magnetopause subsolar point varies less than 6% during this delay.

[9] During the period of interest in this study, the Cluster interspacecraft distance was small in 2004, about 200 km, and in 2005 while not so close, the four spacecraft observations of the magnetopause crossings remained quasi-simultaneous. Thus we only used one Cluster spacecraft for each event.

[10] Before going into the statistical study, we show the first event of our list in Figure 1a, the magnetopause crossings of 22 February 2004 between 1900 and 2100 UT. DSP data are on the left, and Cluster data are on the right. DSP crosses the magnetopause at 1933 UT during an outbound pass, whereas Cluster crosses it at 2010 UT during an inbound part of its orbit. Figure 1a plots the STAFF dynamic spectra of the B_Z 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 two spacecraft. One can see that the natural signal is quite above the interference level. Figure 1b plots the magnetic field modulus and the elevation theta angle calculated from the FGM magnetometer prime parameter data (PPD), for DSP and Cluster. The time of the estimated magnetopause crossing is given by a pink line, at halfway of the magnetic field rotation. Cluster probably travels through the boundary layer between 2010 and 2020 UT. Figure 1c gives the orbit of Cluster and DSP TC1 in the Y, X and Z, X GSE planes from 1800 to 2400 UT. The asterisk is for 1800 UT and the bar for 2100 UT. Whereas the spacecraft are close in local time, they are separated in latitude by 54° (see Table 1). We have used the model proposed by *Sibeck et al.* [1991] to evaluate the magnetopause subsolar point, i.e., its position in the Earth-Sun direction, using the spacecraft coordinates corresponding to the MP crossings. The results are very similar for both spacecraft, 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 min that separate the two crossings permits the comparison of the wave observations for these two crossings by DSP and Cluster, respectively.

[11] Figure 2 gives the three components of the wave power spectra for both Cluster 1 and DSP for this event in the spacecraft reference frame, which is not far from GSE, plus the total magnetic power. Cluster data are is in black and DSP ones in gray. It can be seen that the B_Z component is the less perturbed by interferences that are visible around 8 and 10 Hz; DSP wave data have been filtered below 2 Hz to eliminate the strongest interferences; the spectra can be fitted by power law, rather similar on both spacecraft data sets. This shows the validity of DSP data on the one hand and of the comparison of Cluster and DSP data set on the other hand. In this case study the power is stronger by an order of magnitude at low latitude (DSP) than at high latitude (Cluster, 60°), whereas the power law is the same at both locations.

[12] The aim of the statistical study presented in the next section with the small database we could construct, as explained above, is to confirm or infirm this case study results. In order to maximize the reliability of the data used in the study, the wave power density used in the statistics is calculated in the frequency range 2–3 Hz for the B_Z component. This last point is justified by previous studies showing that the ULF wave power distribution at the magnetopause is roughly isotropic [*Rezeau et al.*, 1989]. To verify this, we have calculated the power for the three components both for Cluster and DSP. We have verified that

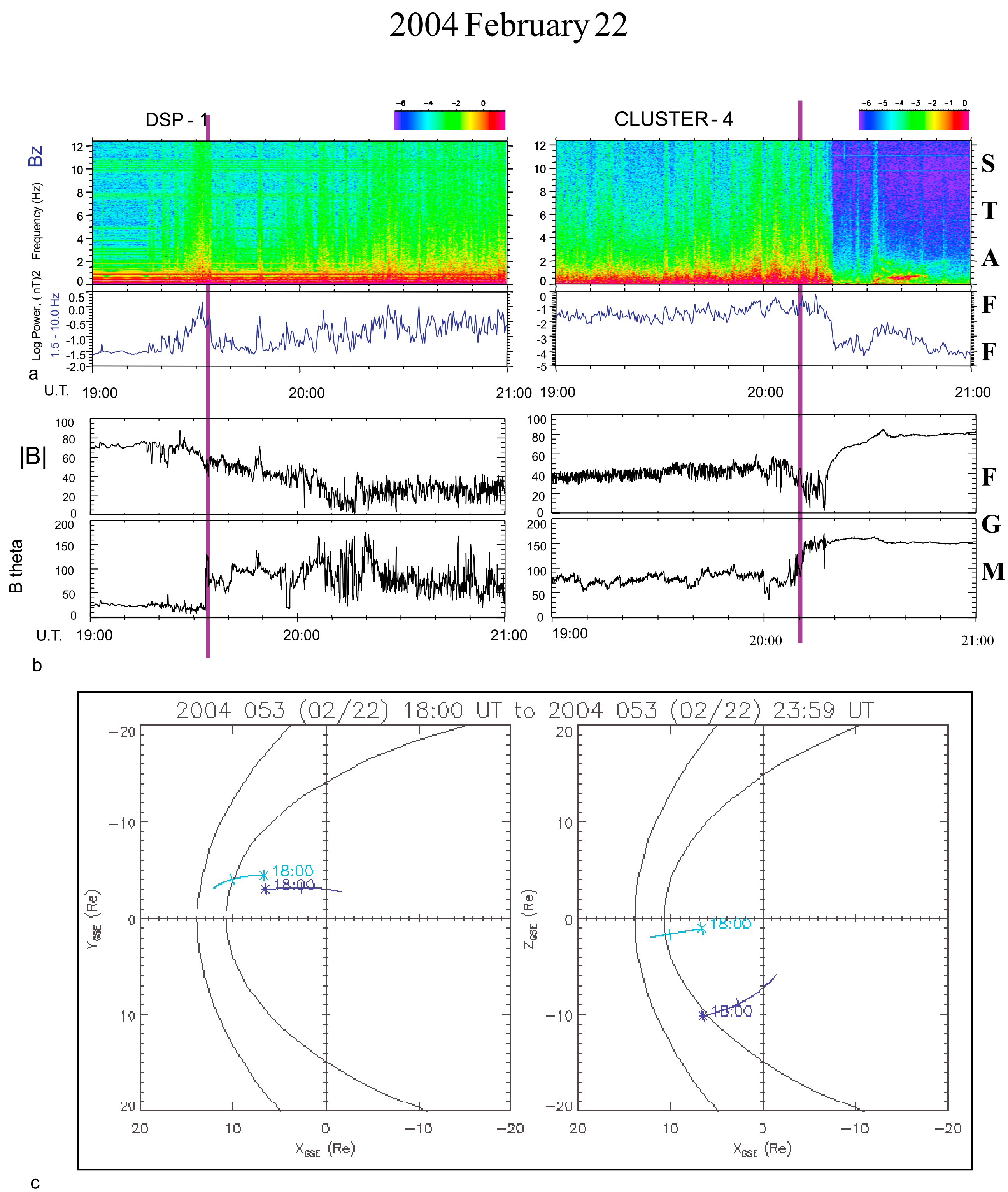

Figure 1. (a) Magnetopause crossing by DSP and Cluster during their outbound and inbound pass, respectively, on 22 February 2004, indicated by a violet line. STAFF dynamic spectra data are shown in Figure 1a (top). Figure 1a (bottom) plots the integrated power in the 1.5–10 Hz frequency range. (b) Modulus and elevation of the magnetic field from the FGM PPD. (c) The orbits of DSP TCI (outbound) and Cluster (inbound) for 22 February 2004 from 1800 to 2400 UT in the X, Y and X, Z GSE plans. Asterisks correspond to 1800 UT (after Figures 9 and 10 of *Cornilleau-Wehrlin et al.* [2005] with permission from Copernicus Publications).

Table 1. List of the Coordinated Events[a]

Date	UT MP Crossing		LT GSE		Latitude GSE, deg		Xsibeck, Re		Power Density, $nT^2\ Hz^{-1}$	
	Cluster	DSP	Cluster	DSP	Cluster	DSP	Cluster	DSP	Cluster	DSP
22 Feb 2004	2007:20	1933:28	0915:00	1015:00	62.3	−8.3	9.4	9.7	0.00316	0.02519
23 Feb 2004	1027:42	1113:10	1345:00	1245:00	35.7	8.7	10.7	10.6	0.02095	0.02754
25 Feb 2004	0402:15	0306:20	0945:00	1020:00	−58.0	−8.3	10.7	10.4	0.00157	0.01669
22 Mar 2004	0813:07	0915:50	0800:00	0900:00	−58.6	−7.7	9.9	11.1	0.00041	0.00521
22 Mar 2004	2233:32	2351:30	1200:00	1115:00	39.2	−7.1	9.9	10.2	0.00293	0.00795
24 Mar 2004	1632:00	1737:00	0810:00	0900:00	−56.8	−7.7	10.4	11.4	0.00015	0.00386
22 Apr 2004	2110:00	1853:45	0950:00	0900:00	35.2	−5.7	10.3	11.0	0.00127	0.01394
24 Apr 2004	1432:01	1502:00	0615:00	0730:00	−56.1	−6.6	9.3	11.1	0.01709	0.00502
8 May 2004	1027:28	0933:50	0615:00	0645:00	−46.0	−5.8	10.8	11.1	0.00429	0.02704
22 May 2004	0848:03	0752:30	0530:00	0645:00	−42.8	−4.5	10.3	10.6	0.00031	0.08416
8 Feb 2005	1830:30	2145:40	1530:00	1530:00	43.0	10.4	8.5	11.2	0.01464	0.02082

[a]The difference in local time for the magnetopause crossings is small.

on average the B_Z power is 1/3 of the total power for the Cluster data set, justifying using the B_Z power for both spacecraft. Conversely, as B_Z component on DSP, especially in the range 2–3 Hz is not too much affected by interferences for the studied events, power is lower for B_Z than for the two other components. Nevertheless we must be cautious with the interpretation of the data analysis: having eliminated the low frequencies of the spectra, we may misinterpret by intensities increases changes that are actually due to Doppler effect [*Lacombe et al.*, 2006; *Mangeney et al.*, 2006]. However, the method adopted permits to do some analysis that we could not perform otherwise.

[13] For each event we have looked at the time delay between the two crossings and the local time of the two crossings, calculated the subsolar points by fitting the *Sibeck et al.* [1991] model with spacecraft positions, calculated the wave power density of the B_Z component (parallel to the spin axis) in the 2–3 Hz frequency range, the average magnetic field modulus in the magnetosheath, the closest to the magnetopause, and looked at the IMF conditions.

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

3. Statistical Results

[15] As already mentioned our data set comprises 23 coordinated crossings, i.e., within about 3 h or less in universal time, out of which 11 crossings are undergone by both Cluster and DSP TC1 within about 1 hr or less in local time separation. In what follows we will use either the full set of 23 events or the small subset of 11 ones, depending on what we are looking at.

[16] To be convinced of the quality of our data set in spite of the level of interferences, we looked at the variation of the B_Z component wave power density (in the 2 to 3 Hz range) on DSP TC1 in the magnetosheath, the closest possible to the magnetopause, as a function of the geocentric distance of the subsolar point. This is shown in Figure 3. Clearly, the wave power decreases as the subsolar point increases, which is equivalent to say that the strongest is the solar wind pressure and the most intense are the ULF DSP waves. This result is consistent with previous studies and validates the use of STAFF experiment DSP B_Z component data.

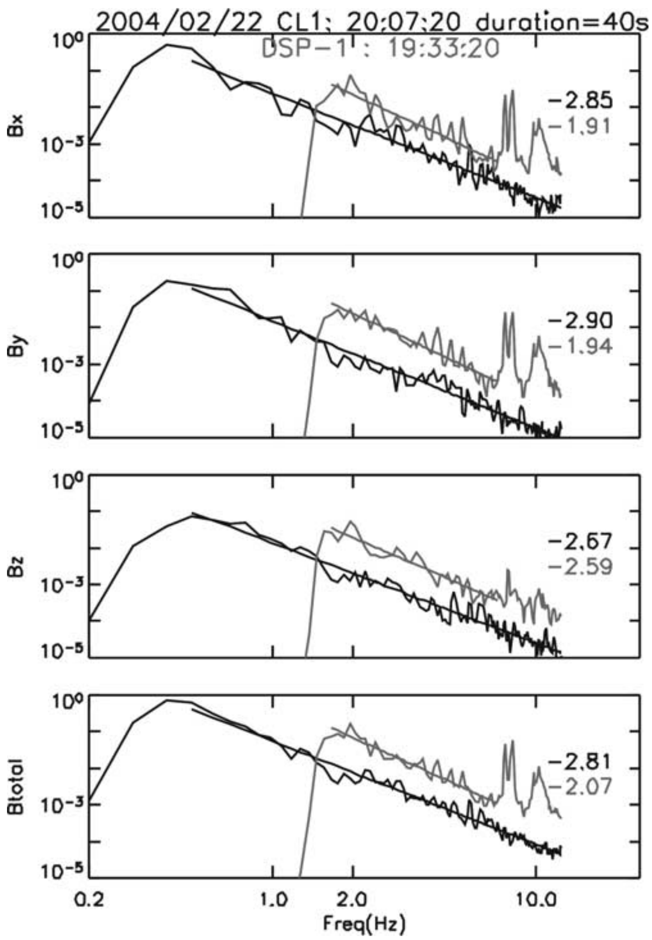

Figure 2. The 40 s integration of ULF wave power ($nT^2\ Hz^{-1}$) in the magnetosheath for the event shown in Figure 1, the closest possible to the magnetopause; the three components in GSE and the total wave power are plotted for DSP (in gray) and Cluster (in black). To avoid interferences, DSP data 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. For B_Z component, the cleanest one, the power law is similar for both spacecraft, but the power is stronger for DSP than observed by Cluster (after Figure 11 of *Cornilleau-Wehrlin et al.* [2005] with permission from Copernicus Publications).

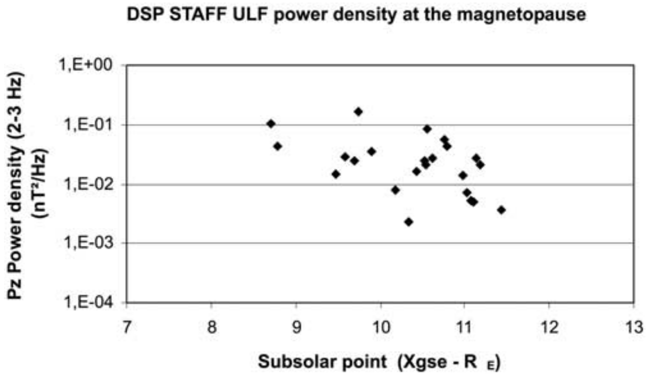

Figure 3. DSP ULF B_Z component wave power density in the 2–3 Hz frequency range (to avoid interferences effects), as a function of the magnetopause subsolar point as calculated by the use of *Sibeck et al.*'s [1991] model.

[17] Being confident that we have a valuable data set, we can go back to the Cluster-DSP comparisons.

[18] We first look at the variation of the wave power density with local time for the 23 events. In this data set, not all crossings occur at the same local time. The orbit apogees have the same local time, but in the GSE X, Y plane, the projection of the orbit is an ellipse which can give some LT hours of difference between the inbound and the outbound crossings of the MP. Then coordinated Cluster DSP crossing in UT may have differences in LT depending on whether this is during outbound or inbound periods. Figure 4 gives the evolution of the wave power density with local time. DSP data are shown in Figures 4a and 4c, and Cluster data are shown in Figures 4b and 4d. Figures 4a and 4b plot the power densities, whereas Figures 4c and 4d are plotted the normalized power density. Normalized mean divided by the square of the B field modulus, averaged in the magnetosheath, close to the magnetopause, in order to get rid of possible influence of the interplanetary conditions, as done by *Attié et al.* [2008]. DSP data, at low latitude, have less dispersed values than Cluster ones that are at high latitude, and the normalization does not change much the dispersion. Nevertheless postnoon data seem to be in a more reduced range of values than morning data. The size of the data set does not permit to make valuable considerations on this, but the morning hours are known to be the seat of more fluctuations, as Kelvin-Helmholtz instabilities or PC5 fluctuations. One must also consider the possible influence of the IMF. This will be looked at below. A clearer result is that the sub solar region around noon is not the seat of more intense ULF waves.

[19] We can try to look at the influence of the local time more carefully by considering only the subset of 11 events for which the crossings occur at the same local time. We have used the mean local time, averaged between the two DSP and Cluster local times (see Table 1). Then in Figure 5a we have plotted the two sets of simultaneous wave power

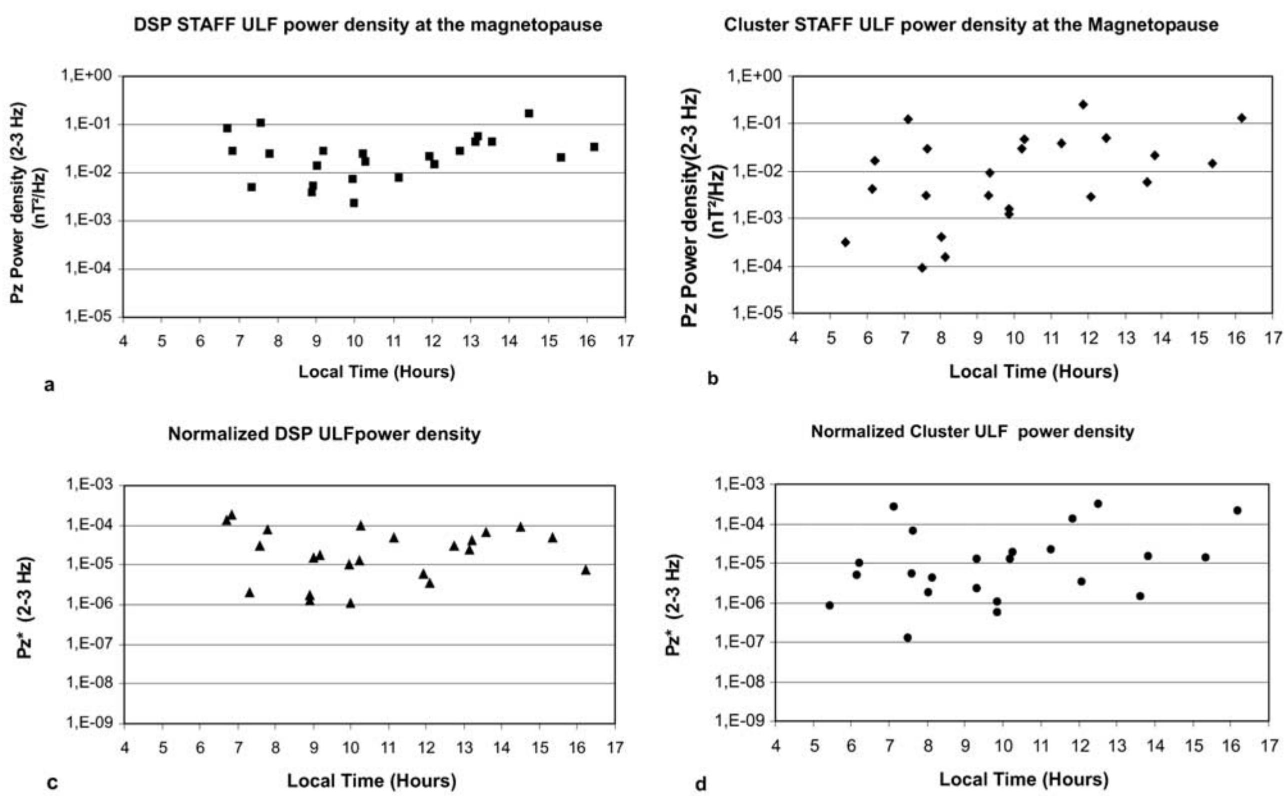

Figure 4. (a and c) DSP and (b and d) Cluster ULF wave power at the magnetopause as a function of local time, for the whole data set of coordinated crossings in UT (23 events). Figures 4a and 4b plot the wave power density; Figures 4c and 4d plot the normalized power density (B_Z wave power density divided by the square of the total magnetic field averaged in the adjacent magnetosheath).

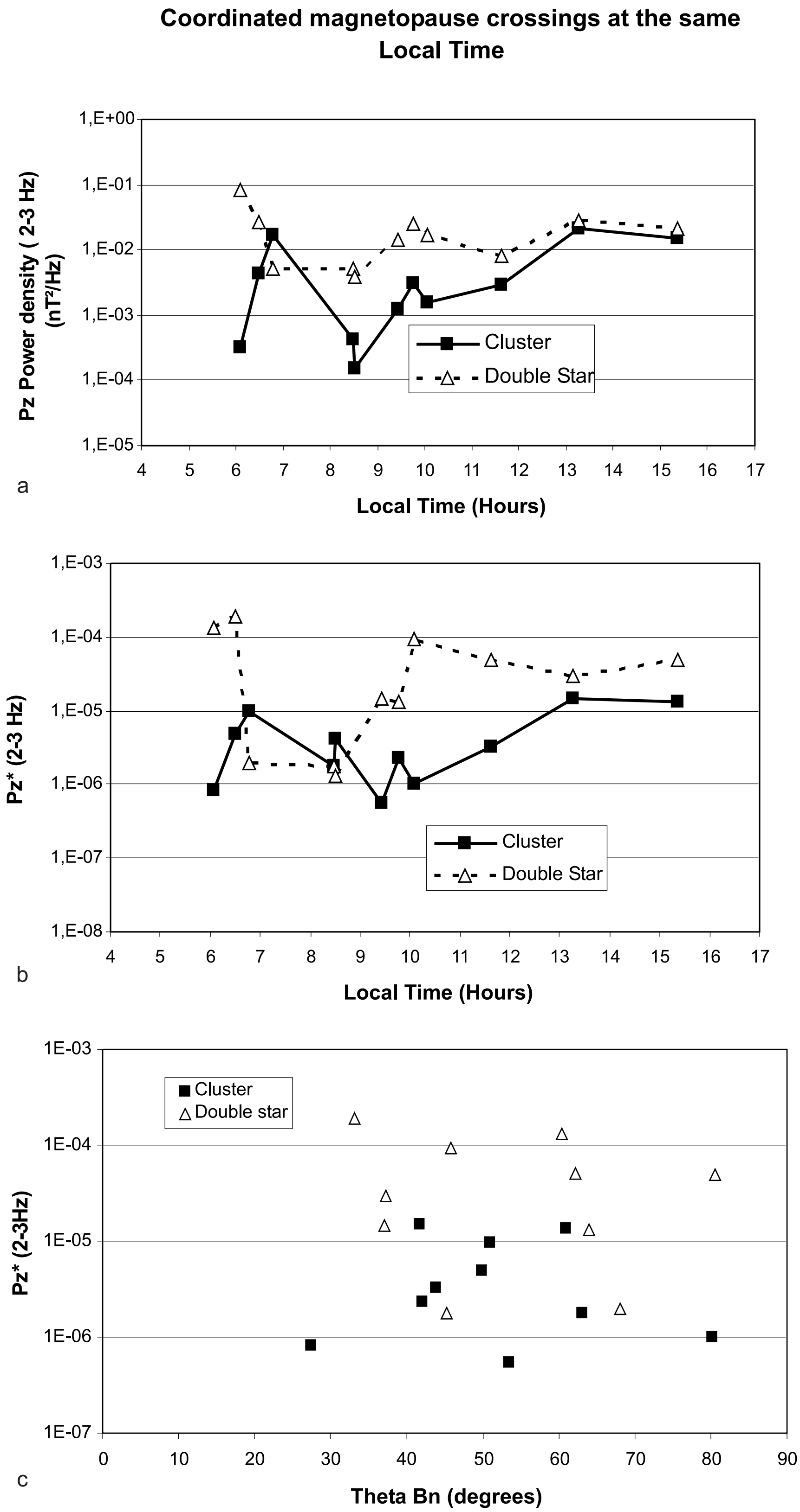

Figure 5. Comparison of DSP and Cluster wave power density (a) for the magnetopause crossings occurring quasi-simultaneously at the same local time (11 events out of 23). DSP values are always bigger than Cluster ones but for one event, discussed in the text. (b) The same for the normalized wave power density (see Figure 4). (c) The normalized power density for both Cluster and DSP events, as a function of the angle θ(B,n), angle between the bow shock normal direction and the IMF direction as measured by ACE, taking into account the appropriate time delay, using a bow shock model [*Formisano*, 1979].

density for coordinated crossings in local time (and UT also) for DSP and Cluster. For all events, except one, the 24 April 2004 crossing, DSP power is bigger than the Cluster power. There does not seem to be a law for the ULF power variation with respect to the local time. The result is not very different for the normalized power, plotted for both spacecraft in Figure 5b. One can say again that the values are less dispersed in the afternoon than in the morning, but on average, DSP data, at low latitude, are most of the time more intense than Cluster data. On average, the value at DSP does not seem to be local-time-dependent.

[20] For the 24 April 2004 event, at about 0630 LT, the Cluster power density is higher than the DSP one, contrary to all other events coordinated in UT and LT (Figure 5a) and to the trend shown by the larger data set in Figure 4. Cluster crosses the magnetopause at 1432 UT and DSP at 1502 UT, and the solar wind velocity as measured by ACE is ~450 km/s, giving a time delay of 52 min. Then we look at what happens between 1340 and 1410 UT in the solar wind upstream of the Earth as seen by ACE. Just at that time there is a change of orientation of the IMF (interplanetary magnetic field), from south to north, accompanied by a rotation in the X,Y plane. Moreover, earlier in the day, just after 0800 UT there has been a pressure pulse, followed by a slow decrease. This can be translated by a magnetopause relaxation and by a possible reconnection toward the flanks (the spacecraft are around 0600 LT). Consistent with this, the subsolar point has increased between the two crossings, or at least as seen by the two spacecraft, the subsolar point being evaluated at 9.3 and 11.1 Re for Cluster and DSP crossings, respectively. The difference in the evaluation of the subsolar point can also result from an oscillation of the boundary, e.g., surface waves due to Kelvin-Helmholtz instability which can give wavelength as big as 3.5 Re [*Owen et al.*, 2004].

[21] The other event for which the normalized power is larger at Cluster corresponds to 24 March 2004, just after 0800 LT. In this case, the Cluster magnetic field in the magnetosheath is exceptionally low, less than 10 nT, which explains the high value of the normalized power, but the reason for this low value has not been identified.

[22] Bow shock orientation is known to influence the wave power level downstream, i.e., in the magnetosheath. To see whether the dip around 0700 LT could be due to the nature of the bow shock, quasi-parallel or quasi-perpendicular, in Figure 5c we plot the normalized ULF wave power as a function of the θ(B,n) angle. This is the angle between the IMF direction and the shock normal. We used *Formisano*'s [1979] bow shock model to estimate the shock position and the normal to the shock at a crossing point C located along Xgse direction from spacecraft position, meaning that C = (X, Ysc, Zsc) GSE, where Ysc and Zsc are the coordinates of Cluster 1 or TC1. As the spacecraft can be on the flank or the dayside of the magnetopause, it is a better way to estimate the bow shock influence than considering a crossing point along the Earth-spacecraft axis.

[23] Solar wind and IMF data are provided by ACE spacecraft. We lagged the data to take into account the propagation time from ACE to C1/TC1 and we averaged the data over 4 min around the magnetopause crossing time.

[24] Looking at the results in Figure 5c if one considers 45° as the limit between quasi-parallel and quasi-perpendicular shock, one could notice that in most cases the shock is quasi-perpendicular. In the quasi-parallel set, P* is high for Double Star cases but can be low for Cluster. In the quasi-perpendicular set, both low and high wave power are recorded. Considering the Double Star data set, each of the two high-power level points seen in Figure 5a before 0700 LT corresponds to a different shock orientation (30° and 60°), and the three low wave power values seen between 0630 and 0900 LT correspond to median shock orientation (45°) and quasi-perpendicular orientation (65°), respectively, the latter one being a case with no solar wind density data available, the corresponding θ(B,n) angle cannot be calculated.. So no link clearly appears between θ(B,n) and P*. Then we cannot sort out any conclusion on the link between the ULF wave power at the magnetopause and the bow shock orientation.

[25] The next question is how big is the influence of the variation in latitude between the two points of measurements? This is first answered by the analysis of Figure 5 which shows that for the same events DSP power density is greater that Cluster one, DSP being at lower latitude and Cluster at higher latitude. For looking more quantitatively at this point, we use again the reduced data set of 11 events. Figure 6a gives the ratio of the wave power density measured at DSP over the one measured at Cluster, as a function of the difference in latitude between both spacecraft. DSP latitude varies between −9° and +10°, thus rather close to the ecliptic plane. Latitudes are given in Table 1 for this data set. Figure 6a shows two things: first the ratio is larger than unity for all events but one, the 24 April 2004 event, which has been discussed above. Second, the DSP over Cluster ratio of the wave power density seems to vary as an increasing function of the difference in latitude, more clearly if one neglects the 24 April 2004 event. The influence of the latitude on the level of the ULF wave power density at the magnetopause seems to be important, which indicates the predominant role or the ecliptic plane for the amplification of the ULF waves and their possible role for solar wind plasma penetration into the magnetosphere. To try to confirm this, we have plotted in Figure 6b the power density as a function of the absolute value of the latitude, for the full data set (2 × 23 events); of course, the DSP data are altogether at the low values of latitude and Cluster ones are more dispersed at high latitude. A trend to have more dispersed values, especially toward the small amplitudes with increasing latitude is visible on the right-hand side of Figure 6b.

4. Summary and Conclusions

[26] The aim of the present study was to try to identify the preferred region of intense ULF waves at the magnetopause, as a possible input for modeling the processes by which intense ULF wave at the magnetopause could participate to the Solar Wind particles penetration into the magnetosphere. The comparison of DSP and Cluster data, due to their different orbits, nevertheless coordinated, the apogees being at approximately the same local time during the first years of the mission, is particularly suited to such a study. The comparative study has permitted to look at latitudinal effects and also at local time ones, question of interest as some models propose that the subsolar point be the preferred

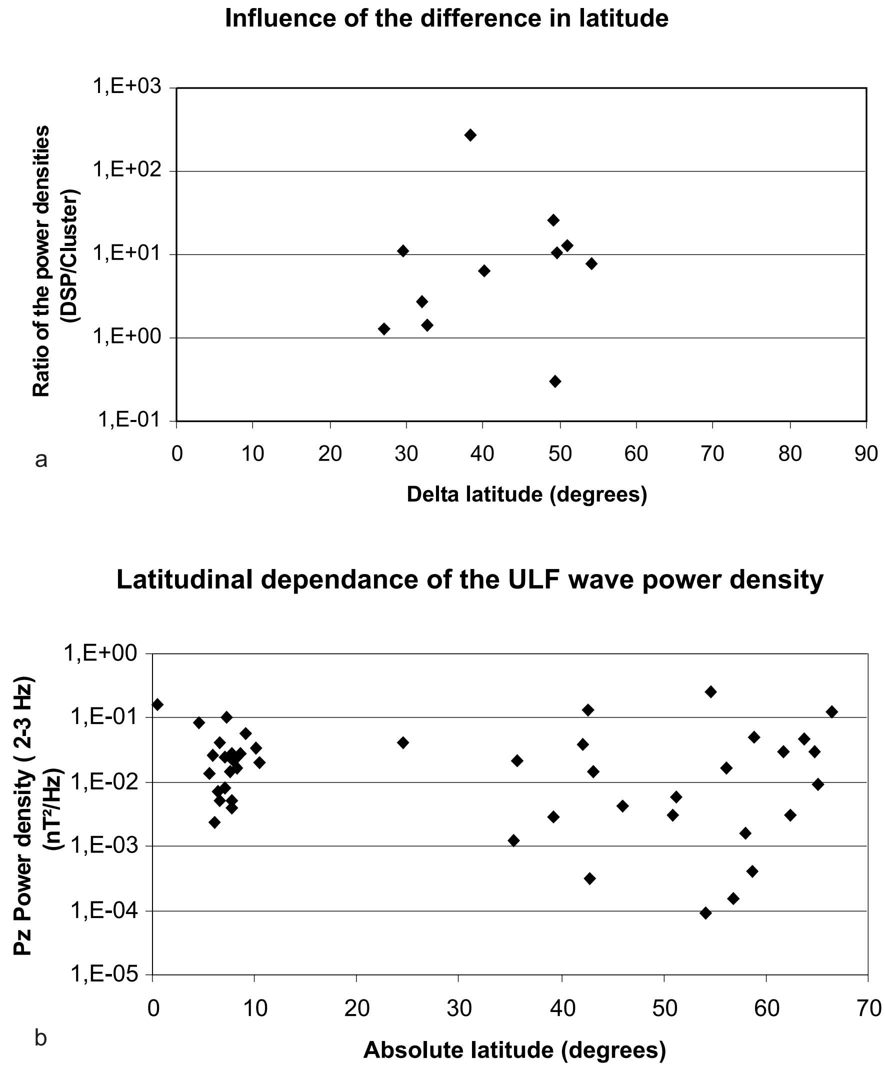

Figure 6. Influence of the latitude of the magnetopause on the wave power density. (a) For the coordinated events (see Table 1), the ratio of the power measured at DSP over the one measured at Cluster, as a function of the difference in latitude between both spacecraft. DSP latitude varies between $-8°$ and $+10°$, thus rather close to the ecliptic plane. (b) The power density for both DSP and Cluster magnetopause crossings, for the 23 events, as a function of the absolute value of the latitude. The low-latitude events correspond to DSP data.

region for penetration mechanisms linked to reconnection or to FTEs.

[27] We have shown (1) in 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 and (2) statistically the dependence of the DSP ULF wave power density on the geocentric distance of the subsolar point. The power increasing as the subsolar point distance decreases, which is linked to an augmentation of the solar wind pressure. Nevertheless one has to be cautious with the present results, as we have been obliged to only consider a limited frequency range, which may hide the influence of Doppler effects.

[28] We have used two small data sets from the time period 21 February 2004 to 22 May 2004 and January–February 2005, one for each spacecraft. We have found 23 coordinated magnetopause crossings, i.e., within less than 3 h, 11 of which were experienced by both spacecraft in less than 1 h separation in local time.

[29] The dependence of the wave power on latitude is clear, both by comparing DSP and Cluster data, and by looking at their ratio as a function of the difference in latitude between the two missions. The ecliptic plane seems to be a more favorable region for plasma penetration, if any due to ULF wave.

[30] Conversely, there is apparently no local time dependence on the ULF wave power density, normalized or not. One can only say that the morning hours crossing have more dispersed intensity values than the afternoon ones at higher latitudes, from the Cluster data set. There seem to be no stronger intensity around noon. As in the work by *Attié et al.* [2008] (with higher latitude Cluster data), we have not been able to detect an influence of the nature of the bow shock (quasi-perpendicular or quasi-parallel), by looking at the dependence of the ULF power vis a vis of the angle

between the bow shock normal and the Interplanetary Magnetic Field. We therefore are not able to confirm the work of *Shevyrev and Zastenker* [2005] and *Shevyrev et al.* [2006] performed with Interball-1 data and showing a link in the turbulence level in the magnetosheath and the nature of the linked bow shock, the level of magnetic fluctuations increasing with the presence of a quasi-parallel bow shock.

[31] In summary, the most striking result of the present study is the importance of the plane of the ecliptics for the ULF wave power, and apparently independently of the local time, the vicinity of noon having apparently no special role.

[32] For further confirmation, of those results and deeper studies, one has to wait for the evolution of Cluster orbit that is going to cross the magnetopause around noon at low latitude.

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References

Attié, D., G. Belmont, L. Rezeau, N. Cornilleau-Wehrlin, and E. Lucec (2008), Power of magnetopause low-frequency waves: A statistical study, *J. Geophys. Res.*, doi:10.1029/2007JA012606, in press.

Balogh, A., et al. (1997), The Cluster magnetic field investigation, *Space Sci. Rev.*, *79*((1–2)), 65–91, doi:10.1023/A:1004970907748.

Belmont, G., and G. Chanteur (1989), Advances in magnetopause Kelvin-Helmholtz instability studies, *Phys. Scr.*, *40*, 124–128, doi:10.1088/0031-8949/40/1/018.

Belmont, G., and L. Rezeau (2001), Magnetopause reconnection induced by magnetosheath Hall-MHD fluctuations, *J. Geophys. Res.*, *106*, 10,751–10,760, doi:10.1029/2000JA900151.

Belmont, G., L. Rezeau, and F. Reberac (1995), Resonant amplification of magnetosheath MHD fluctuations at the magnetopause, *Geophys. Res. Lett.*, *22*, 295–298, doi:10.1029/94GL03078.

Bhattacharjee, A., Z. W. Ma, and X. Wang (1999), Impulsive reconnection dynamics in collisionless laboratory and space plasmas, *J. Geophys. Res.*, *104*, 14,543–14,555, doi:10.1029/1998JA900094.

Carr, C., et al. (2005), The Double Star magnetic field investigation: instrumentation design, performance and highlights of the first year's observations, *Ann. Geophys.*, *23*, 2713–2732.

Cornilleau-Wehrlin, N., et al. (2003), First results obtained by the Cluster STAFF experiment, *Ann. Geophys.*, *21*, 437–456.

Cornilleau-Wehrlin, N., et al. (2005), The STAFF-DWP wave instrument on the DSP equatorial spacecraft: Description and first results, *Ann. Geophys.*, *23*, 2785–2801.

De Keyser, J., M. Roth, F. Reberac, L. Rezeau, and G. Belmont (1999), Resonant amplification of MHD waves in realistic subsolar magnetopause configurations, *J. Geophys. Res.*, *104*, 2399–2409, doi:10.1029/1998JA900060.

Farrugia, C. J., R. C. Elphic, D. J. Southwood, and S. W. H. Cowley (1987), Field and flow perturbations outside the reconnection field line region in flux transfer events: theory, *Planet. Space Sci.*, *35*, 227–240, doi:10.1016/0032-0633(87)90091-2.

Formisano, V. (1979), Orientation and shape of the Earth's bow shock in three dimensions, *Planet. Space Sci.*, *27*, 1151–1161, doi:10.1016/0032-0633(79)90135-1.

Gustafsson, G., et al. (2001), First results of electric field and density observations by Cluster EFW based on initial months of operation, *Ann. Geophys.*, *19*, 1219–1240.

Hasegawa, H., M. Fujimoto, T. D. Phan, H. Rème, A. Balogh, M. W. Dunlop, C. Hashimoto, and R. TanDokoro (2004), Transport of solar wind into Earth's magnetosphere through rolled-up Kelvin-Helmholtz vortices, *Nature*, *430*, 755–758, doi:10.1038/nature02799.

Khotyaintsev, Y., S. Buchert, K. Stasiewicz, A. Vaivads, S. Savin, V. O. Papitashvili, C. J. Farrugia, B. Popielawska, and Y.-K. Tung (2004), Transient reconnection in the cusp during strongly negative IMF B_y, *J. Geophys. Res.*, *109*, A04204, doi:10.1029/2003JA009908.

Lacombe, C., A. A. Samsonov, A. Mangeney, M. Maksimovic, N. Cornilleau-Wehrlin, C. C. Harvey, J.-M. Bosqued, and P. Travnicek (2006), Cluster observations in the magnetosheath: 2. Intensity of the turbulence at electron scales, *Ann. Geophys.*, *24*, 3523–3531.

Mangeney, A., C. Lacombe, M. Maksimovic, A. A. SaMsonov, N. Cornilleau-Wehrlin, C. C. Harvey, J.-M. Bosqued, and P. Travnicek (2006), CLUSTER observations in the magnetosheath: 1. Anisotropies of the wave vector distribution of the turbulence at electron scales, *Ann. Geophys.*, *24*, 3507–3521.

Owen, C. J., et al. (2001), Cluster PEACE observations of electrons during magnetospheric flux transfer events, *Ann. Geophys.*, *19*, 1509–1522.

Owen, C. J., M. G. G. T. Taylor, I. C. Krauklis, A. N. Fazakerley, M. W. Dunlop, and J.-M. Bosqued (2004), Cluster observations of surface waves on the dawn flank magnetopause, *Ann. Geophys.*, *22*, 971–983.

Perraut, S., R. Gendrin, P. Robert, and A. Roux (1979), Magnetic pulsations observed onboard GEOS 2 in the ULF range during multiple magnetopause crossings, in *Proceeding of Magnetospheric Boundary Layer Conference, Alpbach, June 1979*, *Eur. Space Agency Spec. Publ.*, *ESA SP-148*, 113–122.

Pu, Z. Y., and M. G. Kivelson (1983), Kelvin-Helmholtz instability at the magnetopause: Solution for compressible plasmas, *J. Geophys. Res.*, *88*, 841–852, doi:10.1029/JA088iA02p00841.

Retinò, A., et al. (2006), The structure of the separatrix region close to a magnetic reconnection X-line: Cluster observations, *Geophys. Res. Lett.*, *33*, L06101, doi:10.1029/2005GL024650.

Rezeau, L., A. Morane, S. Perraut, A. Roux, and R. Schmidt (1989), Characterization of Alfvenic fluctuations in the magnetopause boundary layer, *J. Geophys. Res.*, *94*, 101–110, doi:10.1029/JA094iA01p00101.

Rezeau, L., F. Sahraoui, E. d'Humières, G. Belmont, N. Cornilleau-Wehrlin, L. Mellul, E. Lucek, P. Robert, P. Décréau, and P. Canu (2001), A case study of low-frequency waves at the magnetopause, *Ann. Geophys.*, *19*, 1463–1470.

Robert, P., et al. (2002), Cluster observations of a flux transfer event (FTE), paper presented at COSPAR 2002, Eur. Space Agency, Houston, Tex., 10–12 Oct.

Russell, C. T., and R. C. Elphic (1979), ISEE observations of flux transfer events at the dayside magnetopause, *Geophys. Res. Lett.*, *6*, 33–36, doi:10.1029/GL006i001p00033.

Sahraoui, F., et al. (2003), ULF wave identification in the magnetosheath: k-filtering technique applied to Cluster II data, *J. Geophys. Res.*, *108*(A9), 1335, doi:10.1029/2002JA009587.

Sahraoui, F., G. Belmont, J.-L. Pinçon, L. Rezeau, A. Balogh, P. Robert, and N. Cornilleau-Wehrlin (2004), Magnetic turbulent spectra in the magnetosheath: New insights, *Ann. Geophys.*, *22*, 2283–2288.

Shevyrev, N. N., and G. N. Zastenker (2005), Some features of the plasma flow in the magnetosheath behind quasi-parallel and quasi-perpendicular bow shocks, *Planet. Space Sci.*, *53*, 95–102, doi:10.1016/j.pss.2004.09.033.

Shevyrev, N. N., G. N. Zastenker, P. E. Eiges, and J. D. Richardson (2006), Low frequency waves observed by Onterball-1 in foreshock and magnetosheath, *Adv. Space Res.*, *37*, 1516–1521, doi:10.1016/j.asr.2005.07.072.

Sibeck, D. G., R. E. Lopez, and E. C. Roelof (1991), Solar wind control of the magnetopause shape, location, and motion, *J. Geophys. Res.*, *96*, 5489–5495, doi:10.1029/90JA02464.

Sonnerup, B. U. Ö. (1980), Theory of low latitude boundary layer, *J. Geophys. Res.*, *85*, 2017–2026, doi:10.1029/JA085iA05p02017.

Tjulin, A., J-L. Pinçon, F. Sahraoui, M. André, and N. Cornilleau-Wehrlin (2005), The K-filtering technique applied to wave electric and magnetic field measurements from the Cluster satellites, *J. Geophys. Res.*, *110*, A11224, doi:10.1029/2005JA011125.

Tsurutani, B. T., A. L. Brinca, E. J. Smith, R. T. Okida, R. R. Anderson, and T. E. Eastman (1989), A statistical study of ELF/VLF plasma waves at the magnetopause, *J. Geophys. Res.*, *94*, 1270–1280, doi:10.1029/JA094iA02p01270.

Vaivads, A., Y. Khotyaintsev, M. André, A. Retinò, S. C. Buchert, B. N. Rogers, P. Décréau, G. Paschmann, and T. Phan (2004), Structure of the magnetic reconnection diffusion region from four-spacecraft observations, *Phys. Rev. Lett.*, *93*, 105001, doi:10.1103/PhysRevLett.93.105001.

Walker, S. N., F. Sahraoui, M. A. Balikhin, G. Belmont, J. L. Pinçon, L. Rezeau, H. S. C. Alleyne, N. Cornilleau-Wehrlin, and M. André (2004), A comparison of wave mode identification techniques, *Ann. Geophys.*, *22*, 3021–3032.

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