Observations of kinetic Alfvén waves by THEMIS near a substorm onset

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Low frequency electromagnetic fluctuations in the vicinity of a magnetospheric substorm onset were investigated using simultaneous observations by THEMIS multiple probes in the near-Earth plasma sheet in the magnetotail. The observations indicate that in the vicinity of a substorm onset, kinetic Alfvén waves can be excited in the high- β plasma sheet ($\beta=2\mu_0 nT/B^2$, the ratio of plasma thermal pressure to magnetic pressure) within the near-Earth magnetotail. The kinetic Alfvén wave has a small spatial scale in the high- β plasma. The parallel electric field accompanying kinetic Alfvén waves accelerates the charged particles along the magnetic field. The kinetic Alfvén waves play an important role in the substorm trigger process, and possibly in the formation of a substorm current wedge.

kinetic Alfvén wave, near-Earth plasma sheet, substorm onset

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Low frequency waves (LFWs) usually occur in the vicinity of the onset of a substorm. They are crucial for energy transfer during substorms [1–3], while the near-Earth plasma sheet (NEPS) in the magnetotail is a key region for the magnetospheric substorm onset [4–6]. Two fundamental substorm models, i.e. the near-Earth neutral line (NENL) model [7] and the current disruption (CD) model [8] both indicate that the substorm onset location is in the NEPS. A major property of the onset of a substorm is magnetic dipolarization, which is accompanied by plasma instabilities and waves [3,9]. The LFWs and instabilities play an important role in the substorm expansion phase trigger process [10,11].

During the substorm expansion phase, the bulk flow of ions usually changes its direction and magnitude in the NEPS [5,6,12]. Accompanying the bulk flow of ions, low frequency waves and instabilities occur in the plasma sheet, such as Pi 2 and Pc 5 pulsations.

The magnetohydrodynamic (MHD) Alfvén wave is converted to kinetic Alfvén waves via the ion finite Larmor radius effect [13,14]. Kinetic Alfvén waves are accompanied by a compressive magnetic field and a parallel electric field. Kinetic Alfvén waves have been implicated in a wide variety of geophysical processes from the ionosphere to the solar corona [15,16].

Kinetic Alfvén waves can exist in plasma with high- β ($\beta=2\mu_0 nT/B^2$, the ratio of plasma thermal pressure to magnetic pressure) [15,17–19]. A fast magnetosonic wave and slow-mode wave are both heavily damped in high- β plasma [15]. In the magnetosphere, the magnetopause and plasma sheet both contain high- β plasma ($\beta \sim 1$ –100). Johnson and Cheng [20] proposed that compressional waves could be converted into kinetic Alfvén waves at the magnetopause where there were large gradients in the density, pressure and magnetic field of the plasma. Lee et al. [21] pointed out that kinetic Alfvén waves played an important role in the transport of the plasma at the dayside magnetopause and in electron acceleration along the magnetic field lines. The

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large gradients in the plasma density and magnetic field at the magnetopause boundary effectively coupled large scale Alfvén waves with kinetic Alfvén waves. The plasma sheet plays an important role in the transfer of energy and matter from the solar wind to the ionosphere [22]. The kinetic Alfvén waves are accompanied by the electric field along the background magnetic field and can accelerate and heat charged particles. Consequently it is important to investigate the properties of kinetic Alfvén waves in the plasma sheet. THEMIS multiple probes can provide simultaneous observations of kinetic Alfvén waves at different locations. They thus provide more detailed features of kinetic Alfvén waves in the vicinity of the onset of a substorm.

The main purpose of this article is to use observations from multiple probes of THEMIS (THA, THD and THE) to investigate the features of the LFWs occurring during substorms (with onsets at 0221 UT and 0245 UT on 16 February 2008). In particular, this study focuses on the features of the kinetic Alfvén wave in the vicinity of the onset and during the expansion phase of the substorm.

1 Observations

The THEMIS mission provides good opportunities to investigate magnetospheric substorms [23]. From December 2007 to April 2008, the THEMIS satellites were in their tail science phase. The apogees of the orbits are in the magnetotail. Substorms with onset times at 0221 UT and 0245 UT on 16 February 2008 were chosen to investigate kinetic Alfvén waves during substorms.

1.1 Overview of the event on 16 February 2008

Figure 1 shows the variations in the AL, AU and AE indices during the period from 0000 UT to 0600 UT on 16 February

2008. There is a clear weak increase in the AE index at 0221 UT identified by the 1st vertical dashed line and an obvious increase in the AE index at 0245 UT identified by the 2nd vertical dashed line in Figure 1. The AL index decreased at both 0221 UT and 0245 UT. On the basis of the AE index variation, it can be inferred that a substorm onset occurred at 0221 UT and another substorm onset or a substorm enhancement during the substorm expansion phase took place at 0245 UT.

During the event, the multiple probes of THEMIS were in the NEPS. The orbits of THA, THD and THE in GSM coordinates are displayed in Figure 2. According to the traces of THEMIS probes, it was found that THE was the nearest to the Earth, indicated by the blue line. THA and THD were far from the Earth, but were in the NEPS.

Figure 3(a)–(c) present the ion density, ion plasma β , Alfvén speed (black line) and proton thermal speed (red line), proton Larmor radius (black line) and ion inertial length (red line), proton cyclotron frequency, the electric and magnetic fields, and the magnetic elevation angles recorded by THE, THD and THA probes. In these three figures, two vertical dashed lines mark the time of onset of the substorm. In the vicinity of 0221 UT, the ion density was 0.7 cm^{-3} at the THE location, 0.5 cm^{-3} at the THD location and 0.35 cm^{-3} at the THA location. According to detection results of these three probes, ion plasma β , was usually larger than 1 before 0245 UT as shown in the second panel. In the third panel, the local Alfvén speed (black line) approached the ion thermal speed (red line) during the expansion of the plasma sheet after the substorm onset time. The proton gyroradius was about 7000 km and its inertial length was about 300 km in the near-Earth plasma sheet. The proton cyclotron frequency was near 0.3 Hz. Shortly after the substorm onset time of 0221 UT, the dominant component of the magnetic field was the B_z component. The magnetic elevation angle θ , increased sharply at the onset time, from

Figure 1 Variations in AU, AL and AE indices from 0000 UT to 0600 UT on 16 February 2008. There are sharp increases in the AE index at 0221 UT and 0245 UT, marked by the vertical dashed lines.

Figure 2 Orbits of THA, THD and THE probes are shown from 0130 UT to 0330 UT.

about 30° to 75° at the THE location and from $\sim 20^\circ$ to 75° at the THD location. However, the angle increased weakly at the THA location. Large gradients of ion density and the electromagnetic field in the plasma sheet were observed by all three THEMIS probes, the THE, THD and THA.

The B_x components were positive at the THE and THD locations, but at the THA position the B_x was negative. This means that the THE and THD were located in the northern magnetotail, while THA was located in the southern magnetotail. Combining the orbits of these three THEMIS probes and the magnetic field data, we deduce that the neutral sheet (i.e. the current sheet) was located between the THD and THA positions, and it was tilted toward the southern hemisphere from the magnetic equatorial plane. Comparing the magnetic field elevation angle observed by the THE, THD and THA probes at the substorm onset location, we infer that the THD was the nearest probe to the substorm onset location and THA was the furthest from it.

The plasma density and electric and magnetic fields were obviously disturbed in the vicinity of the onset. We investigate these disturbances in detail in the following section.

1.2 Kinetic Alfvén wave analysis

The distinct property of kinetic Alfvén waves is that the ratio of their electric and magnetic fields almost equals the local Alfvén speed. Kinetic Alfvén waves are accompanied by a parallel electric field that accelerates the charged particles along the magnetic field. Previous studies [15,17] have shown that the gradients of the plasma density and magnetic

field are two major factors that excite kinetic Alfvén waves in high- β plasma. The compression magnetic field is another feature of kinetic Alfvén waves.

Figure 4(a)–(c) show, from top to bottom, the fluctuations of ion density, the plasma thermal pressure (black line) and magnetic pressure (red line), the compressive component of the magnetic field, the parallel electric field, the Alfvén speed and the ratio of the electric field E_y component to the magnetic field B_x component, and the Poynting flux observed by THD, THE and THA, respectively. The panel formats in the three figures are the same.

Figure 4(a) shows the low-frequency fluctuations of the ion density, pressure, electromagnetic field and Poynting flux, which were observed by the THD probe. There were obviously intense ion density fluctuations near the substorm onset time (e.g. 0221 UT), indicated by the first vertical dashed line in the first panel. The phase of the ion thermal pressure disturbance was the reverse of the phase of the disturbance of the magnetic pressure. The parallel magnetic field fluctuations became marked at and after the onset time of the substorm. The parallel electric field increased markedly near onset and lasted for about 3 min. After the substorm onset time, the local Alfvén speed and the ratio of $\delta E_y / \delta B_x$ were almost equal. The Poynting flux became very strong and its direction changed. These features of the low-frequency fluctuations are consistent with the properties of kinetic Alfvén waves. At about 0245 UT, the amplitudes of the parallel magnetic field, parallel electric field, and Poynting flux observed by the THD became very small.

Fluctuations detected by the THE, which are displayed in

Figure 3 Plasma, magnetic field and electric field were observed by THE, THD and THA probes. From top to bottom, the parameters shown in each panel are the ion density N_{ion} , ion plasma β , local Alfvén speed (black line) V_A and ion thermal velocity (red line) v_{th} , proton gyroradius ρ_{cp} and proton inertial length λ_p , proton cyclotron frequency f_{cp} , electric field, magnetic field and the magnetic elevation angle θ .

Figure 4 Fluctuations of ion density, pressure, electromagnetic field and Alfvénic Poynting flux detected by the THD, THE and THA probes. From top to bottom, the parameters shown in each panel are the ion density fluctuation δn , fluctuations of thermal pressure δp_m and magnetic field pressure δp_m (black line) and magnetic field compressional component disturbance $\delta B_{\parallel}$, electric field along the magnetic field component $E_{\parallel}$, Alfvén speed V_A (black line), the ratio of $\delta E_y / \delta B_x$, the ratio of $\delta E_z / \delta B_x$, x and y components of Poynting flux S_x and S_y , Poynting flux z component S_z (black line), and the parallel component $S_{\parallel}$ (red line).

Figure 4(b), were similar to those observed by the THD at about 0221 UT. In general, the amplitudes of ion density and pressure fluctuations observed by the THE were smaller than those observed by the THD. At about 0245 UT, strong disturbances in the magnetic and electric fields were also detected by the THE. The Poynting flux was also intense at this time.

Since the THA was located in the near-Earth magnetotail of the southern hemisphere, and far from the substorm onset location, the amplitudes of the plasma density and the electromagnetic field disturbances were very small at substorm onset time, 0221 UT. However, during the later substorm expansion phase, the fluctuations became intense, as shown in Figure 4(c).

2 Discussion and summary

The above observations of low-frequency fluctuations indicate that in the magnetotail plasma sheet containing high- β plasma, kinetic Alfvén waves are excited near the substorm onset location. Because the kinetic Alfvén wave is accompanied by a parallel electric field, the wave plays an important role in triggering a substorm.

The magnetopause is full of high- β plasma. Lee et al. [21] pointed out that the kinetic Alfvén wave had an associated parallel electric field which was broken down in the “frozen-in” condition and decoupled the plasma from field lines at the magnetopause. Charged particles then entered the magnetosphere throughout the magnetopause.

From the orbits of the THD, THE and THA probes, as shown in Figure 2, we deduced that these three probes were located at a small distance from each other. Comparing the simultaneous fluctuations detected by the THD, THE and THA in the NEPS at different locations, as shown in Figure 4(a)–(c), we deduced that the kinetic Alfvén wave was excited at a local region at the substorm onset time. Hasegawa and Mima [24] proposed that the kinetic Alfvén wave had a scale length of MHD waves in the direction parallel to the magnetic field and a scale length of the ion gyroradius in the perpendicular direction. Our observational result is consistent with the theoretical conclusions of Hasegawa and Mima [24].

Since the THD was the probe nearest the substorm onset location at 0221 UT, the amplitudes of plasma density and electromagnetic field fluctuations observed by THD were much larger than those observed by the THE and THA. We infer that the kinetic Alfvén wave can be easily excited at the substorm onset location since the gradients of the plasma density and magnetic field are both large near the substorm onset location in the NEPS. This can be seen in Figures 3 and 4. The fluctuations of the plasma density, the magnetic field, the plasma thermal pressure and magnetic pressure lasted for longer than the fluctuations of the electric field and Poynting flux.

Around 0221 UT and 0245 UT, THD and THE observed strong fluctuations of the compression magnetic field, parallel electric field and Poynting flux, which were associated with kinetic Alfvén waves occurring within an interval of 3–5 min. These observations are consistent with the results obtained by Wygant et al. [16].

In summary, kinetic Alfvén waves can be excited in a high- β plasma sheet at the substorm onset time in the near-Earth magnetotail. The kinetic Alfvén wave has small spatial scale in the high- β plasma. The parallel electric field accompanied by kinetic Alfvén waves accelerates charged particles along the magnetic field. The kinetic Alfvén waves play an important role in the substorm trigger process, and possibly in the formation of the substorm current wedge.

A theoretical study on the kinetic Alfvén wave excitation mechanism in the high beta plasma sheet will be considered in our future work.

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