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Low Frequency Electromagnetic Waves Observation During Magnetotail Reconnection Event

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1. Introduction

Magnetic reconnection is a very important physical process in astrophysical and laboratory plasmas, which enables reconfiguration of the magnetic field topology and converts the magnetic field energy to plasma kinetic and thermal energy. The diffusion region is a crucial region of reconnection where magnetic field and plasma decouple from each other and strong wave activity and complex wave particle interactions occur. In general, the regions where the energy conversion takes place, e.g. substorm, ionosphere, shocks, produce wave emissions or wave turbulence covering a wide frequency range. Reconnection sites are not an exception. Understanding the role of waves and wave turbulence in the energy conversion, energy transport, and structure formation of the reconnection sites is an important and challenging task. When the reconnection takes place at ion inertial length, the wave-particle interaction plays an important role in reconnection process. Both the whistler dynamics and kinetic Alfvén waves can strongly influence the structure of the dissipation region during magnetic reconnection. Hall term in the generalized Ohm's law brings the dynamics of whistler waves into the fluid equations [1]. The only place where a reconnection site can be studied in great detail is laboratory and the Earth magnetosphere (or other environments in our solar system that have been visited by spacecraft, e.g. solar wind, other planets, comets). The spacecraft observations give much more detailed picture of the plasma dynamics at the smallest electron scales than the laboratory experiments, mainly due to the possibility to resolve particle distribution functions and fields at small scales. As the reconnection involves many processes at different spatial and temporal scales, numerical simulations serve as a superior tool for understanding the environment and physical processes near reconnection sites. The subsolar magnetopause and magnetotail are the two main regions in the Earth magnetosphere where the reconnection process has been observed by spacecrafts. The magnetotail reconnection is generally symmetric. In a sense plasmas on both sides of the current sheet have very similar properties. The opposite situation is observed at the magnetopause where the reconnection is mainly asymmetric. Another important difference between the magnetopause and magnetotail is that the typical spatial scales, e.g. ion inertial length, are usually a factor of ten smaller at the magnetopause. This is important for in situ studies where the instrument resolution becomes a limiting

factor. Although there is significant amount of studies dealing with low frequency electromagnetic waves at the magnetopause and in the magnetotail, but only in few cases was accompanied by reconnection processes. In many cases it has been speculated about such relationship. In this paper we summarize in situ observations of low frequency electromagnetic waves where reconnection signatures are well defined as well as those observations where one only speculates about such relationship.

2. Whistler observed by spacecrafts in the magnetosphere

Whistler is often observed in the magnetosphere. As early as 1960s, plasma wave was observed in the plasma sheet and neutral sheet region of the distant magnetotail by Ogo1, 3, and 5 satellites, which provide measurements only in the near-earth regions of plasma sheet (at radial distances $\sim 17\text{Re}$). Brody et al [2] have reported observations of brief bursts of whistler mode magnetic noise near the neutral sheet. Scarf et al. [3], using measurements from the Imp7 spacecraft at a radial distance of about 30 Re , have reported observation of moderately intense electric field oscillations in the region immediately outside the plasma sheet and a very intense low-frequency magnetic noise in the high-density region of the plasma sheet. Imp8 observed the whistler waves in the region near the neutral sheet in the magnetotail at radial distances ranging from -46.3 to -23.1 Re [4]. Three principal types of plasma waves are detected: broad band electrostatic noise, whistler mode magnetic noise bursts, and electrostatic electron cyclotron waves. Gurnett et al. [4] suggested that the whistler waves are most likely produced by current-driven plasma instabilities. The whistler waves are also observed by ISEE3 in the plasma sheet [5] and magnetotail flux ropes [6].

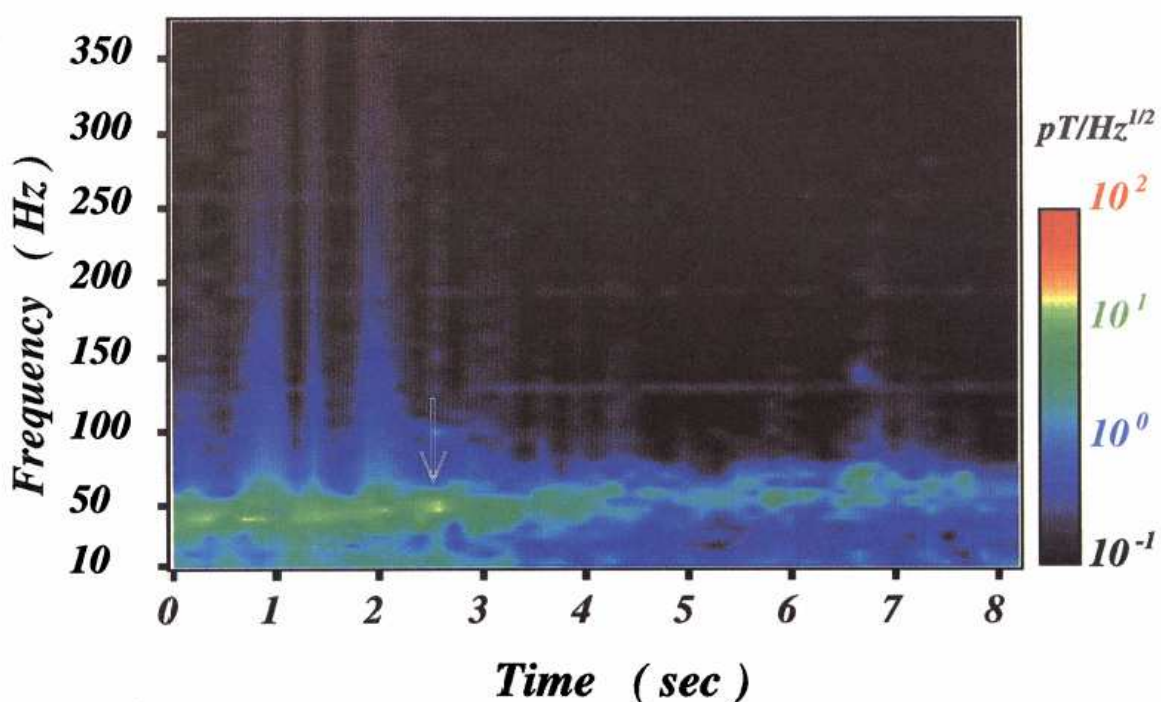


Plate 1. Dynamic spectra of magnetic field from wave form data around 1138.53UT on December 23, 1994. The Geotail was located in the near magnetotail at $(-46.94, -6.62, -5.37)\text{ Re}$. The electron cyclotron frequency is 135Hz during the 8s period

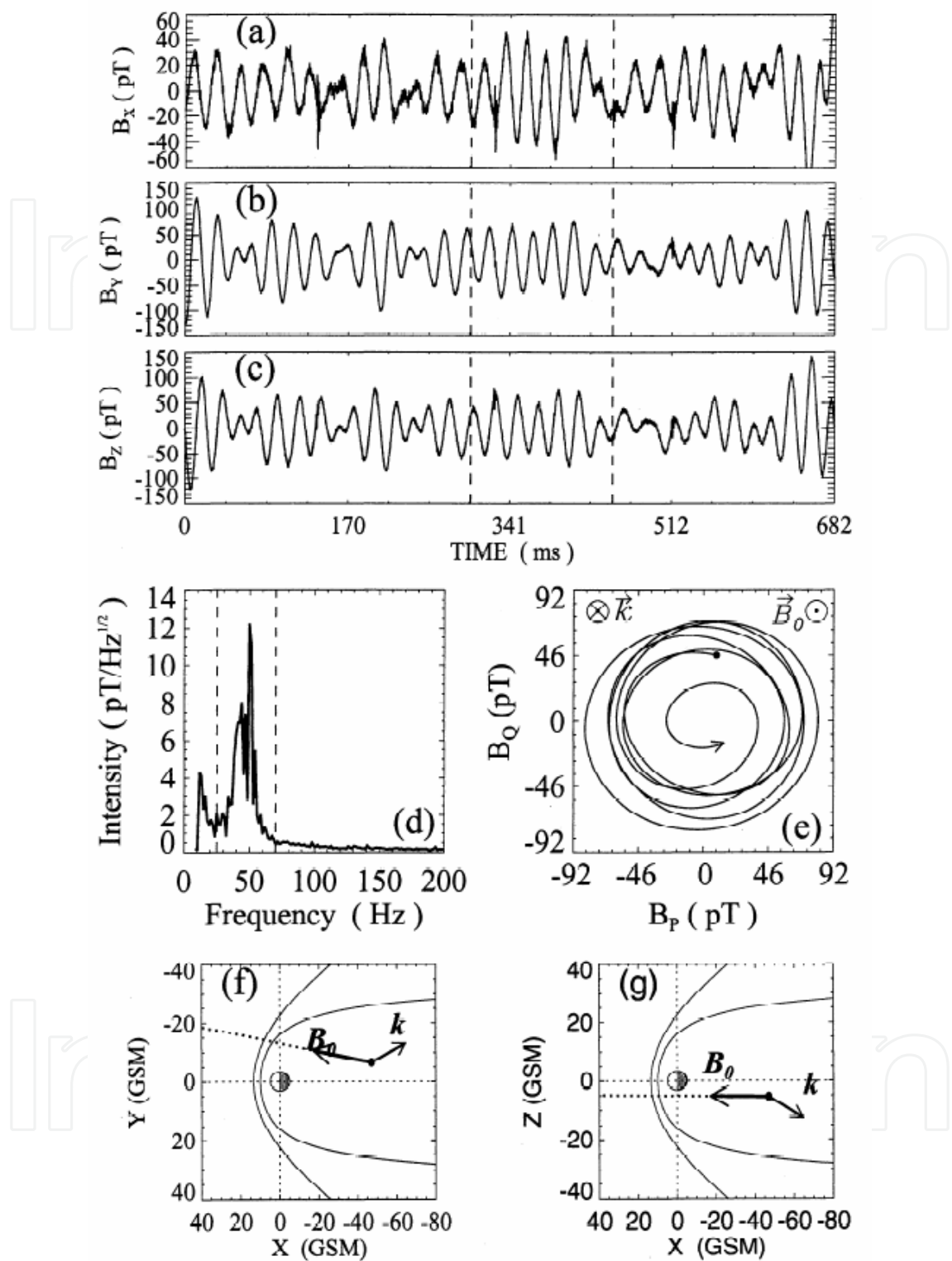


Fig. 1. (a)-(c) Magnetic field waveforms, (d) spectrum, (e) hodograph, and (f) and (g) k vector plots. B_x , B_y and B_z are the magnetic field components in directions from Earth to the Sun from dawn to dusk, and parallel to the Geotail spin axis, respectively. B_P and B_Q are two arbitrary orthogonal axes which are perpendicular to k vectors of the whistler mode waves. The wave was recorded around 1138:54UT on December 23, 1994 (see the white arrow in Plate 1)

It is suggested that superthermal electrons with highly anisotropic pitch angle distributions generate the whistler waves. Zhang et al. [7] analyze whistler waves observed by Geotail in the magnetotail at radial distance ranging from -210 Re to -10 Re, and they found that whistler waves can exist in both plasma sheet and plasma sheet boundary layer, and propagate quasi-parallel to the ambient magnetic field with an average propagation angle of 23 degrees. They thought that it is the energetic electron beams that generate the whistler waves. Plate 1 shows the dynamic spectra of magnetic field from wave form data around 1138.53UT on December 23, 1994. The Geotail was located in the near magnetotail at (-46.94, -6.62, -5.37) Re. The electron cyclotron frequency is 135Hz during the 8s period. Details of the bursts marked by a white arrow in Plate 1 are shown in Figure 1. Figure 1a, 1b and 1c are magnetic waveforms for a period of 0.7s. They are quasi-monochromatic waves with amplitude around 70pT. Figure 1d confirms that the central frequency (ω) of bursts is 50Hz. The hodograph in Figure 1e (obtained from the data between 300 and 450 ms in Figure 1a, 1b and 1c by using the minimum variance method [8] indicates the wave is right-hand circularly polarized with respect to the ambient magnetic field. The electron cyclotron frequency was 180Hz at this time, the central frequency (50Hz) is $0.28 \Omega_e$. This frequency is well between the electron cyclotron frequency and the lower hybrid frequency. All the wave character shows the magnetic bursts are whistler mode waves.

The above observations discussed the whistler wave activities in the magnetotail. No reconnection events and whistler wave activities were observed by spacecrafts simultaneously in current sheets.

3. Whistler and magnetic reconnection observed by spacecrafts in the magnetotail simultaneously

Whistler waves associated with reconnection in the Earth's magnetopause were also observed by Geotail [9]. Wind observed low frequency Alfvén /whistler waves associated with the LHDI (Low Hybrid Drift Instability) in the near-vicinity of the X-line of reconnection far from the Earth at about 57 Re in the magnetotail [10]-[11]. Cluster II STAFF instrument provides the good opportunity to study the low frequency electromagnetic waves. In succession, the whistler wave and reconnection event observed by Cluster will be significantly discussed.

3.1 Magnetic reconnection event and whistler wave on August 21, 2002

Cluster crossed the magnetotail plasma sheet from 07:00 UT to 09:00 UT on August 21, 2002. Figure 2 gives the ion flow velocity components (V_x), magnetic field components (B_x , B_y , B_z), plasma density, total magnetic field (B), and plasma Beta, which are observed by C1(black), C3 (green) and C4 (blue) during the interval of 07:50UT - 08:00UT on August 21, 2002. All Cluster spacecrafts were on the dawn side and in plasma sheet. It can be seen that a high-speed tailward ion flow ($V_x < 0$) accompanied by southward magnetic field component was observed by three satellites and it lasted about 5 min. The tailward ion flow with southward magnetic field component appeared at 07:53:50 UT on C1 and C3, and at 07:54:05 UT on C4. The velocity of tailward ion flow was very large and its maximum value even exceeded 1500 km/s. The maximum southward magnetic field component reached 25 nT. Generally, such a high speed tailward ion flow with a large southward magnetic field component is produced by magnetic reconnection. The tailward ion flow with southward magnetic field component disappeared at 07:58:30UT. Figures 1e and 1f give the ion density and plasma beta (β) observed by C1 and C4. From 07:50UT -07:56UT, the plasma β was

larger than 0.7, with a peak value 3.17 at 07:54:45UT, where the ion density was about $0.3/\text{cm}^3$, the total magnetic field was about 15nT, and the proton temperature was about 5897 eV. Thus according to general identification criterion of plasma sheet [12], the Cluster satellites were located in the plasma sheet at least between 07:50UT -07:56UT. The reconnection event details see the reference [13].

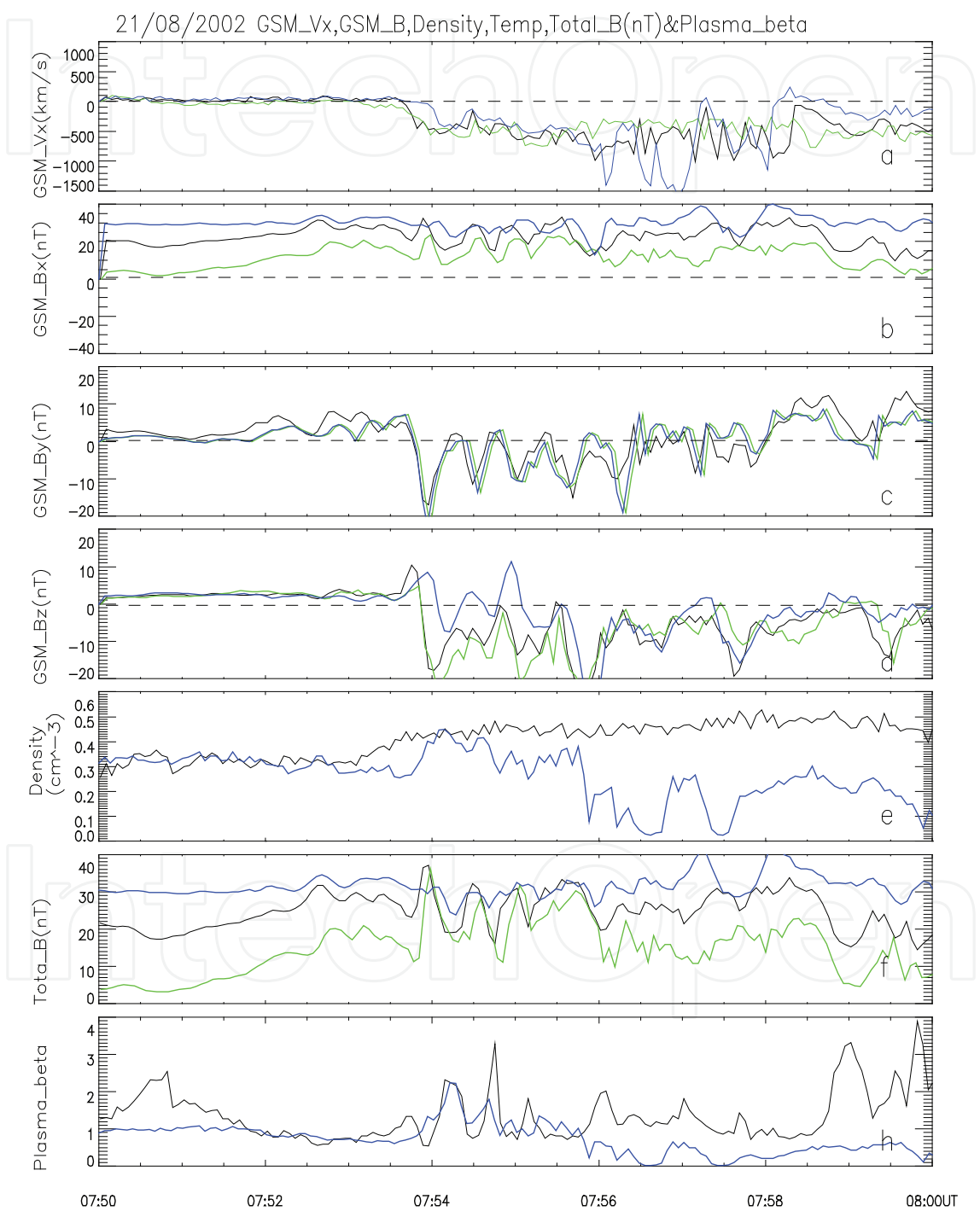


Fig. 2. Plasma parameters observed by C1 (black), C3 (green) and C4 (blue) during the interval of 07:50UT - 08:00UT on August 21, 2002. From top to bottom: plasma flow (Vx), magnetic field components (Bx, By, Bz), ion density

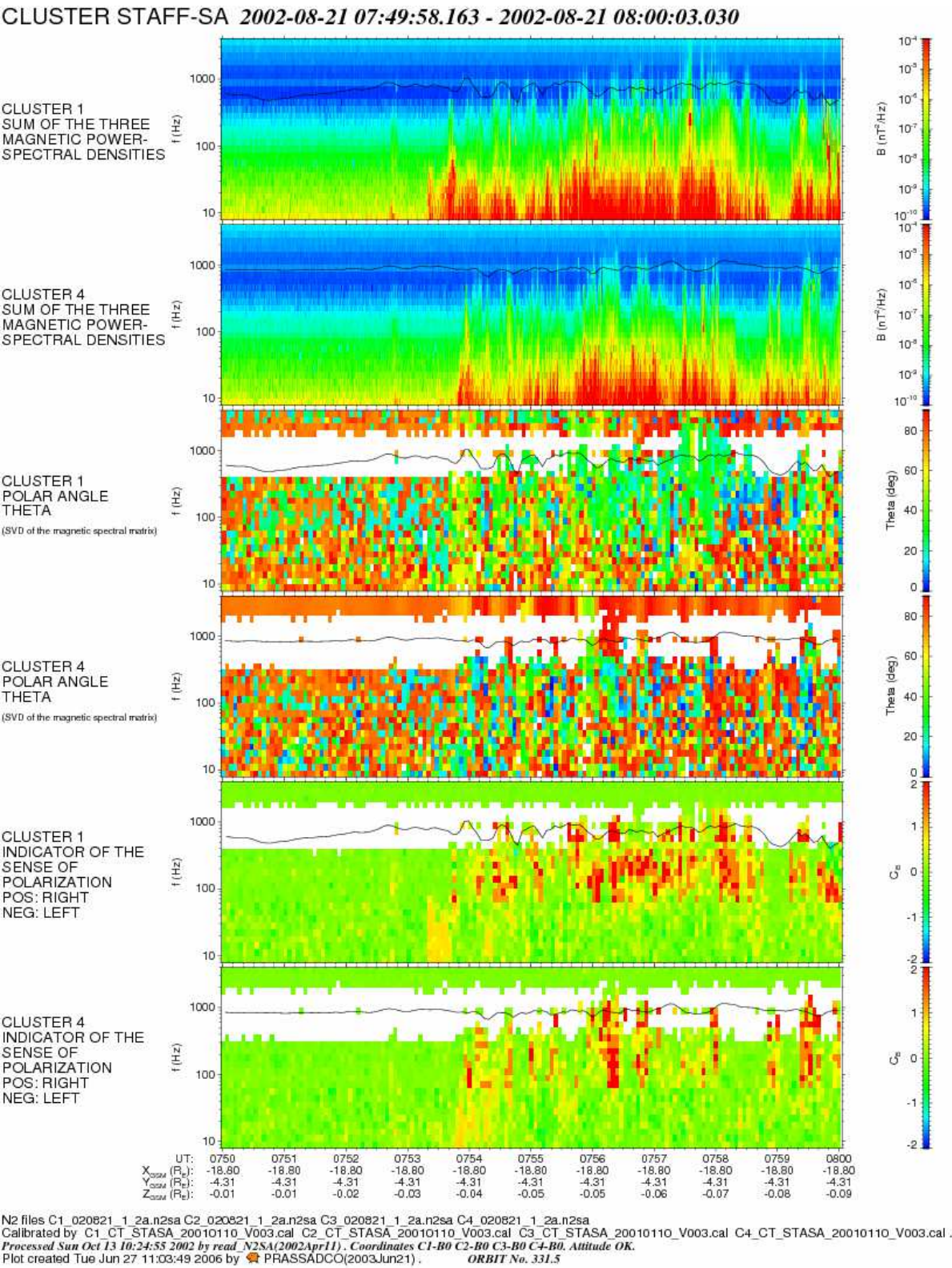


Fig. 3. Wave characteristics observed by C1 and C4 during the period of 07:50UT-08:00UT on August 21, 2002. From top to bottom, Panels 1-2: the dynamic spectra of total field turbulence B-power; Panels 3-4: the polar angles (THETA) of the wave normal direction with respect to ambient magnetic field; Panels 5-6: the sense of polarization. Black curves on the dynamic spectra are the electron cyclotron frequency

The waves in the frequency range 10Hz-4kHz observed by STAFF are analyzed by means of PRASSADCO tool (Propagation Analysis of STAFF-SA Data with Coherency tests)[14]. All three satellites (C1, C3 and C4) observed the whistler waves prior to southward turning of B_z component. The wave characteristics observed by C1, C2 and C3 were nearly identical. However the wave characteristics observed by C4 were different from those of other three satellites. Thus only the wave characteristics observed by C1 and C4 are displayed here. Figure 3 shows the wave characteristics observed by C1 and C4 during the interval of 07:50 UT-08:00 UT on August 21, 2002. The black curves represent the electron cyclotron frequency. The first and second panels show the power-spectral densities of magnetic field. The third and fourth panels represent the polar angles (Θ) of the wave normal direction with respect to the ambient magnetic field. These angles are obtained from the magnetic power spectral with the method of SVD [14]. The fifth and sixth panels represent the sense of polarization, in which the values of $c_B < 0$ indicate a right-hand polarized wave, and the values of $c_B > 0$ indicate a left-hand polarized wave. During the period of 07:50UT-08:00UT, weak (yellow) and enhanced (red) wave activities were observed. The frequency range of waves was between ion cyclotron frequency and electron cyclotron frequency.

total magnetic field (B) and plasma beta. Since the waves prior to the southward turning of B_z component and the waves in the higher frequency range during the magnetic reconnection event were quasi-parallel ($\theta \leq 40$ degree) propagating and right-hand polarized waves, they are typical whistler modes. The waves in the lower frequency range during the magnetic reconnection event were quasi-perpendicular propagating and linearly polarized wave, and they may result from a superposition of several linearly polarized waves [15].

The above analysis shows that the intense whistler activities appeared about 30s prior to the southward turning of magnetic field. The whistler waves were greatly enhanced after the southward turning of magnetic field. In addition, as reconnection proceeded, the wave frequency became higher and higher. When tailward flows reached the maximum, the wave frequency got closer to the electron cyclotron frequency.

3.2 Magnetic reconnection event and whistler wave on September 17, 2003

Figure 4 gives the ion flow velocity components (V_x), magnetic field components (B_x , B_y , B_z), and total magnetic field (B), respectively, which are observed by C1 (line), C3 (dot line) and C4 (broken line) during the interval of 13:00UT - 13:30UT on 17-09-2003. At 13:11:30UT, high-speed tailward ion flow was observed by C1, C3 and C4 at same time (see figure 4, a). It lasted to 13:19:30UT. At 13:11:30UT, C1, C3 and C4 observed southward field component (see figure 5, d). It lasted to 13:15:00UT and then changed northward. The northward magnetic field component lasted to 13:16:50UT, and changed southward again. It lasted to 13:19:30UT. During the period of 13:00:00UT~13:19:30UT, C1, C3 and C4 observed the earthward

During the period of 13:11:30UT~13:19:30UT, C1, C3 and C4 observed almostly dawnward magnetic field (see figure 4, c). Sometime, this field changed duskward. These field characters coincide with Hall magnetic field polarity of collisionless reconnection. Thus this event was a collisionless reconnection event, and it was observed at 13:11:30UT. Figure 5 shows the wave characteristics observed by C1 and C4 during the interval of 13:00-13:30UT on 17-09-2003. The first and second panels from top to bottom show the power-spectral densities of magnetic field observed by C1 and C4, respectively. At 13:10:40UT, the magnetic field power-spectral have enhanced already. The third and fourth panels show the power-spectral densities of electric field observed by C1 and C4, respectively. The electric field power-spectral enhanced earlier than the magnetic field power-spectral. The fifth and sixth

panels represent the polar angles (Theta) of the wave normal direction with respect to the ambient magnetic field observed by C1 and C4, respectively. These electromagnetic waves propagated in the quasi-parallel direction are right-hand polarized (The seventh and eighth panels represent the sense of polarization, in which the values of $c_B > 0$ indicate a right-hand polarized wave, and the values of $c_B < 0$ indicate a left-hand polarized wave. See the red regions). During the period of 13:00-13:30UT, weak (yellow) and enhanced (red) wave activities were observed. The frequency range of waves was between ion cyclotron frequency and electron cyclotron frequency. They may be a whistler mode. The enhanced wave activities were observed earlier than reconnection event 30s. These enhanced waves included the superposition of many linearly polarized waves.

4. Conclusion and discussion

The above observation and analyses discussed two reconnection events and whistler wave activities event. The observation shows the low frequency electromagnetic waves is very strong during the reconnection event period. Before the reconnection event was observed, the strong whistler wave activities are observed in the current sheet. According to above analyses for the character and relationship of reconnection and wave activities, we can get the following conclusions. Hall magnetic field and whistler waves were observed in the plasma sheet, and whistler activities prior to reconnection. These wave activities in plasma sheet maybe play an important role on the generation of reconnection, and they maybe excite the reconnection. After reconnection event took place, with the reconnection on going, the frequency of enhanced wave activities increased and the polarization enhanced. During this kind of events, Cluster located in the Hall magnetic field region of reconnection.

The above studies show that the whistler waves can be excited prior to the reconnection event. The analysis of whistler group velocity and ion flow velocity indicates that this phenomenon could not be caused by the propagation time difference between whistler waves and ion flow velocity. The whistler group velocity can be estimated from the whistler dispersion equation:

$$V_g = \frac{d\omega}{dk} = 2c^2 k / [2\omega + \frac{\omega_{pe}^2 \Omega_e}{(\omega - \Omega_e)^2}] \quad (1)$$

where $\omega_{pe} = (4\pi n_e e^2 / m_e)^{1/2}$ and $\Omega_e = eB_0 / m_e$ are the electron plasma frequency and cyclotron frequency, respectively. If the wave frequency $\omega \ll \Omega_e$, the V_g can become as

$$V_g = \frac{2c}{\omega_{pe}} \sqrt{\Omega_e \omega} = \frac{2c}{f_{pe}} \sqrt{f_e f} \quad (2)$$

At the beginning of reconnection observed by C1 (on 17-09-2003 13:00-13:30UT), $n_e = 0.2/\text{cm}^3$, $f_{pe} = 8.98 \times 10^3 n_e^{1/2} \approx 4.0 \times 10^3 \text{ Hz}$, $f \approx 40 \text{ Hz}$, and $f_e \approx 700 \text{ Hz} < f_{pe}$. Thus the group velocity is about 25000 km/s . The ion flow velocity is about 600 km/s . The group velocity is about 23 times the ion flow velocity. The ion inertial length (d_i) in the reconnection layer in the magnetotail near $\sim 18 R_E$ is about 500 km . Since the length of reconnection layer is proportional to the square root of d_i and about several times the ion inertial length in the magnetotail, the length of reconnection layer in the magnetotail is about $1-2 R_E$ [9][16]-[17]. So the propagation time difference of whistler and ion flow from

the neutral line of reconnection to the Cluster satellite position is about 10s. Thus even the propagation time difference is considered, the observed whistler appears at least 30s earlier than the reconnection event. The whistler waves were excited in the central plasma sheet prior to the reconnection event. Both theoretical and experimental studies also showed that there are whistler waves and kinetic Alfvén waves in the reconnection layers. Recently theoretical studies showed that whistler and Alfvén wave instabilities can even be excited in the current sheet prior to the reconnection [18]-[21].

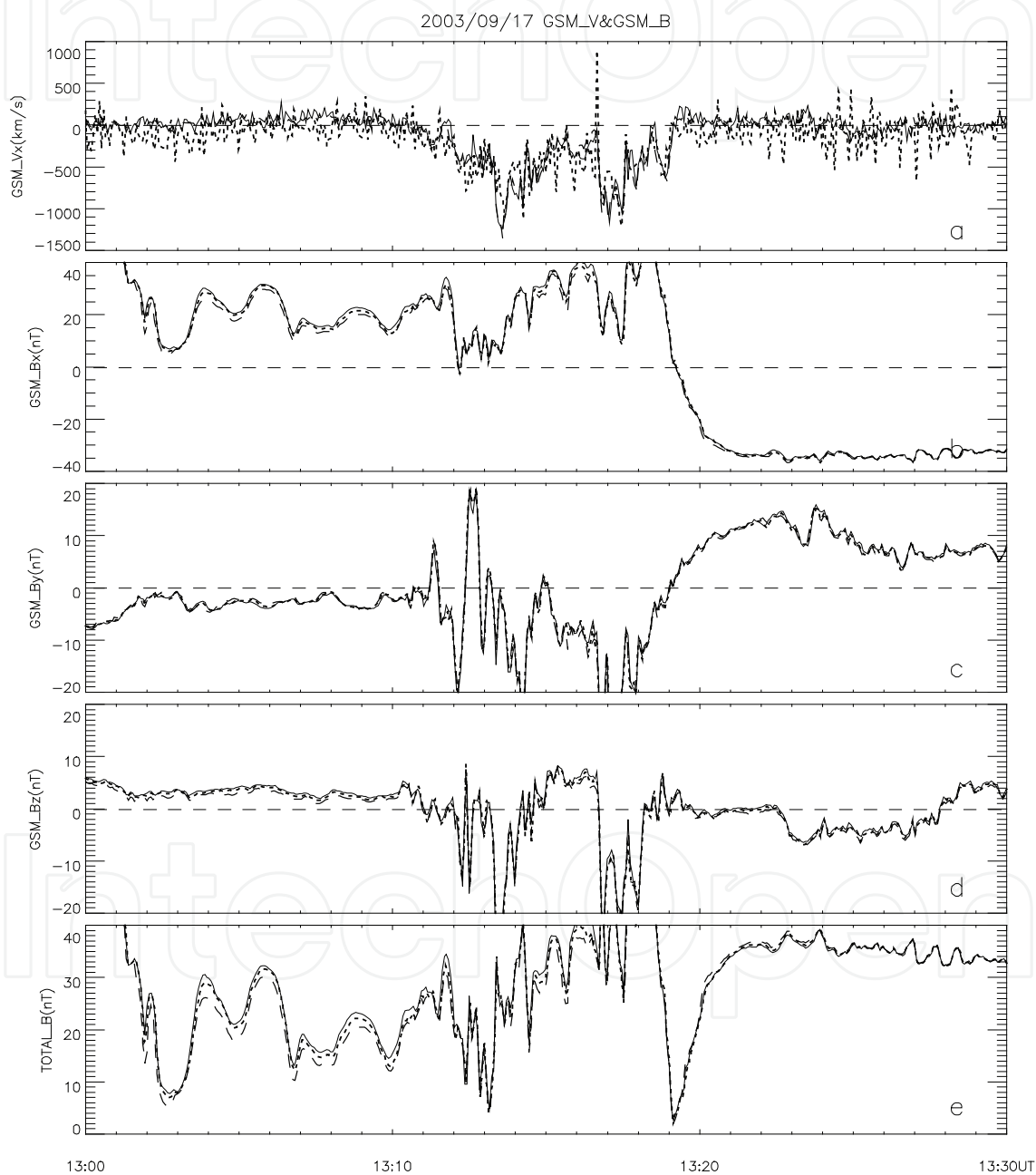


Fig. 4.

Fig 4 shows the flow and magnetic field character on 09-17-2003. a, b, c, d, e give x- component of the ion flow; x-, y-, z- components of magnetic field, and total magnetic field, respectively. The line, dot, broken lines show the data observed by C1, C3 and C4 respectively.

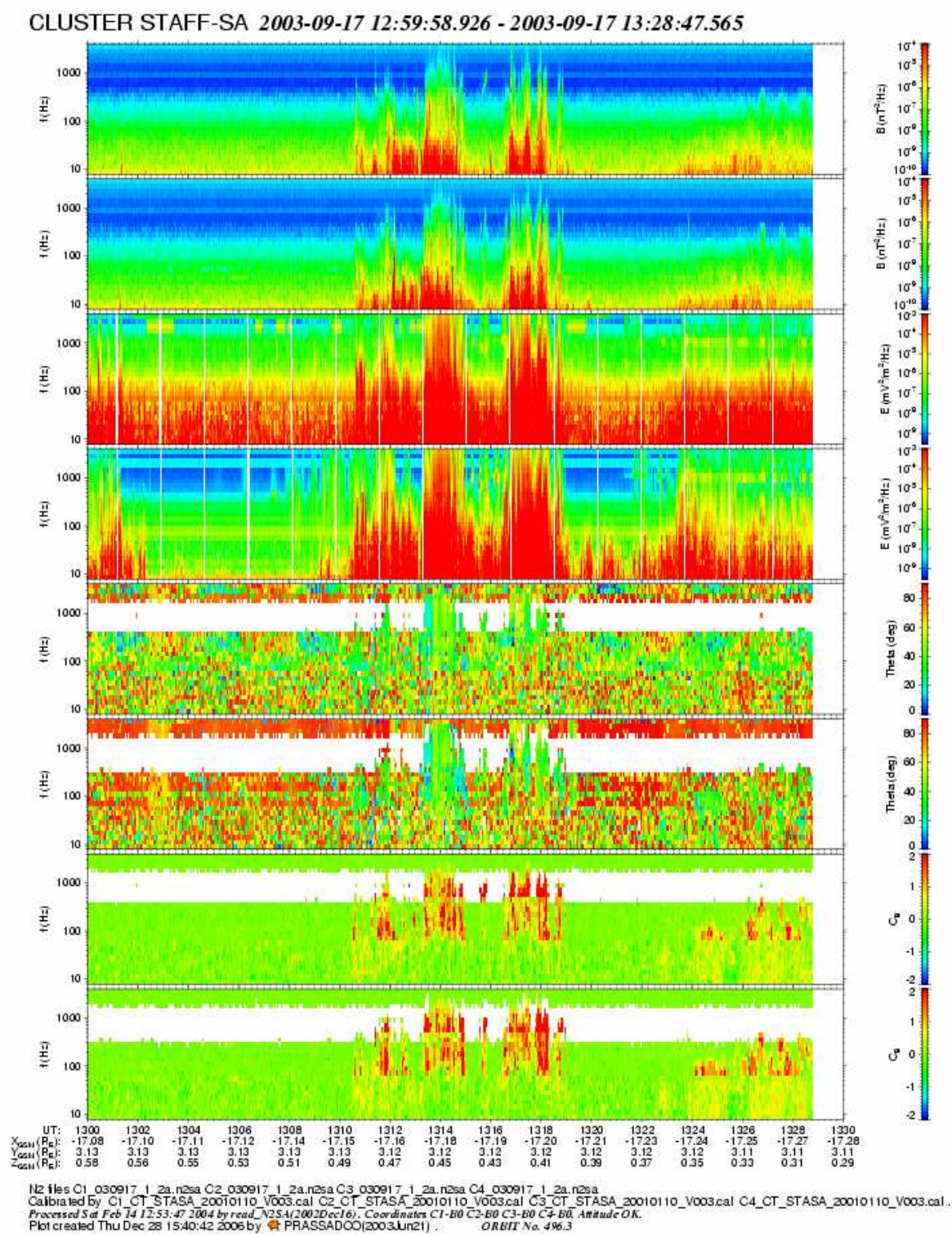


Fig. 5.

Fig. 5 show the characters of waves observed by C1 and C4 on 17-09-2003. From top to bottom, Panels 1-2: the dynamic spectra of total field turbulence B-power; Panels 3-4: the dynamic spectra of total field turbulence E-power; Panels 5-6 the polar angles (THETA) of the wave normal direction with respect to ambient magnetic field; Panels 7-8: the sense of polarization. Black curves on the dynamic spectra are the electron cyclotron frequency. The

spectrograms intensities , polar angles size and sense of polarization indicated by color-coded according to the scale on the right.

Up to present, the problem of triggering of magnetic reconnection in the tail is still not fully understood. The MHD theory of collisionless reconnection requires that anomalous resistivity exist in the reconnection layer. The whistler waves prior to the reconnection may play an important role in the triggering of reconnection. The satellite observations show that besides whistler waves, there are LHWs [22]-[23] and solitary waves [24]-[26][10]-[11] in magnetopause and magnetotail reconnections. Also during dayside magnetopause reconnection, whistler modes could be converted to LHW modes [27]-[29]. However it is still an open question that what role these waves play exactly in the reconnection process and triggering of reconnection.

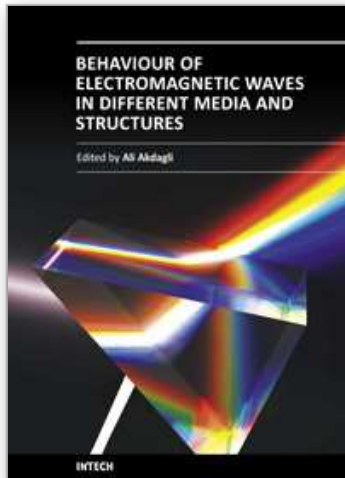
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Behaviour of Electromagnetic Waves in Different Media and Structures

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This comprehensive volume thoroughly covers wave propagation behaviors and computational techniques for electromagnetic waves in different complex media. The chapter authors describe powerful and sophisticated analytic and numerical methods to solve their specific electromagnetic problems for complex media and geometries as well. This book will be of interest to electromagnetics and microwave engineers, physicists and scientists.

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