CLUSTER MEASUREMENTS OF ULF WAVES IN THE EARTH'S MAGNETOTAIL

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ABSTRACT

ULF waves are an important ingredient of the Earth's magnetosphere. In the magnetotail they manifest themselves on small scales (e.g. turbulence) via intermediate scales (e.g. wave-guide modes) to large scales (e.g. oscillation of the whole magnetotail). Using the four Cluster spacecraft both spatial and temporal variations of the ULF waves can be investigated. We discuss three different kinds of oscillations in the Earth's magnetotail: magnetotail eigen modes; Alfvén waves in the near-PSBL lobe; and magnetic turbulence in the plasma sheet. We will also shortly introduce the magnetotail flapping motion.

1. INTRODUCTION

In this paper we will discuss probing of ULF waves with multiple spacecraft. It was already pointed out by e.g. Zhou et al. [1] that multipoint observations are essential to understand the processes in the Earth's magnetosphere. Until the launch of partner spacecraft multipoint observations were mainly by chance conjunctions. A first start was made with ISEE 1 and 2, launched in 1977, which were in identical orbits and for which the inter-spacecraft separation could be changed by moving ISEE 2. Included was also ISEE 3, which monitored the solar wind at the Lagrangian L1 point (and was later renamed to ICE).

With the launch of the Cluster spacecraft in 2000, a dedicated multi-spacecraft mission was started and new projects, like Double Star (launched in 2004 and 2005), THEMIS (to be launched in 2006) and MMS (to be launched in 2013) are the logical successors in order to get a more detailed multipoint view of the magnetospheric processes.

In this paper we will summarize three topics of (ULF) wave studies in the magnetotail: (1) Eigen modes of the magnetotail and current sheet: We have observed driven eigenmode oscillations of the magnetotail at large and found evidence for current sheet eigenmodes; (2) Alfvén waves in the plasma sheet boundary layer: We use magnetic field (FGM) and electric field (EDI) data to study Alfvén waves, which are generated near a reconnection region in the tail and propagate Earthward in the lobes, preferentially during O^+-rich intervals; (3) A statistical study of plasma sheet turbulence: We used

Cluster data to study turbulence in the tail current sheet as a function of local time and plasma flow direction. At ULF frequencies the turbulence seems to be driven by a streaming instability.

Magnetotail flapping motions also occur in the lower frequency part of the ULF waves. In the last section we will shortly introduce flapping observed both by Cluster and Double Star and refer to Sergeev et al. [these proceedings] for a more elaborate overview of this topic.

2. EIGEN MODES OF THE MAGNETOTAIL

The Cluster mission has made it possible to investigate the eigen modes of the magnetotail with temporal and spatial resolution. Three examples will be shown in this section: Internal plasma sheet waves (wave-guide modes); A kink mode oscillation of the current sheet as a whole; and a breathing mode of the magnetotail
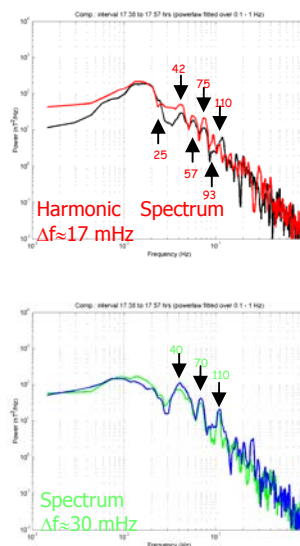
2.1 17 July 2001: Internal plasma sheet waves

Figure 1. Power spectra of 12 minutes of Cluster magnetic field data for C1/2 (left panel) and C3/4 (right panel.

On 17 July 2001, the Cluster spacecraft entered the neutral sheet, during a fast (~500 km/s) Earthward flow. Although the inter-spacecraft separation was 1800 km, two significantly different spectra were measured by C1/2 and C3/4 (see Figure 1, taken from Volwerk et al. [2]). These waves are driven by the fast flow, and fit a numerical model by Lee et al. [3] rather well.

From a linear fit of the observed frequencies with the model (numbers shown in Table 1), one obtains a mass density 0.08 and 0.04 AMU/cm^3. The plasma data from Cluster show that in the CIS experiment there is no difference in density for the two sets of spacecraft. However, the hot ion analyser shows a density variation between the two set. The latter data, unfortunately, may not be trustworthy, because of instrument mode changes (see Volwerk [4]).

Table 1. Spectral harmonics compared with the numerical results from Lee et al. [3].

harmonic	1	2	3	4	5	6	#
C1/2	25	42	57	75	93	110	mHz
C3/4	25	40	70	110			mHz
Lee et al.	5	10	17	22	24	27	mHz

2.2   22 August 2001: Tail kink mode oscillation

On 22 August 2001 an oscillation of the whole magnetotail, driven by strong plasma flow, was observed. The low pass filtered data showed a damped large scale oscillation in B_x (see Figure 2, taken from Volwerk et al. [5]).
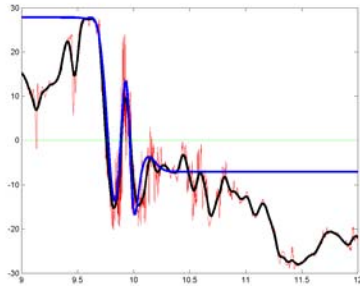

Figure 2. Cluster B_x data (red) for 22 August 2001 and low pass filtered data (black) and modelled kink mode oscillation (blue).

Using the model by Roberts [6,7] for Harris type current sheet MHD eigen modes, one finds that the magnetic pressure varies as:

$$\frac{i\omega}{\rho} p_{1m} = -v_A^2 \frac{dv_z}{dz} - \frac{B}{\mu_0 \rho}\left(\frac{dB}{dz}\right)v_z,$$

from which one obtains for the magnetic field variation, using an offset Harris sheet:

$$b_{1m} = \frac{\rho}{\omega}\left[-v_A^2 \frac{dv_z}{dz} - \frac{B}{\mu_0 \rho}\left(\frac{dB}{dz}\right)v_z\right]\cos\left(\omega t - \frac{\pi}{2} + \phi\right)e^{-\pi}.$$

The blue line in Figure 2 shows that this damped kink mode oscillation can well model the Cluster observations [5].

2.3   12 August 2001: Breathing mode

On 12 August 2001 the Cluster spacecraft measures a rapid flux transport event. Volwerk et al. [8] show that a reconnection event transports magnetic flux and evacuates the inner part of the tail, which then starts to oscillate. Figure 3 shows the magnetic field and plasma date for this event.
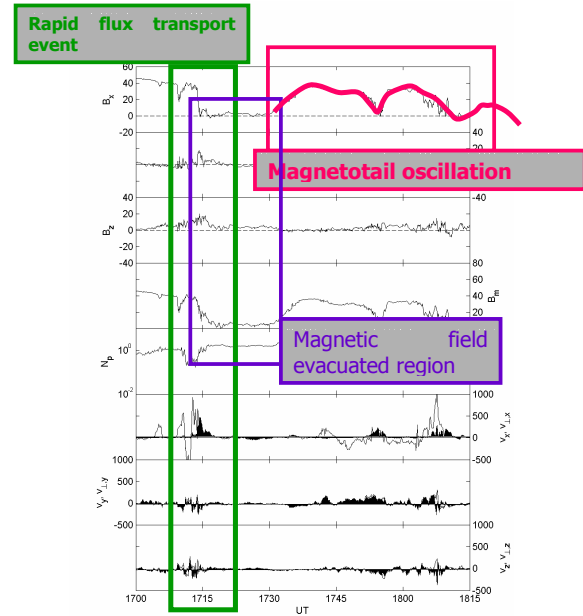

Figure 3. Magnetic field and plasma data for 12 August 2001. Green box shows flux transport event, blue box the interval of magnetic field evacuated region and the red box the breathing mode oscillation.

The flux transport can well be described theoretically using the frozen in field condition and modelling the $B_z(t)$ and perpendicular flow v(t) as Gaussians. Looking at the data in Figure 3 these assumptions are not bad.

$$\frac{\partial B}{\partial t} = \nabla \times (v \times B),$$

$$\frac{\partial B_x}{\partial t} = \frac{\partial}{\partial z}\left(v_x B_z - v_z B_x\right),$$

$$\left[B_z(t)\middle|v(t)\right] = \left[B_{z,0}\middle|v_0\right]\exp\left\{-\frac{t^2}{2\sigma^2}\right\},$$

$$\Delta B_x \propto L^{-1}\left(v_0 B_{z,0}\cos\alpha - v_0 B_x \sin\alpha\right)\Delta T \approx 33\,\text{nT}.$$

The following oscillation of the tail, a symmetric (sausage) mode fits well with the model by Seboldt [9] for such an oscillation. Observed is $f_0 \approx 0.8$ mHz and model, using Cluster parameters, gives $f_0 \approx 0.5$ mHz.

3. ALFVÉN WAVES IN THE NEAR-PSBL LOBE

There are abundant waves in the Plasma Sheet Boundary Layer (PSBL). Takada et al. [10] have shown in a statistical study of Geotail data that the low-frequency waves are Alfvénic and may be generated by ion beams. The lobes, however, are usually considered to be a quiet and empty region with stable, strong magnetic field.
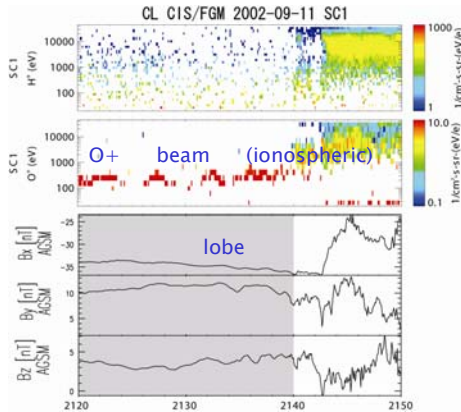

Figure 4. Top panels: the CIS spectrograms for H^+ and O^+ clearly showing an O^+ beam at several hundreds eV. Bottom panels: The magnetic field data.

Takada et al. [11] studied the Cluster data for 10 events in 2001 and 2002, in which the spacecraft move from the lobe into the PSBL. The conditions they set for the events are:

- Spacecraft at $X < -6\ R_E$, $|Y| < 10\ R_E$
- Electric field data from EDI for at least 1 SC
- Density $n_p < 0.03\ \text{cm}^{-3}$

On 11 September 2002 C1 observed an O^+ beam in the lobe and transverse wave activity (see Figure 4). Right hand polarized waves show up in the wavelet spectra in B and E (red boxes in Figure 5) with periods of 2 – 5 min., decreasing as Cluster moves towards the PSBL.
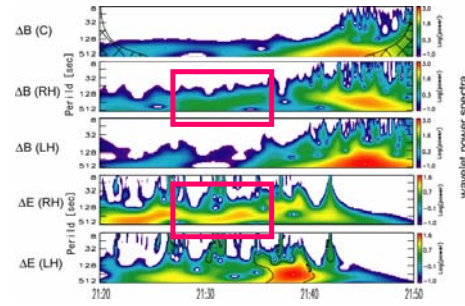

Figure 5. Wavelet analysis of B (3 components) and E (2 components). The red box shows the increased right-handed polarized waves activity.

Spectral analysis of the B- and E-field data from C3 shows that the right hand mode dominates during the interval, with peak frequency near 4 mHz, shown in Figure 6 left panel. There is a strong peak in the high frequency range of the 2 electric field components at the O^+ gyro frequency.
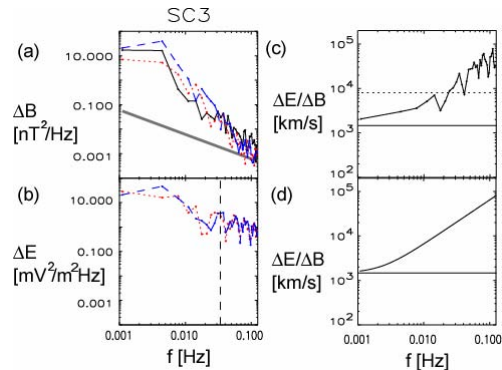

Figure 6. Left panel: The power spectra for the magnetic (top) and electric (bottom) field. At low frequency the right-hand polarized waves (dashed blue line) dominate, then left-hand (dotted red) and compressional (solid black). Right panel: The spectral ratios $\Delta E/\Delta B$ for the right-hand waves (top) and the theoretical dispersion curve (bottom). Horizontal solid lines mark local V_A.

Calculating $\Delta E/\Delta B$ over the spectral frequency range shows a curve that resembles well the dispersion curve for kinetic Alfvén waves as described by Stasiewicz et al. [12], see Figure 6 right panel. Taking all events, and plotting $\Delta E/\Delta B$ at the peak frequency vs. V_A, one finds that the Alfvénic nature of the waves is well supported. There is a spread of ±50% around V_A.

The minimum variance direction and the Poynting flux of these Alfvén waves show that energy transport is mainly field aligned and Earthward. Therefore these waves, on field lines mapping to the polar cap, may be responsible for cusp/cleft acceleration processes.
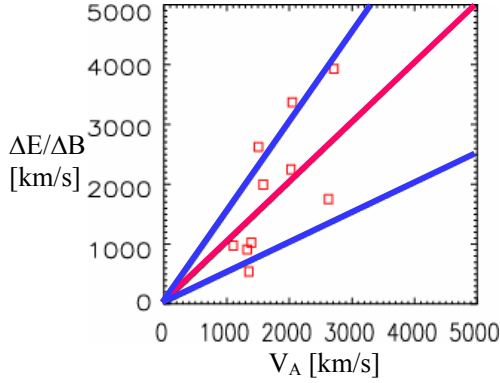
Figure 7. The ration ΔE/ΔB vs.V_A for all 10 events in red squares. The red line shows $\Delta E/\Delta B = V_A$ and the blue lines a ±50% deviation.
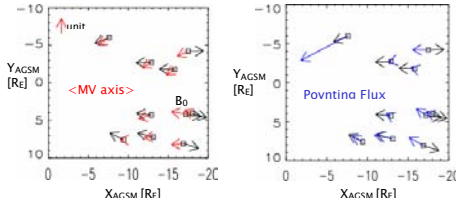

Figure 8. Propagation direction from MVA analysis and Poynting flux of the waves in abberated GSM

All events, except one, showed an O^+ beam, which significance will be discussed later. The presence of the O^+ beam may not be a necessary condition for the waves to develop, however it increases the amplitude of the waves, and makes them visible in the following way. The Alfvénic property of the lobe waves was shown in Figure 7. Therefore we can assume that the relation (1) $|\Delta E_\perp|/|\Delta B_\perp| \sim V_A$ is statistically satisfied for the observed waves. If the Poynting flux, $S_\parallel = \Delta E_\perp \cdot \Delta B_\perp$, is constant, then (2) $\Delta B_\perp \propto V_A^{-1/2}$ is obtained, i.e., the perpendicular magnetic field fluctuations decrease as the Alfvén velocity increases. As we mentioned before, the amplitudes of the magnetic field fluctuations are very small, even during the O^+ rich periods. In the case that the O^+ ion is absent, the Alfvén velocity increases and $\Delta B_\perp$ drops down to noise level. This could be one of the reasons why the lobe waves are rarely observed without O^+ beams.

The source of these waves is still under discussion. In general, there are two external wave sources such as the magnetopause/magnetosheath (outer source) and the PSBL/plasma sheet (inner source). The close association with substorms in all the cases (not shown) suggests an inner source. In the PSBL, the low-frequency waves are often detected as KAW by Geotail [13] and by Polar [14]. The leakage of PSBL waves to the lobe is plausible to explain the lobe wave features consistent with the KAW-like feature.

4. PLASMA SHEET TURBULENCE

Turbulence in the Earth's plasma sheet is strongly discussed, specially the driving forces and the scaling of the turbulence. We use the Cluster FGM and CIS data to investigate magnetotail turbulence. First investigations have shown that one might discern 3 different slopes in the power spectrum [see e.g. 15,16,17,18,19,20]. Two slopes in the power spectrum have now been well examined: α_1 and α_2 in Figure 9, by using spectral power analysis. This method poses problems for the region of α_3.
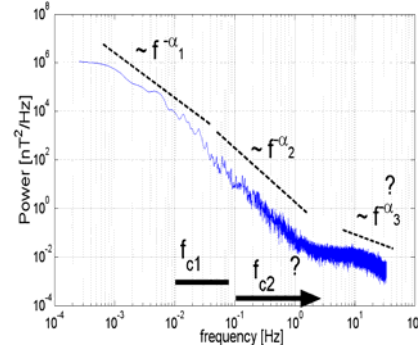

Figure 9. The different spectral slopes for turbulence in the Earth's plasma sheet, investigated by spectral Fourier analysis. α3 cannot be determined in this way.

At higher frequencies, the power spectra are influenced by the magnetometer noise, and thus other methods need to be found in order to obtain the spectral index and an estimate for the spectral slope and the dissipation scale. Wavelet analysis can look at smaller structures in the data, and the scalogram can be fitted with a power law: $P \propto [c_\perp | c_\parallel] f^\alpha$. There exists a scale dependent anisotropy in $c_\perp$ and $c_\parallel$ (see bottom panel Figure 9), and there is transient driving of the power, only when bulk plasma flow is present (see top panel Figure 9).

Vörös et al. [21] investigated the turbulence using Probability Density Functions (PDF) obtained by taking two-point differences in the time series using various time lags τ:

$$\delta B = B(t+\tau) - B(t)$$

$$P(X) = \frac{1}{nh} \sum_{i=1}^{n} w\left(\frac{X - X(t_i)}{h}\right)$$

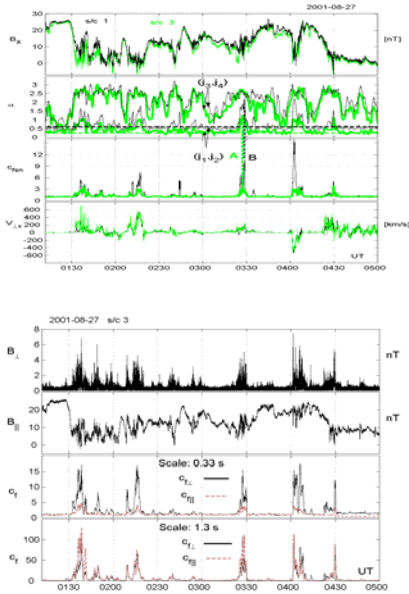$$w(s) = 0.5 \text{ for } |s| \leq 1, \text{ otherwise } 0.$$

Figure 10. Top panel: The magnetic field fluctuations, spectral slope α, power c and plasma bulk flow. Power is only present when flows are present. Bottom panel: Parallel and transverse magnetic field fluctuations and the power $c_\perp$ and $c_\parallel$ in both components.

Using quiet time data (i.e. no flow) Vörös et al. [21] obtained a model P(δB,τ) and used synthetic data with a known dissipation scale, τ_D, added to the quiet time data, to study the variation in P(δB,τ). Afterwards they looked at data sets with varying plasma flow velocity to find the dissipation scale. The shape of P(δB,τ) (scale evolution of points near P(δB,τ)$_{max}$) is dependent on the flow velocity as in the two examples shown in Figure 11.

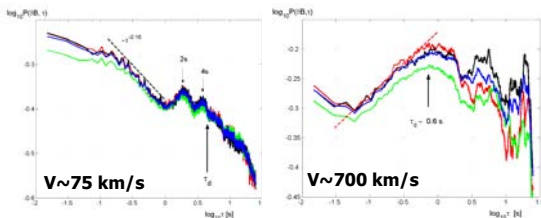Figure 11. Scale evolution of points near P(δB,τ)$_{max}$ as a function of plasma bulk velocity. At greater plasma flow the dissipation moves to smaller scales.

Using a set of 41 intervals from 2001 they obtained a strong dependence of the dissipation timescale vs. bulk velocity, shown in Figure 12. The velocity dependence of dissipation scale is a generic feature of many turbulent flows, thus its examination can facilitate the recognition of intermittent turbulence in the plasma sheet.
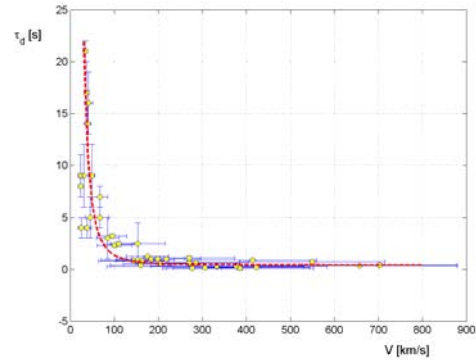

Figure 12. Dissipation scale as a function of bulk velocity.

5. MAGNETOTAIL FLAPPING

Another oscillation mode of the Earth's magnetotail is the so-called flapping motion, see Sergeev et al. [22]. During these events, Cluster observes multiple passings of the neutral sheet. An example of such a signature is given in Figure 13.
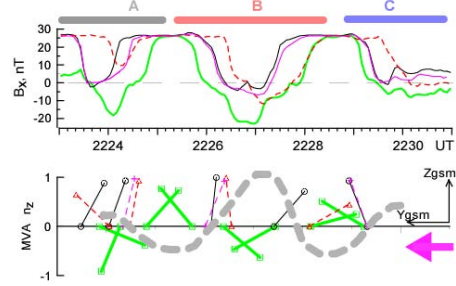

Figure 13. Flapping motion of the current sheet. Top panel: Bx measured by the Cluster spacecraft. Bottom panel: Normal direction of the current sheet (arrows) and the inferred shape of the current sheet (dashed line).

Timing analysis on the data, to obtain the normal direction of the tail current sheet, is performed. This shows that the tilt of the current sheet is mainly in the yz-direction. These waves are travelling in the yz-direction and are always moving away from the midnight meridian, see Runov et al. [23]. This suggests an internal source for these waves, e.g. reconnection, however, this source has not yet been identified. A further review of these flapping motions can be found in Sergeev et al. [these proceedings].

Interestingly, this flapping motion is not a local phenomenon. During a Cluster – Double Star conjunction on August 5, 2004, current sheet flapping was observed by both experiments. Cluster was located near $x_{GSM} \approx$ - 15.5 R_E and Double Star near $x_{GSM} \approx$ -11 R_E. Zhang et al. [24] showed that there was near perfect

agreement between the two data sets, and thus that the flapping motion of the magnetotail is a global oscillation which extends from the tail hinging point to at least 19 R_E downtail .

ACKNOWLEDGEMENTS

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