



## Source of whistler emissions at the dayside magnetopause

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[1] Observations of whistler emissions are common in the magnetosphere near the dayside magnetopause. We show that one of the major source regions for these emissions is magnetic field minima that form along magnetic flux tubes at high latitudes. Using multispacecraft Cluster observations we experimentally confirm for the first time the existence of the magnetic field minima at high latitudes and we show that whistler emissions propagate away from the magnetic field minima. The strongest whistler emissions are observed on the magnetospheric flux tubes that are newly opened due to the magnetic reconnection. These flux tubes still have a density of magnetospheric plasma, but part of the high energy magnetospheric electrons have already been lost from the flux tubes. The partial loss of high energy electrons most probably causes anisotropy in electron distributions at high energies which should be the source of whistler emissions. Whistler emissions on opened flux tubes disappear as soon as the plasma density of flux tubes increases due to the entering of magnetosheath ions. We speculate that whistler emissions can most probably be used to trace the dynamics of the first opened field lines and thus the dynamics of magnetic reconnection sites.  
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### 1. Introduction

[2] The observations of whistler waves in space plasmas are important because in most cases they are associated with dynamic processes involving the electron distribution functions. Whistler-mode waves have been observed at the magnetopause [Stenberg *et al.*, 2005], near the equator in form of chorus [Santolík *et al.*, 2004a], in the magnetosheath as so called lion roars [Baumjohann *et al.*, 1999] and in laboratory plasmas [Ji *et al.*, 2005].

[3] A detailed case study of whistler emissions observed by Cluster spacecraft near the magnetopause has shown that they are generated in localized regions [Stenberg *et al.*, 2005]. Due to the simultaneous multispacecraft observations the authors are able to show that the transverse size of the generation region is  $\sim 100$  km which is comparable to

the characteristic ion gyroradius. In addition, the observations of electron distribution function suggests that these waves are generated on the first open field lines where part of the magnetospheric electrons are lost, forming anisotropic electron distribution functions that are able to generate waves [Stenberg *et al.*, 2005].

[4] In this paper we concentrate on the whistler emission generation at the dayside magnetopause. We show that one of the source regions of whistler emissions is magnetic field minima that are present in the magnetosphere at high latitudes. They have been suggested as a possible source of chorus emissions based on statistical studies [Tsurutani and Smith, 1977]. It has been shown that similar magnetic field minima along the flux tubes are the source region of equatorial chorus emissions [Santolík *et al.*, 2004b]. Here we observationally demonstrate the existence of magnetic field minima at high latitudes at the dayside magnetopause and we confirm that they are a source of whistler emissions. Such magnetic field minima at high latitudes have also been studied from the point of view of trapping energetic particles in the cusp regions [Delcourt and Sauvaud, 1999]. In addition, we show that the strongest emissions are on the most recently opened flux tubes and discuss how the whistler generation is related to the reconnection process.

### 2. Event Overview

[5] The event that we analyze in detail is 6 April 2004, 0330–0440 UT. We use the electric field and the satellite potential data from the EFW and WHISPER instruments, the magnetic field data from FGM and STAFF instruments and electron data from the PEACE instrument [Escoubet *et al.*, 1997, and references therein]. Spacecraft orbit and location can be seen in Figure 1. The orbit of Cluster spacecraft is such that they move from the cusp into the plasma sheet and thereafter into the magnetosheath. During the interval that we concentrate on, 0330–0440 UT, the Cluster spacecraft are in the plasma sheet except for the last 10 min when they cross the magnetopause and enter the magnetosheath, see Figure 2.

[6] This event has been studied earlier as a large scale reconnection event where flux transfer events (FTEs) associated with reconnection have been observed both at Cluster and on Double Star spacecraft [Dunlop *et al.*, 2005]. That study suggests that the large scale reconnection X-line from which FTEs emanate is located 5–10  $R_E$  sunward from Cluster and thus FTEs observed at Cluster are all moving tailward. Figure 2a shows magnetic field  $B = |\mathbf{B}|$  observations and it can be seen that as the Cluster spacecraft move closer and closer to the magnetopause, the magnetic field becomes more varying. FTEs can be seen as repeated increases in the magnetic field magnitude, for example a very clear example can be seen at  $\sim 0418$  UT.

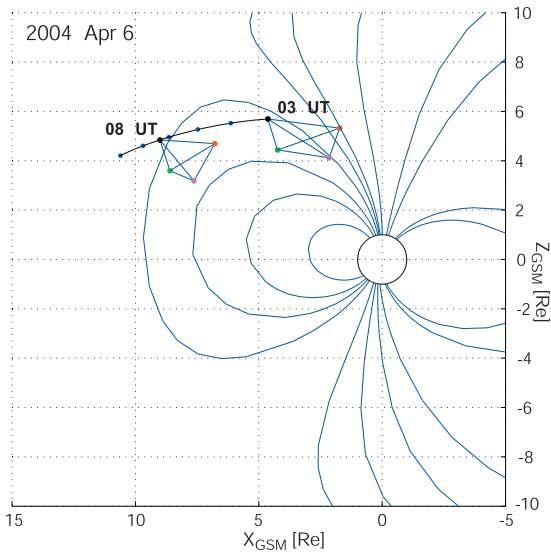
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**Figure 1.** Cluster s/c 1 orbit. At two positions are shown spacecraft configuration scaled up by a factor 50. Magnetic field lines represent Tsyganenko 89 model.

[7] Figure 2b shows the spatial derivative of  $B$  along the magnetic field line,  $\partial_s B = \nabla|\mathbf{B}| \cdot \mathbf{B}/|\mathbf{B}|$ .  $\partial_s B$  is estimated from multispacecraft observations of Cluster using linear interpolation. There is a change in  $\partial_s B$  from being positive to negative at  $\sim 0400$  UT. Positive (negative)  $\partial_s B$  means that

the magnetic field minimum is in the antiparallel (parallel) direction along the magnetic flux tube. During the whole time period Cluster move approximately antiparallel to the magnetic field, therefore the change in  $\partial_s B$  from positive to negative implies that at the time when  $\partial_s B$  is around zero the Cluster spacecraft are close to the magnetic field minimum of the flux tube. The importance of this is discussed later.

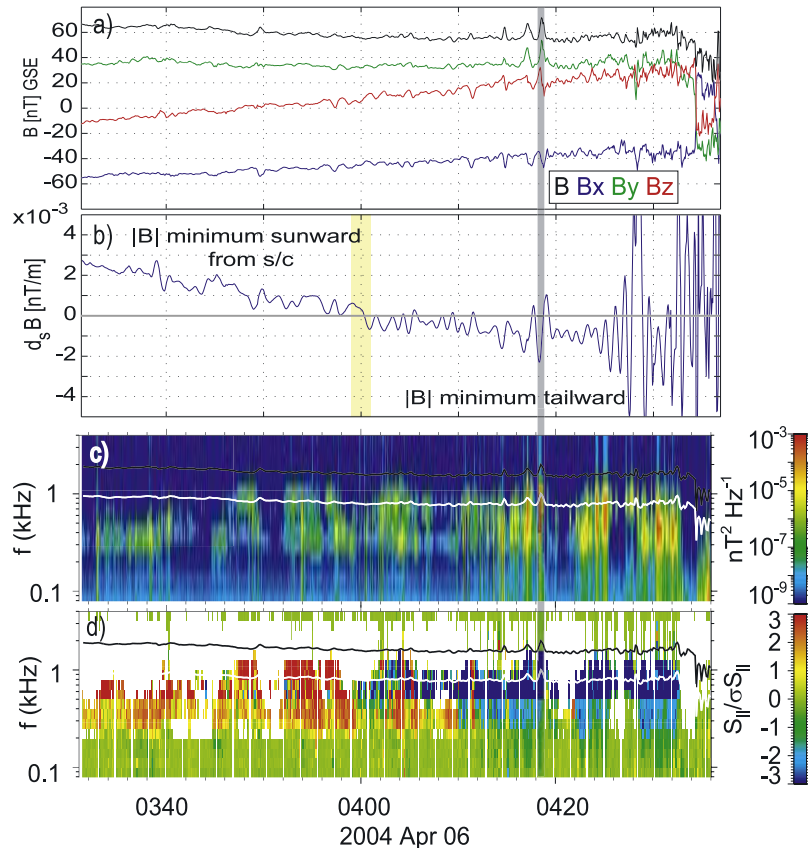
[8] Whistler wave observations during the event are shown in Figures 2c and 2d. Figure 2c shows magnetic field wave spectrogram, whistlers are seen as banded wave emissions at frequencies between a few hundred Hz and 1 kHz. Whistler emissions have frequencies around and below half of the electron gyrofrequency. The intensity of wave emissions increases as the spacecraft approach the magnetopause and emissions disappear as the spacecraft enter the magnetosheath at  $\sim 0433$  UT.

[9] Figure 2d shows the field-aligned component of the Poynting flux of the waves normalized by its standard deviation. It can be clearly seen that until  $\sim 0400$  UT whistlers are parallel while afterwards mainly antiparallel to the magnetic field. The change in the direction of wave Poynting flux coincides with the change in the sign of  $\partial_s B$ . Thus, the direction of the Poynting flux is consistent with waves propagating away from the magnetic field minimum of the flux tube.

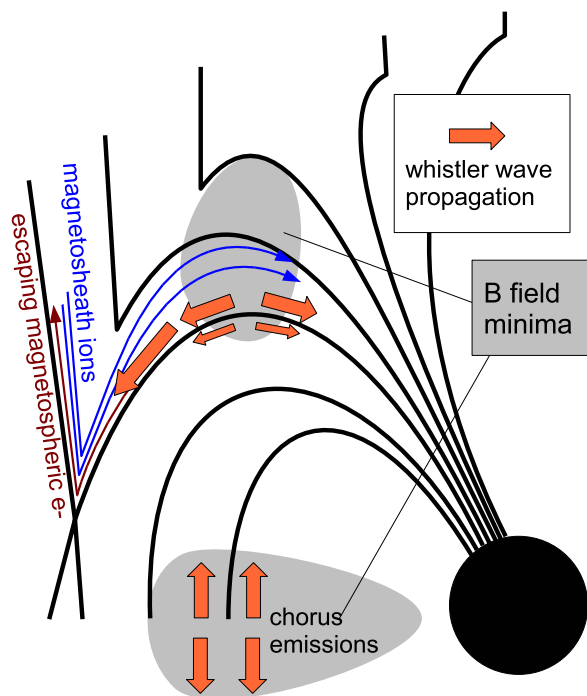
### 3. Discussion

#### 3.1. Source Region

[10] The observations suggest two conclusions. First, the source of emissions should be close to the magnetopause



**Figure 2.** Overview of the event. Cluster sc4 observations. (a) Background magnetic field. (b)  $\partial_s B$ . (c) Spectrogram of magnetic field fluctuations. The black line marks electron gyrofrequency  $f_{ce}$  and the white line  $f_{ce}/2$ . (d) Field-aligned Poynting flux of the waves normalized by its standard deviation. The vertical gray bar marks the time interval that is studied in detail.



**Figure 3.** A sketch explaining the generation of whistler waves near the magnetic field minimum along the magnetic flux tubes. At the magnetopause the strongest emissions are on flux tubes that are newly opened due to reconnection.

because the wave amplitude increases as we approach the magnetopause crossing. Secondly, the source region should be close to the region where  $\partial_r B$  changes the sign, i.e. the magnetic field minimum of the flux tube. The sketch interpreting observations is shown in Figure 3. The magnetic field minimum along the flux tubes that forms at high latitudes is marked in grey and the propagation direction and strength of the whistler emissions is sketched with orange arrows. The sketch also shows chorus emissions that are observed at low latitudes in the inner magnetosphere; these emissions similarly have the source regions near the magnetic field minimum, however in the inner magnetosphere the magnetic field is more dipolar and therefore the magnetic field minimum of the flux tubes is in the equatorial plane. The details on the relation of the whistler emissions at the magnetopause to reconnection are discussed below.

[11] We have checked whether Cluster crossings of the magnetopause during other times show similar properties of the whistler generation regions. The preliminary analysis shows that indeed in those cases when there are strong whistler emissions near the magnetopause their properties are similar - emissions are stronger closer to the magnetopause and whistlers propagate away from the magnetic minimum of the flux tube. However, there are a few cases where Cluster did not cross near a magnetic minimum of the flux tube and whistlers did not show the change in the propagation direction. These cases can be consistent with magnetic minimum of the flux tube being located further away or being absent. To resolve these questions many more events will have to be studied.

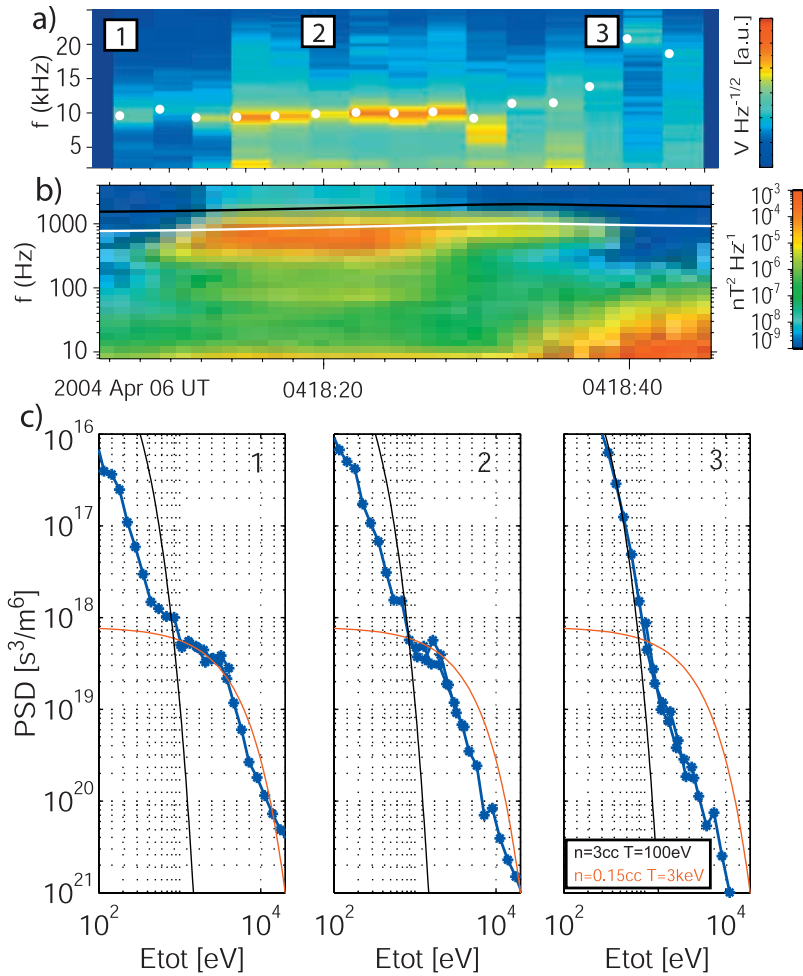
### 3.2. Free Energy Source of Whistlers

[12] The free energy source of whistler waves is most probably the anisotropy  $T_{\perp} > T_{\parallel}$  in electron distribution function. The whistler resonance condition  $v_{\parallel \text{res}} = (f - f_{ce})\lambda_{\parallel}$  gives resonant energies to be about 10–25 keV in the relevant frequency range. We have obtained an approximate value of the parallel wave length  $\lambda_{\parallel} \sim 50\text{--}70$  km from the theoretical whistler dispersion relation for parallel propagation, whistler frequency range is  $f \sim 400\text{--}800$  Hz (Figure 2) and cyclotron frequency  $f_{ce} \sim 1700$  Hz. *Stenberg et al.* [2005] show that the anisotropy in electrons ( $T_{\perp} > T_{\parallel}$ ) can form on the freshly opened flux tubes when the magnetospheric energetic electrons with pitch angles close to the magnetic field leave the flux tubes first and electrons with higher pitch angles take a longer time to leave. We do not analyze quantitatively the anisotropy of electrons in our case. While qualitatively they show the same picture as in the case of *Stenberg et al.* [2005], in our case the resonant energy of electrons is several tens of keV and at those energies there are too few data points from the electron instrument to draw reliable conclusions (in the case of *Stenberg et al.* [2005] resonant energy was around 1 keV and therefore quantitative study was possible). Instead, we demonstrate qualitative arguments.

[13] Figure 4 shows high frequency emissions, whistler wave emissions and sample electron distribution functions from a very short time interval in detail. We use high frequency emissions in Figure 4a to see the plasma density variations throughout the interval. Approximate value of the plasma frequency is marked by white dot and one can see that throughout the interval, the plasma frequency is about 10 kHz while from shortly before 0418:40 UT it starts to increase reaching about 20 kHz. The increase in plasma density can be seen also in the changes of satellite potential (not shown). Whistler wave emissions can be seen in Figure 4b, within a 40 s interval there is about 20 s long time interval with whistler emissions and it can be seen that the emissions are observed before the density increase. We can notice that strong high frequency emissions are correlated with strong whistler emissions indicating a region of unstable electron distribution functions.

[14] Whistler emissions in Figure 4b show dispersion where the low frequency emissions are seen first and the high frequency emissions last. Such a dispersion is not typical for all the observed whistler emissions at magnetopause. There can be emissions with no clear signatures of dispersion or even reversed dispersion. A deeper study on what are the possible causes of the dispersion is ongoing (*G. Stenberg, manuscript in preparation, 2007*).

[15] Figure 4c shows the integrated electron distribution functions from 3 time instants - one before whistler emissions, one within the region of whistler emissions and one just after. In addition, as a reference, two model distribution functions are plotted, the red line represents plasma sheet population (hot and tenuous) and the black line represents magnetosheath population (dense and cold). Before the whistler emissions electrons are predominantly of plasma sheet origin while after the whistler emissions electrons are predominantly of magnetosheath origin. Thus we have a consistent picture where whistler emissions appears on the first open flux tubes, where the high energy plasma sheet electrons start to disappear due to leaving the magneto-



**Figure 4.** Cluster s/c 4 observations. (a) Spectrogram of electric field fluctuations at high frequencies. The approximate location of the local plasma frequency is marked by a white dot. Numbers 1, 2, and 3 indicate the regions in which electrons distribution functions shown in Figure 3c are measured. (b) Spectrogram of magnetic field fluctuations. Black line marks  $f_{ce}$  and white line marks  $f_{ce}/2$  frequencies. (c) Electron distribution functions integrated over all pitch angles and all azimuthal angles. Two model distribution functions are drawn for guidance.

sphere and flux tubes start to be filled with the magnetosheath electrons. Note that we estimated that whistler emissions are in resonance with high energy electrons, 10–25 keV. Thus it is an anisotropy forming in the plasma sheet electrons at these high energies that is the most probable source of instability. Magnetosheath electrons enter the newly opened flux tube as field aligned beams, but their energy is too low to affect whistler generation. They can still contribute to the generation of emissions around plasma frequency that are seen simultaneously with whistler emissions, see Figure 4a. Observations do not indicate that magnetosheath electrons would be accelerated to high energies due to the reconnection process. Plasma density in the newly opened flux tubes is still low because magnetosheath ions have not yet reached the spacecraft. As soon as the plasma density increases due to more and more magnetosheath ions reaching the spacecraft and magnetosheath electrons filling the flux tube, whistler emissions cease and instead low frequency broad band fluctuations appear. Whistler emissions most probably disappear due to the lack of the anisotropy in electrons, plasma sheet electrons are gone and magnetosheath electrons have a small opposite anisotropy,  $T_{\perp} < T_{\parallel}$ . In addition, the whistler emissions most

probably do not propagate into this region from the nearby first open flux tubes due to the density gradient.

[16] If whistler emissions are associated with the opening of flux tubes due to magnetic reconnection then they can be used to remotely study the dynamics of reconnection sites. The emissions should be present only during ongoing reconnection and the width of the generation region should depend on the size of the reconnection site as well as the reconnection rate. Thus, in our case the comparison between spacecraft (not shown) gives that the thickness of the region where emissions are observed is about 400 km. This is approximately equal to the expected distance between the electron and ion edges when spacecraft are located at a few  $R_E$  distance from the reconnection site, as is expected in our case [Dunlop *et al.*, 2005].

[17] In addition, Figure 2 suggests that there can be a one-to-one correlation between the times when FTEs pass the spacecraft and the times of more intense whistler emissions. In particular, such a clear correlation is seen for several minutes before 04:20 UT. A possible explanation of this correlation is that during FTEs the magnetopause moves closer to the spacecraft. Therefore, the spacecraft can change their relative location with respect to the magneto-

pause from being on the closed field lines relatively far away from the magnetopause to the first open field lines where whistler wave emissions are observed. Thus, the relative motion of the spacecraft with respect to the magnetopause during FTEs would cause the correlation of whistler emissions and FTEs. In addition, FTEs are associated with increased reconnection rate that can lead to more intense whistler emissions in association with FTEs. However, whistlers are also seen outside FTE regions. Therefore, there can be other reasons, such as surface waves, that bring the spacecraft closer to the magnetopause or further away from it, thus contributing to the bursty nature of the emissions. More quantitative and detailed observational studies as well as comparisons with numerical simulations are required to explore the capability of remote studies of reconnection sites using whistler emissions.

[18] There can be other mechanisms that can create anisotropy in electron distribution function. One such mechanism that would be efficient very close to the magnetopause and very close to the magnetic field minimum along the flux tube is magnetic pumping [Berger *et al.*, 1958; Tsurutani and Smith, 1977]. Plasma is trapped around the magnetic field minimum along the flux tube. The temporal increase of the magnetic field magnitude at the minimum will lead to the creation of anisotropic electron distributions. Figure 2a shows that the magnetic field magnitude during the passing of FTEs can locally increase by up to 20%. Preliminary studies comparing different spacecraft show that the magnetic field magnitude increase extends only a few hundred km into the magnetosphere from the bulge of a passing FTE (the bulge is formed by flux tubes opened during the reconnection). This would imply that a magnetic pumping mechanism would work only in the region of magnetic field minimum that is very close to the first opened flux tubes. The expected anisotropy from magnetic pumping effect is small ( $T_{\perp}/T_{\parallel} \leq 1.2$ ), but the studies of the whistler emissions in the magnetosheath (so called lion roars) have shown that anisotropy as small as  $T_{\perp}/T_{\parallel} \sim 1.1$  can be responsible for the whistler emission generation in the magnetosheath [Baumjohann *et al.*, 1999]. To estimate the efficiency of magnetic pumping requires further studies involving events where Cluster is close to the magnetic minimum and trying to correlate wave emissions during those events with passing FTEs.

#### 4. Conclusions

[19] We have studied whistler wave emissions near the high-latitude dayside magnetopause during one of the Cluster spacecraft crossings of this region. During this event there was an ongoing reconnection at the dayside magnetopause with the reconnection site being several earth radii sunward from the Cluster spacecraft. There were multiple FTEs passing the location of Cluster spacecraft. Our results can be summarized.

[20] (1) We present for the first time experimental evidence that magnetic flux tubes of magnetospheric origin that are passing close to the magnetopause have magnetic field minimum in the high-latitude regions.

[21] (2) During the event we observe intense whistler wave emissions. The intensity of emissions is largest on the magnetospheric side of the magnetopause, but waves almost disappear in the magnetosheath like plasma. Also high

frequency wave emissions with frequencies near the plasma frequency are observed in the same region.

[22] (3) The field-aligned Poynting flux of whistler emissions show that they propagate along the magnetic field lines in the direction away from the magnetic field minimum that is consistent with the waves being generated there. Note that similarly, the magnetic field minimum at the equatorial plane inside the inner magnetosphere is the source region of the chorus emissions.

[23] (4) The wave intensity maximizes at the first opened field lines where density is still magnetospheric but electrons are most probably anisotropic due to the high energy field-aligned electrons being lost to the magnetosheath.

[24] (5) The anisotropy of magnetospheric electrons is the most probable free energy source of the whistler emissions.

[25] (6) Magnetic pumping requires further study as a possible alternative mechanism of electron anisotropy generation.

[26] (7) Our observations explain earlier statistical results that chorus emissions at the dayside magnetopause can have maximum at high latitudes [Tsurutani and Smith, 1977].

[27] (8) Our results show that whistler emissions can most probably be used to trace the dynamics of the first opened field lines and thus remotely analyze the dynamics of reconnection site. However, more studies are required to understand both the qualitative and quantitative relation of wave emissions to the dynamics of reconnection.

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