AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Space Physics

RESEARCH ARTICLE

10.1002/2014JA020753

Key Points:

- Plasma sheet Pi2 frequency band waves are mostly associated with BBFs
- The second main driver of plasma sheet Pi2 waves is substorm current system
- Plasma instabilities and solar wind changes may occasionally drive Pi2 waves

Correspondence to:
Y. S. Ge,
ysge@mail.iggcas.ac.cn

Citation:
Wang, G. Q., Y. S. Ge, T. L. Zhang, R. Nakamura, M. Volwerk, W. Baumjohann, A. M. Du, and Q. M. Lu (2015), A statistical analysis of Pi2-band waves in the plasma sheet and their relation to magnetospheric drivers, *J. Geophys. Res. Space Physics*, *120*, 6167–6175, doi:10.1002/2014JA020753.

Received 18 OCT 2014
Accepted 9 MAR 2015
Accepted article online 13 MAR 2015
Published online 4 AUG 2015

A statistical analysis of Pi2-band waves in the plasma sheet and their relation to magnetospheric drivers

G. Q. Wang[1], Y. S. Ge[2], T. L. Zhang[1,3], R. Nakamura[3], M. Volwerk[3], W. Baumjohann[3], A. M. Du[2], and Q. M. Lu[1]

[1]CAS Key Laboratory of Geospace Environment, Department of Geophysics and Planetary Science, University of Science and Technology of China, Hefei, China, [2]Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China, [3]Space Research Institute, Austrian Academy of Sciences, Graz, Austria

Abstract We use the Cluster data from 2001 to 2009 to investigate the occurrence of Pi2-band waves in the plasma sheet. To study the generation mechanisms of these waves, we examine the association between Pi2-band waves and dynamic processes in the plasma sheet (fast flows and substorm activity) and the direction of the solar wind velocity. For a total of 80 large-amplitude Pi2-band waves in the plasma sheet, we find that Cluster records fast flows during 62 events, 11 waves without fast flows occur during substorm time, 3 events occur when the solar wind velocity significantly changes its direction, and 4 events are not associated with any of the above activities. Most of the observed Pi2-band waves are predominantly compressional, while 2 events are transverse. Based on this statistical study, we suggest that fast flows maybe the main driver of Pi2-band waves/oscillations in the plasma sheet, especially considering that most of these waves are compressional. The relatively small number of other events indicates that other mechanisms also play a role in creating Pi2-band waves/oscillations in the plasma sheet but are relatively rare. In all wave events of this study, the plasma pressure and magnetic pressure vary in antiphase, suggesting that these waves have the slow-mode feature.

1. Introduction

Pi2 pulsations (periods of 40 to 150 s) on the ground have been widely investigated [e.g., *Baumjohann and Glassmeier*, 1984; *Olson*, 1999; *Keiling and Takahashi*, 2011]. They are often associated with some dynamic magnetospheric processes, such as substorms [e.g., *Olson*, 1999; *McPherron et al.*, 2008]. Ground Pi2 pulsations are an important transient response of the coupling between the magnetosphere and the ionosphere [*Keiling and Takahashi*, 2011]. Our understanding of the generation mechanism of Pi2 pulsations has been greatly improved with more conjunctive observations on the ground and in space. It has been found that ground Pi2 waves can be driven by dynamic processes in the plasma sheet, such as bursty bulk flows (BBFs) [*Angelopoulos et al.*, 1992, 1994; *Kepko and Kivelson*, 1999; *Kepko et al.*, 2001; *Cao et al.*, 2008, 2010] and ballooning instability [*Keiling*, 2012].

Recently, some Pi2 waves in the magnetotail were found to be related to the Pi2 waves observed on the ground [*Volwerk et al.*, 2008]. Large-amplitude waves in the Pi2 frequency range in the plasma sheet are often found accompanied with fast flows [*Bauer et al.*, 1995; *Sigsbee et al.*, 2001, 2002]. Using the Active Magnetospheric Particle Tracer Explorers/Ion Release Module satellite data, *Bauer et al.* [1995] found three strong Pi2-band waves (Pi2s) in the plasma sheet at radial distances between 12 and 15 R_E during substorms, which were accompanied with fast flows. A common feature of these waves is the antiphase between plasma pressure and the magnetic pressure.

While studying the compressional waves in the current sheet by using Cluster data, *Volwerk et al.* [2003] found that the total power of waves in the Pi2-band frequency range increased with the plasma flow velocity and saturated at the velocity of about 400 km/s. Using Time History of Events and Macroscale Interactions during Substorms (THEMIS) data, *Du et al.* [2011] studied a strong wave with a period of ~100 s in the plasma sheet at $X \sim -11\ R_E$. However, they found that this wave was not accompanied with any fast flow and had both slow and Alfvén mode features. Previous studies have shown that the ballooning instability can drive ballooning mode waves within the Pi2-band frequency range in the near-Earth plasma sheet (NEPS) before substorm onset [*Roux et al.*, 1991; *Pu et al.*, 1997; *Saito et al.*, 2008]. *Panov et al.* [2012] studied a strong wave within the Pi2-band frequency range in the NEPS. They found that this wave exhibited signatures of kinetic ballooning/interchange instability fingers that developed in a bent current sheet. The observed current sheet bending was found to be driven by the change of the solar wind velocity direction. Thus, without fast flows, Pi2s may also be driven by instabilities in the plasma sheet, such as the kinetic ballooning/interchange instability in a bent current sheet due to the variations of solar wind velocity direction. *Sergeev et al.* [2008] have shown that the change of the solar wind velocity, even small variations, could cause significant changes in the near and middle plasma sheet.

In this paper, we use Cluster and OMNI data to give an overview of the internal and external conditions of large-amplitude Pi2s in the plasma sheet. We first check the relationship between Pi2s and fast flows. Then, we check how many Pi2s accompanied with no fast flows are observed during substroms. And finally, we check how many waves in the rest are observed while the solar wind velocity direction has a significant change in the noon meridian GSM plane.

2. Observation

In this study, we use the magnetic field data with 4 s resolution recorded by the Fluxgate Magnetometer (FGM) [*Balogh et al.*, 2001] and the 4 s ion data recorded by the Cluster Ion Spectrometer (CIS) [*Rème et al.*, 2001] from Cluster 1 (C1) during their tail seasons from 2001 to 2009 [e.g., *Fu et al.*, 2012a, 2012b]. The data are selected when C1 is located in the plasma sheet beyond a geocentric solar magnetospheric (GSM; this coordinate system is used throughout the paper without mentioned) distance of $X_{GSM} = -10\ R_E$ and inside of $|Y_{GSM}| < 12\ R_E$. The solar wind and interplanetary magnetic field (IMF) data from the OMNI database used in this study are 1 min resolution and have been shifted to the bow shock nose.

In order to find the Pi2s in the central plasma sheet, we define a neutral sheet crossing event as a 1 h interval, centered around a reversal of the B_x component of magnetic field. The beginning and ending time of these intervals mark the neutral sheet crossing events. Two adjacent B_x reversals within half an hour are considered to be the same neutral sheet crossing event. This leads to a total of 650 neutral sheet crossing events.

For all these neutral sheet crossing events in the studied data set, we search for Pi2s with the following criteria: (i) The wave period is within the Pi2 period range (40–150 s). (ii) The waves are located in the plasma sheet where $B_{xy} = (B_x^2 + B_y^2)^{1/2} < 15$ nT [*Baumjohann et al.*, 1989]. (iii) The maximum amplitude (peak to trough) of the waves is greater than 5 nT. (iv) There are at least three full wave cycles in order to accurately determine the wave properties. This leads to a total of 92 events, where for 80 events, the CIS ion data and solar wind/IMF data are available.

2.1. Event 1: 27 September 2006

On 27 September 2006, we identify a Pi2 wave starting at ~15:15 UT while C1 is located near −14.5, 1.9, and 0.7 R_E. As shown in Figure 1, the three components of the magnetic field in GSM and mean field-aligned (MFA) coordinate system, the dynamic wavelet power spectrum of the B_x component (in GSM), the ion density, the ion velocity, the ion thermal pressure and magnetic pressure and their band-pass filter, the *AL* index, the V_x and V_z components of the solar wind velocity (in GSM), and the angle of the solar wind velocity direction in the *x-z* plane (in GSM) are plotted from top to bottom. Figure 1a shows that the B_y and B_z components of the magnetic field are near zero and B_x reverses its sign during this interval, which indicate that C1 is located near the neutral sheet. A clear wave signal is seen in the B_x component with a maximum amplitude of ~20 nT between 15:15 and 15:23 UT, while the B_y and B_z components have only small fluctuations.

In order to get the feature of the wave on compressional, we have transformed the magnetic field data from GSM to MFA coordinate system. The MFA system is defined with its *z* axis parallel to the low-pass-filtered magnetic field with a shortest period of 300 s, its *y* axis parallel to the vector product of the mean magnetic field vector and *x* axis in GSM, and its *x* axis completes the right-handed coordinated system. We calculate the mean wave amplitude (MWA) in each component of the magnetic field in MFA system as the square root of the sum of the power spectrum density through fast Fourier transform over the Pi2-band frequency range during the Pi2-band wave events. If the ratio (marked as Rc) of the compressional MWA to the transverse MWA (square root of the sum of the two transverse MWA value's square) is larger (less) than 1.5 (0.67), we regard the compressional (transverse) component magnetic field as the dominant component. The compressional and transverse components are thought to be comparable while the Rc is between 0.67 and 1.5. The Rc of this wave between two vertical lines is ~0.86. So the compressional and transverse components of this wave are comparable by using above criteria.

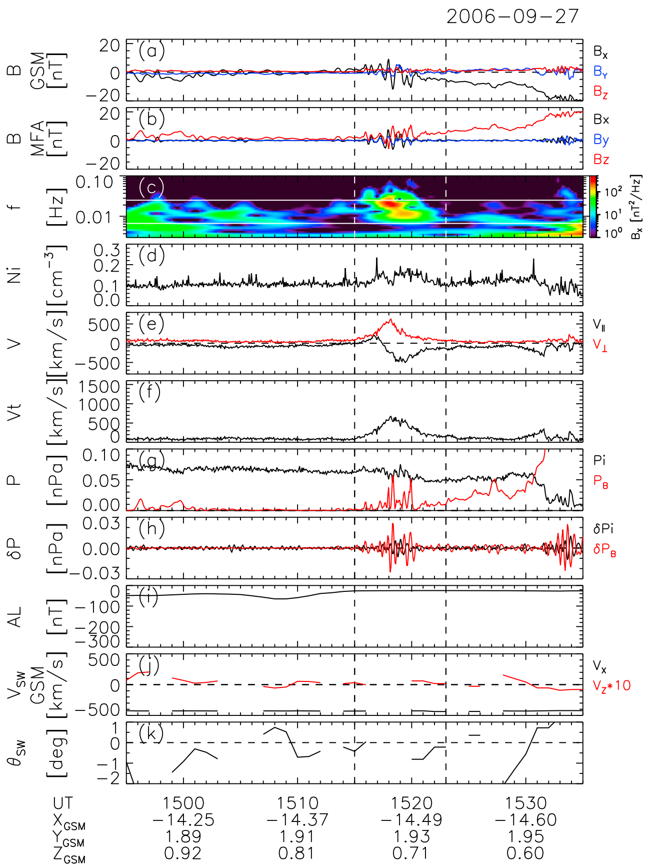

Figure 1. Data from Cluster 1 (C1) and OMNI on 20 August 2003 between 14:55 UT and 15:35 UT. (a) The three components of the magnetic field in GSM and (b) in mean field-aligned coordinate system, (c) the spectrogram of B_x component, (d) the ion density, (e) the ion bulk velocity which has been converted into components that are parallel and perpendicular to the background magnetic field, (f) the amplitude of the ion bulk velocity, (g) the ion thermal and magnetic pressure and (h) their band-pass-filtered variations within periods of 20 and 50 s, (i) the *AL* index, (j) the V_x and V_z components of the solar wind velocity in GSM, and (k) the angle of the solar wind velocity direction changing in the noon meridian GSM plane. Two white horizontal lines in spectrogram indicate the time period 40 and 150 s. The vertical lines correspond to the onset and the end of Pi2-band wave.

In order to analyze the time and frequency properties of the waves, we perform the wavelet transformation on the magnetic field component B_x. In Figure 1c, we find that the dominant frequency of this wave is ~20 mHz. The ion density shown in the Figure 1d is near 0.1 cm^{-3} and increases up to ~0.2 cm^{-3} during the Pi2-band wave.

Fast flows can drive Pi2s in the plasma sheet. In order to find that how many Pi2s are accompanied with fast flows, we defined a fast flow event as the amplitude of the ion perpendicular component velocity that exceeds a threshold of 150 km/s during the Pi2s' time interval. During the Pi2-band wave, the perpendicular component of ion velocity in Figure 1e becomes larger while the amplitude of the Pi2-band wave becomes larger. It indicates a strong link between the fast flow and the fluctuations of the magnetic field. The maximum value of this fast flow is ~670 km/s. The BBF selection criteria of *Angelopoulos et al.* [1994] is as follows: BBFs are segments of continuous ion flow magnitude V_i above 100 km/s in the plasma sheet, during which V_i exceeds 400 km/s at least for one sample period in the inner plasma sheet ($\beta > 0.5$); samples of $V_i > 400$ km/s that are less than 10 min apart are considered to belong to the same BBF, even if the velocity drops below 100 km/s between these samples. The fast flow during the time interval of this wave can be regarded as a BBF by using the criteria of *Angelopoulos et al.* [1994].

Figure 1g shows that the ion thermal pressure and the magnetic pressure vary with a distinct period of about 30 s. The dominant frequency of the ion thermal pressure and the magnetic pressure is not in Pi2-band frequency range, which may be affected by the compressional component of the magnetic field. Band-pass filtering with a period band of 20 to 50 s is performed on the ion thermal pressure and the magnetic pressure. Figure 1h clearly shows that the ion thermal pressure and the magnetic pressure vary in antiphase.

In order to investigate whether these Pi2s are associated with substorms, we use an *AL* index criterion to determine the presence of substorms [*Hsu and McPherron*, 2002, 2007]. A substorm onset timing procedure has been proposed by *Hsu and McPherron* [2002]. The procedure scans the *AL* index for any possible enhancement of the westward electrojet, which is related with the auroral expansion. The criteria used for determining the substorm onset from *AL* index by *Hsu and McPherron* [2007] are as follows: (1) A negative bay and a sudden change in slope in the *AL* index are necessary for selecting an event. (A negative bay means a negative perturbation in the *AL* index, and a sudden change means an enhancement in the rate of decrease of *AL*.) The duration of the negative bay must be longer than 20 min. (2) For a negative bay event to be selected, the minimum *AL* must be lower than 100 nT. (3) If the time duration of a disturbed interval is longer than 3 h,

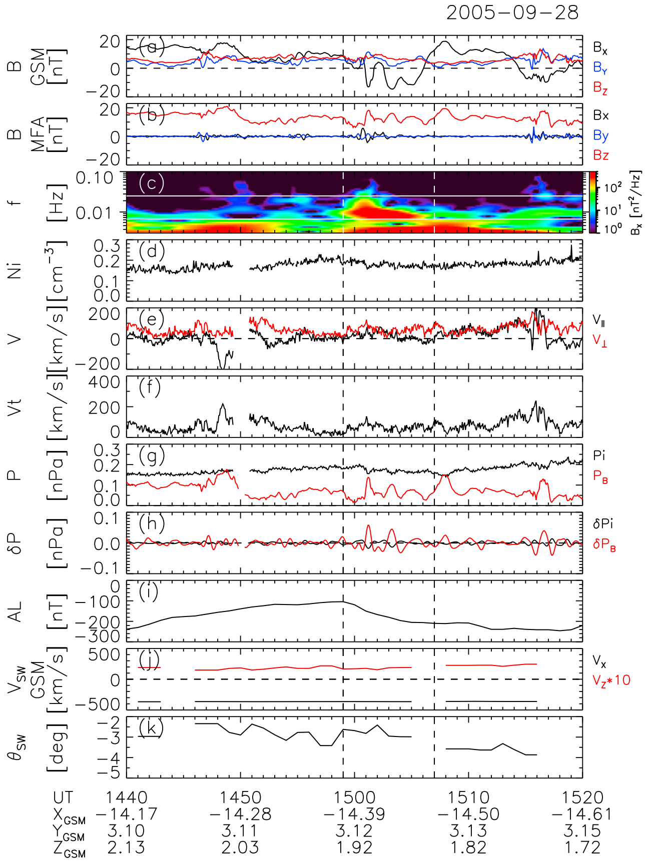

Figure 2. Data from C1 and OMNI on 28 September 2005 between 14:40 UT and 15:20 UT. The format is the same as in Figure 1 except that the thermal pressure and magnetic pressure are band-pass filtered with a period of 40 and 150 s.

we select more than one onset if there is more than one sharp break in slope followed by a second minimum in *AL*. By scanning the *AL* index data 3 h prior or later the Pi2s' onset, we visually determine whether a Pi2-band wave is observed during a substorm. Figure 1i shows that low absolute *AL* value indicates that the geomagnetic activity is quite weak while the wave is observed.

Panov et al. [2012] found a Pi2-band wave in the plasma sheet observed during the time interval that has no fast flows or substorms. They found that the solar wind velocity changes about 2° in 10 min in the noon meridian GSM plane, which causes the plasma sheet changes ~8°. The bending plasma sheet causes the ballooning/interchange instabilities, which drive the Pi2-band wave. So we want to check whether the Pi2 is linked with the dominant change in the solar wind velocity direction (~2° in 10 min in the noon meridian GSM plane). Statistical study [*Mailyan et al.*, 2008] found that the delay time of the solar wind from probe to the bow shock nose has some error and error of most cases is within 10 min. Therefore, we only consider the solar wind velocity variation between 10 min prior and after the Pi2s onset as the solar wind conditions. We use a 10 min window sliding during this 20 min interval to calculate the change of the solar wind direction in the noon meridian GSM plane. Then the maximum change angle during this 10 min window is regarded as the change of the solar wind direction in the noon meridian corresponding to the Pi2s. The solar wind speed is near 500 km/s, and V_z is near 0 with a change no more than 20 km/s. The solar wind velocity direction changes no more than 1.5° in the GSM *x-z* plane in 10 min window.

2.2. Event 2: 28 September 2005

The second example of a wave event, measured on 28 September 2005, is shown in Figure 2. A Pi2 wave is mainly seen in the B_x component with largest amplitude ~20 nT from 14:59 to 15:07 UT while C1 is located near −14.4, 3.1, and 1.9 R_E. From Figure 2b, we can find that the amplitude of the transverse component of the magnetic field in Pi2-band is larger than or comparable with that of the compressional component between 15:00 UT and 15:02 UT, and then the amplitude of the compressional component is larger than that of the transversal compressional. The value of the Rc is ~1.1, which indicates that the compressional and transverse components of the magnetic field of this wave are comparable. Identified from the B_x spectrogram (Figure 2c), the dominant frequency of the Pi2 waves is around 10 mHz. The parallel and perpendicular components of the ion velocity are less than ~100 km/s during this interval. One spacecraft may miss some fast flows [*Cao et al.*, 2006], so we check the other three Cluster spacecraft and find that no fast flow is observed during this interval. The ion density is near or below 0.2 cm^{-3} with small fluctuations. As shown in the Figure 2g, the ion thermal pressure is larger than the magnetic pressure, while the amplitude of the ion thermal pressure variations is smaller than that of the magnetic pressure. The variations of the ion thermal pressure and the magnetic pressure in the Pi2-band frequency are shown in Figure 2h, and they also appear

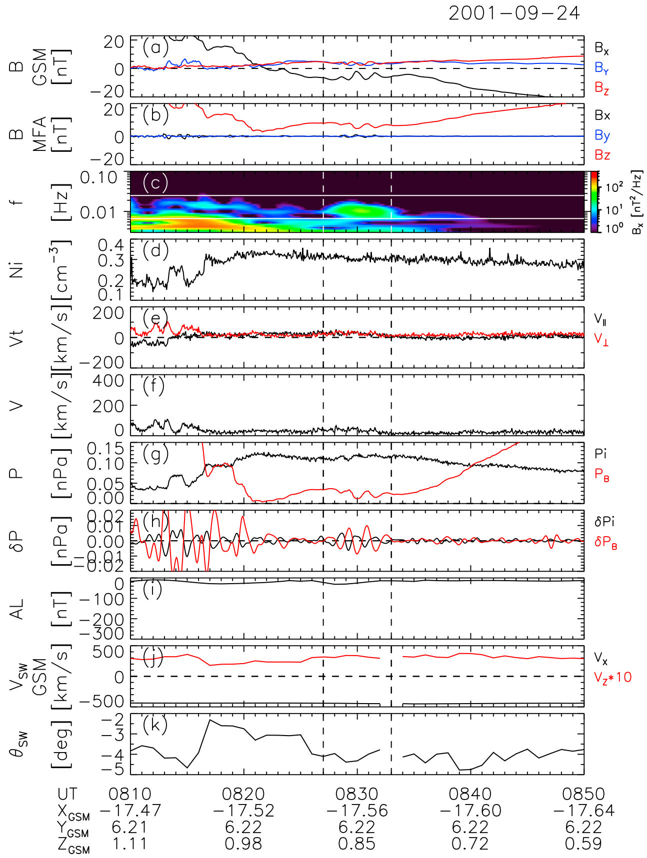

Figure 3. Data from C1 and OMNI on 24 September 2001 between 08:10 UT and 08:50 UT. The format is the same as in Figure 2.

in antiphase during the wave interval. In order to investigate whether this Pi2 is associated with substorm, we use an *AL* index criterion to determine the presence of substorms [*Hsu and McPherron*, 2007]. At 14:59 UT, the *AL* index suddenly decreases and reaches its minimum value of −200 nT at 15:19 UT, indicating that the Pi2 wave is observed during an *AL* substorm expansion phase. The solar wind velocity direction changes no more than 1.2° in the GSM *x-z* plane in 10 min window.

2.3. Event 3: 24 September 2001

Figure 3 shows the third example of a Pi2 wave event, which occurs between 08:27 UT and 08:33 UT on 24 September 2001 when C1 is located near −17.5, 6.2, and 0.9 R_E. From Figure 3a, we can see that the power of the Pi2 wave is mainly in the B_x component, while the fluctuations in the other components are very small. The value of the Rc is ~1.65, which indicates that the compressional component of the magnetic field of this wave is dominant. The dominant frequency of the wave is ~10 MHz, which can be identified from the B_x spectrogram. The ion density is about 0.3 cm^{-3}, and the ion velocity is less than 100 km/s. Other Cluster spacecraft also observe no fast flow during this interval. The fluctuations of the ion thermal pressure and the magnetic pressure vary in antiphase. *AL* index shows that there is no clear substorm activity during this time. From Figure 3k, we find that the solar wind velocity direction changes ~2° in the GSM *x-z* plane in 10 min window.

2.4. Event 4: 22 September 2001

Figure 4 shows a Pi2 wave occurring between 04:59 UT and 05:12 UT on 22 September 2001 when C1 is located near −18.3, 5.5, and −1.5 R_E. The wave power in the B_x component is also predominant with maximum amplitude of about 10 nT, and the dominant frequency of the wave is ~10 mHz. The amplitude of the compressional component of the magnetic field is clearly larger than the transverse component (see in Figure 4b). However, there is also strong transverse component of the magnetic field between 05:05 UT and 05:09 UT. The Rc is ~1.3, which indicates that the compressional and transverse components of the magnetic field are comparable. The ion density gradually increases from ~0.3 to ~0.4 cm^{-3} with small fluctuations. No fast flows are observed by the C1 and other Cluster spacecraft. From Figure 4g, the fluctuations of the magnetic pressure are clearly greater than those of the ion thermal pressure. They vary in antiphase in the Pi2-band frequency range during the wave interval. The V_x and V_z components of the solar wind velocity are almost constant (V_y is also almost constant but not shown here), and the direction of the velocity has no significant change during this time interval.

3. Statistical Study of the Pi2 Events

Figure 5 displays the spatial distribution of all 80 Pi2s in the Earth's magnetotail plasma sheet. The distribution in *x-y* plane is in accordance with the characteristic of the C1 spacecraft orbit. The distribution in *y-z* plane, which

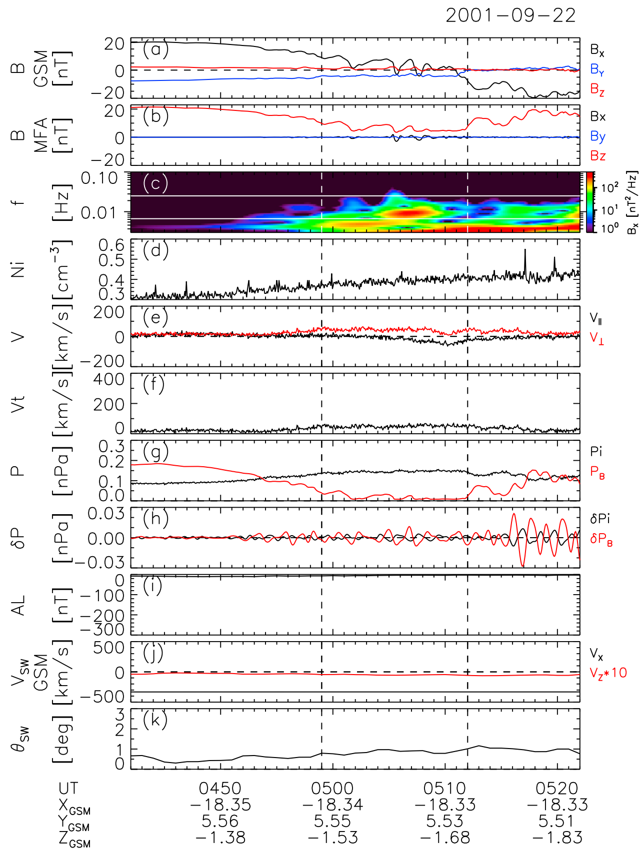

Figure 4. Data from C1 and OMNI on 22 September 2001 between 04:42 UT and 05:22 UT. The format is the same as in Figure 2.

represents the location of the plasma sheet, shows the effect of the magnetic dipole tilt. We find that 50 out of 80 Pi2s are in the premidnight sector, which indicates that the premidnight sector is more active than the postmidnight sector and agrees with the findings of *Volwerk et al.* [2003] but also *Nagai and Machida* [1998]. The mean duration of 80 Pi2s, which is determined by visual inspection (scan all three components of the magnetic field and their wavelet spectrogram), is about 15 min (the minimum duration is ~5 min, and the maximum duration is ~42 min).

Table 1 shows the classification of the magnetospheric drivers and some features of the Pi2s. We find that 62 out of 80 Pi2s are accompanied with the fast flows (38 with BBFs determined by the criteria from *Angelopoulos et al.* [1994]). The variations of the ion thermal pressure and the magnetic pressure of all these 62 events are in antiphase. Out of these 62 events, 42 waves have dominant compressional component, while the other 19 have comparable compressional and transverse components and 1 has dominant transverse components.

Other mechanisms, such as substorm current wedge and ballooning instability, have also been proposed to drive the Pi2s in the plasma sheet. We analyze the rest 18 events by examining the *AL* index to determine the presence of the substorms, following the *AL* index criterion used by *Hsu and McPherron* [2007]. Eleven out of 18 events occur during *AL* substorms. In these 11 events, 8 are mainly the compressional waves, 1 has dominant transverse component, and 2 have comparable compressional and transverse components. The ion thermal pressure and the magnetic pressure also vary in antiphase.

By using OMNI data and AM-03 mode, *Panov et al.* [2012] found that about 2° change of the solar wind direction in 10 min window corresponds to about 8° change of the plasma sheet orientation tailward of 15 R_E

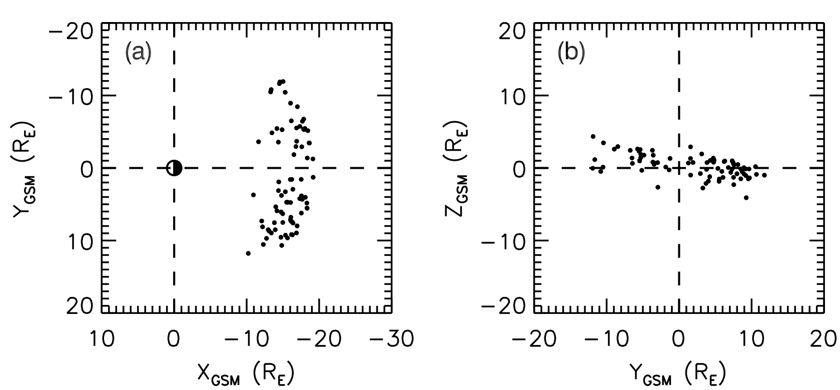

Figure 5. The spatial distribution of the 80 Pi2-band waves observed by C1 in *x-y* (GSM) and *y-z* (GSM) plane.

Table 1. Statistical Study of the Magnetospheric Drivers and Features of the Pi2-Band Waves

	Fast Flows	Substorms	Others
Event number	62 (42)[a]	11[b]	7 (3)[c]
Compressional	42	8	6
Transverse	1	1	0
Comparable	19	2	1

[a]Sixty two Pi2s are accompanied with fast flows. Forty two out of these waves are observed during substorms.

[b]Eleven Pi2s are observed during substorms and accompanied with no fast flows.

[c]Seven Pi2s are observed during nonsubstorm and accompanied with no fast flows (three observed while the solar wind velocity direction changes larger than 2° in 10 min in the noon meridian in GSM plane).

in the noon meridian GSM plane. We use a 10 min window to examine the change of the solar wind velocity direction in the noon meridian GSM plane. In these 7 events that are observed without fast flows during nonsubstorm, 3 events occur when the solar wind velocity significantly changes its direction, and the maximum changes of solar wind velocity direction are ~2.0°, ~2.1°, and ~3°, respectively. All these 3 events are compressional waves.

There are 4 Pi2s in our studied events that are not accompanied by fast flows, occur during nonsubstorm times, and have no significant change in the solar wind velocity direction. Among these events, three Pi2s are compressional waves, and the other one has comparable compressional and transverse components. All these waves, the ion thermal pressure, and the magnetic pressure vary in antiphase.

4. Summary and Discussions

In this paper, we have studied the occurrence of the large-amplitude Pi2-band waves in the plasma sheet and their relation to fast flows, substorms, and the solar wind velocity direction during the Cluster tail season from 2001 to 2009. Eighty Pi2s are selected for our statistical study. The average duration of the large-amplitude Pi2-band waves is about 15 min. Sixty-two Pi2s are accompanied with fast flows, 11 events without fast flows occur during substorms, 3 Pi2s occur when the solar wind velocity direction significantly changes ($>2°$ in the noon meridian GSM plane), and 4 are not associated with any fast flows, substorms, or significant change of the solar wind velocity direction. The ion thermal pressure and the magnetic pressure vary in antiphase during all 80 events. Most of the events (56 Pi2s) are compressional waves, while 22 events have comparable transverse and compressional components. There are 2 Pi2s that have dominant transverse components.

Some strong magnetic field fluctuations in the plasma sheet are found to be accompanied with fast flows [*Bauer et al.*, 1995; *Sigsbee et al.*, 2002; *Fu et al.*, 2011]. In our study, the majority of the Pi2s in the plasma sheet are accompanied with fast flows. This result suggests that in most of the cases, fast flows are the main driver of these waves, which agrees with the results of *Volwerk et al.* [2003]. *Volwerk et al.* [2003] found that the spectral power of the compressional waves in the tail current with Pi2-band frequencies increased with the plasma flow velocity up to a perpendicular flow velocity of ~400 km/s and saturates at higher velocities. They concluded that fast flows can drive turbulence in the Earth's tail current sheet. It is also worthy to note that fast flows have been found to be associated with the current sheet flapping [*Sergeev et al.*, 2006], which may also produce perturbations in the magnetic field with quasiperiods in Pi2 frequency band. It is not excluded in our current study that some Pi2 waves are associated with the flapping in the thin and wavy current sheet [*Fairfield et al.*, 1981; *Nakagawa and Nishida*, 1989].

Besides fast flows, other dynamic processes in the plasma sheet, such as substorm current wedge (SCW) and ballooning instability, are also proposed to drive Pi2s [*Bauer et al.*, 1995; *Saito et al.*, 2008]. *Bauer et al.* [1995] reported three events with strong magnetic oscillations in the plasma sheet during substorms, which had dominant compressional component and anticorrelated proton pressure and magnetic pressure variations. They suggested that the transient response of the plasma sheet to the formation of the SCW drives these magnetic oscillations. In our survey, 8 compressional wave events that are not associated with fast flows that occur during substorms can be explained by the plasma sheet oscillations excited by the formation of the SCW at substorm onsets [*Bauer et al.*, 1995]. However, there is one substorm time Pi2-band wave that appears transverse, which could be the result of mode conversion to become Alfvénic fluctuations [*Du et al.*, 2011].

Recent studies also suggested that the Pi2s in the plasma sheet might be associated with plasma sheet instabilities [*Panov et al.*, 2012]. The Pi2-band oscillations of the magnetic field reported by *Panov et al.* [2012] are attributed to the kinetic ballooning/interchange instability that developed in a bend current sheet driven by the change of the solar wind velocity direction. Our survey shows that the solar wind direction significantly changes during several Pi2s, suggesting that some Pi2s in the plasma sheet can be driven purely by the plasma instabilities while this mechanism may happen in relatively rare cases. There are 4 events in our study that are not associated with fast flows, substorms, and the significant change of the solar wind velocity direction. In these cases, other mechanisms, such as impulsive reconnection [*Fu et al*., 2013a, 2013b], can drive Pi2s, although the current observations in this study may not confirm it. It is also worthy to note that out of 62 fast flow-driven Pi2s, 42 events also occur during substorms and 22 during the expansion phase of substorms. Considering the strong association between BBFs and substorms, it is not surprising that some Pi2s in the plasma sheet may be the combined effect of fast flows and the formation of the SCW.

Acknowledgments
This work in China was supported by the NSFC grants 41174156, 41474144, and 41121003. The work in Austria was supported by EU FP7 grants 263325 and ECLAT and Austrian Science fund FWF P23862-N16 and fund P24740-N27. We appreciate Cluster Active Archive at http://caa.estec.esa.int/ and Cluster project FGM and CIS teams. We acknowledge CDAWeb service for OMNI data at http://cdaweb.gsfc.nasa.gov/.

Michael Balikhin thanks the reviewers for their assistance in evaluating this paper.

References

Angelopoulos, V., W. Baumjohann, C. F. Kennel, F. V. Coroniti, M. G. Kivelson, R. Pell at, R. J. Walker, H. Lühr, and G. Paschmann (1992), Bursty bulk flows in the inner central plasma sheet, *J. Geophys. Res.*, *97*(A4), 4027–4039, doi:10.1029/91JA02701.

Angelopoulos, V., C. F. Kennel, F. V. Coroniti, R. Pellat, M. G. Kivelson, R. J. Walker, C. T. Russell, W. Baumjohann, W. C. Feldman, and J. T. Gosling (1994), Statistical characteristics of bursty bulk flow events, *J. Geophys. Res.*, *99*(A11), 21,257–21,280, doi:10.1029/94JA01263.

Balogh, A., et al. (2001), Cluster magnetic field investigation: Overview of in-flight performance and initial results, *Ann. Geophys.*, *19*, 1207–1217.

Bauer, T. M., W. Baumjohann, and R. A. Treumann (1995), Neutral sheet oscillations at substorm onset, *J. Geophys. Res.*, *100*(23), 737.

Baumjohann, W., and K. H. Glassmeier (1984), The transient response mechanism and Pi2 pulsations at substorm onset: Review and outlook, *Planet. SpaceSci.*, *32*, 1361.

Baumjohann, W., G. Paschmann, and C. A. Cattel (1989), Average plasma properties in the central plasma sheet, *J. Geophys. Res.*, *94*, 6597–6606, doi:10.1029/JA094iA06p06597.

Cao, J. B., et al. (2006), Joint observations by Cluster satellites of bursty bulk flows in the magnetotail, *J. Geophys. Res.*, *111*, A04206, doi:10.1029/2005JA011322.

Cao, J. B., et al. (2008), Characteristics of middle- to low-latitude Pi2 excited by bursty bulk flows, *J. Geophys. Res.*, *113*, A07S15, doi:10.1029/2007JA012629.

Cao, J. B., et al. (2010), Geomagnetic signatures of current wedge produced by fast flows in a plasma sheet, *J. Geophys. Res.*, *115*, A08205, doi:10.1029/2009JA014891.

Du, J., T. L. Zhang, R. Nakamura, C. Wang, W. Baumjohann, A. M. Du, M. Volwerk, K.-H. Glassmeier, and J. P. McFadden (2011), Mode conversion between Alfvén and slow waves observed in the magnetotail by THEMIS, *Geophys. Res. Lett.*, *38*, L07101, doi:10.1029/2011GL046989.

Fairfield, D. H., E. W. Hones Jr., and C.-I. Meng (1981), Multiple crossing of a very thin plasma sheet in the Earth's magnetotail, *J. Geophys. Res.*, *86*, 11,189–11,200, doi:10.1029/JA086iA13p11189.

Fu, H. S., Y. V. Khotyaintsev, M. André, and A. Vaivads (2011), Fermi and betatron acceleration of suprathermal electrons behind dipolarization fronts, *Geophys. Res. Lett.*, *38*, L16104, doi:10.1029/2011GL048528.

Fu, H. S., Y. V. Khotyaintsev, A. Vaivads, M. André, and S. Y. Huang (2012a), Occurrence rate of earthward-propagating dipolarization fronts, *Geophys. Res. Lett.*, *39*, L10101, doi:10.1029/2012GL051784.

Fu, H. S., Y. V. Khotyaintsev, A. Vaivads, M. André, V. A. Sergeev, S. Y. Huang, E. A. Kronberg, and P. W. Daly (2012b), Pitch angle distribution of suprathermal electrons behind dipolarization fronts: A statistical overview, *J. Geophys. Res.*, *117*, A12221, doi:10.1029/2012JA018141.

Fu, H. S., et al. (2013a), Dipolarization fronts as a consequence of transient reconnection: In situ evidence, *Geophys. Res. Lett.*, *40*, 6023–6027, doi:10.1002/2013GL058620.

Fu, H. S., et al. (2013b), Energetic electron acceleration by unsteady magnetic reconnection, *Nat. Phys.*, *9*, 426–430, doi:10.1038/NPHYS2664.

Hsu, T. -S., and R. L. McPherron (2002), An evaluation of the statistical significance of the association between northward turnings of the IMF and substorm expansion onsets, *J. Geophys. Res.*, *107*(A11), 1398, doi:10.1029/2000JA000125.

Hsu, T.-S., and R. L. McPherron (2007), A statistical study of the relation of Pi2 and plasma flows in the tail, *J. Geophys. Res.*, *112*, A05209, doi:10.1029/2006JA011782.

Keiling, A. (2012), Pi2 pulsations driven by ballooning instability, *J. Geophys. Res.*, *117*, A03228, doi:10.1029/2011JA017223.

Kepko, L., and M. G. Kivelson (1999), Generation of Pi2 pulsations by bursty bulk flows, *J. Geophys. Res.*, *104*, 25021, doi:10.1029/1999JA900361.

Kepko, L., M. Kivelson, and K. Yumoto (2001), Flow bursts, braking, and Pi2 pulsations, *J. Geophys. Res.*, *106*, 1903–1915, doi:10.1029/2000JA000158.

Keiling, A., and K. Takahashi (2011), Review of Pi2 models, *Space Sci. Rev.*, *161*, 63–148, doi:10.1007/s11214-011-9818-4.

Mailyan, B., C. Munteanu, and S. Haaland (2008), What is the best method to calculate the solar wind propagation delay?, *Ann. Geophys.*, *26*, 2383–2394, doi:10.5194/angeo-26-2383-2008.

McPherron, R. L., J. M. Weygand, and T.-S. Hsu (2008), Response of the Earth's magnetosphere to changes in the solar wind, *J. Atmos. Sol. Terr. Phys.*, *70*, 303–315, doi:10.1016/j.jastp.2007.08.040.

Nagai, T., and S. Machida (1998), Magnetic reconnection in the near-Earth magnetotail, in *New Perspectives on the Earth's Magnetotail, Geophys*. *Monogr*. *Ser*, vol. 105, edited by A. Nishida, D. N. Baker, and S. W. H. Cowley, pp. 211–224, AGU, Washington, D. C.

Nakagawa, T., and A. Nishida (1989), Southward magnetic field in the neutral sheet produced by wavy motions in the dawn-dusk direction, *Geophys. Res. Lett.*, *11*, 1265–1268, doi:10.1029/GL016i011p01265.

Olson, J. V. (1999), Pi2 pulsations and substorm onsets: A review, *J. Geophys. Res.*, *104*, 17,499–17,520, doi:10.1029/1999JA900086.

Panov, E. V., et al. (2012), Kinetic ballooning/interchange instability in a bent plasma sheet, *J. Geophys. Res.*, *117*, A06228, doi:10.1029/2011JA017496.

Pu, Z. Y., A. Korth, Z. X. Chen, R. H. W. Friedel, Q. G. Zong, X. M. Wang, M. H. Hong, S. Y. Fu, Z. X. Liu, and T. I. Pulkkinen (1997), MHD drift ballooning instability near the inner edge of the near-Earth plasma sheet and its application to substorm onset, *J. Geophys. Res.*, *102*(A7), 14397, doi:10.1029/97JA00772.

Rème, H., et al. (2001), First multispacecraft ion measurements in and near the Earth's magnetosphere with the identical Cluster Ion Spectrometry (CIS) experiment, *Ann. Geophys.*, *19*, 1303–1354.

Roux, A., S. Perraut, A. Moranc, P. Robert, A. Korth, G. Kremser, A. Pederson, R. Pellinen, and Z. Y. Pu (1991), Plasma sheet instability related to the westward traveling surge, *J. Geophys. Res.*, *96*(A10), 17697, doi:10.1029/91JA01106.

Saito, M. H., Y. Miyashita, M. Fujimoto, I. Shinohara, Y. Saito, K. Liou, and T. Mukai (2008), Ballooning mode waves prior to substorm-associated dipolarizations: Geotail observations, *Geophys. Res. Lett.*, *35*, L07103, doi:10.1029/2008GL033269.

Sergeev, V. A., D. A. Sormakov, S. V. Apatenkov, W. Baumjohann, R. Nakamura, A. V.Runov, T. Mukai, and T. Nagai (2006), Survey of large-amplitude flapping motions in the midtail current sheet, *Ann. Geophys.*, *24*, 2015–2024.

Sergeev, V. A., N. A. Tsyganenko, and V. Angelopoulos (2008), Dynamical response of the magnetotail to changes of the solar wind direction: An MHD modeling perspective, *Ann. Geophys.*, *26*, 2395–2402.

Sigsbee, K., C. A. Cattell, F. S. Mozer, K. Tsuruda, and S. Kokubun (2001), Geotail observations of low-frequency waves from 0.001 to 16 Hz during the November 24, 1996 Geospace Environment Modeling substorm challenge event, *J. Geophys. Res.*, *106*, 435–445, doi:10.1029/2000JA900090.

Sigsbee, K., C. A. Cattell, D. Fairfield, K. Tsuruda, and S. Kokubun (2002), Geotail observations of low-frequency waves and high-speed earthward flows during substorm onsets in the near magnetotail from 10 to 13 R_E, *J. Geophys. Res.*, *107*(A7), 1141, doi:10.1029/2001JA000166.

Volwerk, M., et al. (2003), A statistical study of compressional waves in the tail current sheet, *J. Geophys. Res.*, *108*(A12), 1429, doi:10.1029/2003JA010155.

Volwerk, M., R. Nakamura, W. Baumjohann, T. Uozumi, K. Yumoto, and A. Balogh (2008), Tailward propagation of Pi2 waves in the Earth's magnetotail lobe, *Ann. Geophys.*, *26*, 4023–4030, doi:10.5194/angeo-26-4023-2008.