Cluster observations of simultaneous resonant interactions of ULF waves with energetic electrons and thermal ion species in the inner magnetosphere

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1. Introduction

In this study, we report in situ observations on the simultaneous periodic modulations in the drifting energetic electrons (∼100 keV) and in the bouncing thermal ion species (O+ at ∼4.5 keV and H+ at ∼280 eV) with the same frequency of 3.3 mHz during the storm recovery phase on 21 October 2001. The Cluster fleet was traveling outbound in the inner magnetosphere from the Southern to Northern Hemisphere on the morning sector (0900 MLT). The ultra-low-frequency (ULF) waves from the magnetic field and electric field measurements show a mixture of several dominant wave components in the transverse modes. The poloidal mode at the modulation frequency of 3.3 mHz appears to be a standing wave with an odd harmonic, although other wave components reveal propagating features. The radial extent of this standing wave is around 0.58 RE. The oscillation periods of the energetic electron fluxes (∼100 keV) and the thermal O+ (∼4.5 keV) and H+ (∼280 eV) fluxes are observed the same as the period of the poloidal standing wave, indicating that the energetic electrons and the thermal ion species are modulating by the same wave. Further, we suggest the simultaneous drift resonances of the energetic electrons around 94 keV and the bounce resonances of the thermal O+ around 4.5 keV and H+ around 280 eV with the same poloidal standing wave. In addition, the electron energy spectra variations reveal the accelerations of the electrons in the energy range of 50–110 keV, which are most likely due to the drift resonances. This is the first study to show both energetic particles (radiation belt population, ∼a few hundred keV) and thermal ions (background plasma population, ∼a few keV) can be affected by the same ULF wave simultaneously. Furthermore, this study implies that the superdense ionospheric origin O+ ions in the inner magnetosphere during storm times can modify the local field line eigenfrequency and result in the energetic electron accelerations by the ULF waves in the deep region of the radiation belt.


1. Introduction

The ultra-low-frequency (ULF) Pc5 pulsations, with the period of 150–600 s [Jacobs et al., 1964], are believed to be capable of accelerating the radiation belt energetic electrons via drift resonances [e.g., Elkington et al., 1999, 2003; Zong et al., 2009]. Many studies have revealed the particle flux modulations associated with the ULF wave activities in the magnetosphere [e.g., Brown et al., 1968; Kokubun et al., 1977; Baker et al., 1980; Su et al., 1980; Kremser et al., 1981; Takahashi et al., 1985a, 1990]. Physically, when a particle with charge q and energy W interacts with an ULF transverse standing wave, the particle energy change rate is given by Northrop [1963] and Southwood and Kivelson [1981]:

\[
\frac{dW}{dt} = qE \cdot V_d
\]

where E denotes the electric field of the transverse wave and V_d is the drift velocity of the particle. The drift-bounce...
resonance condition of the charged particle with the ULF transverse standing wave can be described theoretically as [Southwood et al., 1969]:

\[ \omega - m\omega_d = N\omega_b \]

where \( \omega \) is the wave angular frequency, \( \omega_d \) and \( \omega_b \) are the particle drift and bounce frequencies, respectively, \( m \) represents the azimuthal wave number, and \( N \) is an integer which depends on the harmonic mode of the standing wave. Since the particle drifts in the azimuthal direction, it is inferred from equation (1) that in a symmetrical dipole field, the drift-bounce resonance can only occur between particles and the waves which have an azimuthally polarized electric field (i.e., poloidal mode). Elkington et al. [1999] proposed that the resonance could also occur for the radially polarized electric field (i.e., toroidal mode), when the Earth’s dipole magnetic field reveals a noon-midnight asymmetry.

[3] Previous studies have reported the ground-based and satellite observations of ULF waves associated with the unstable ring current ions [e.g., Hughes et al., 1978b; Glassmeier et al., 1999; Wright et al., 2001; Yeoman and Wright, 2001; Baddeley et al., 2002, 2004; Wilson et al., 2006]. They suggested the excitations of the ULF waves by drift-bounce resonances of those unstable ions. Hughes et al. [1978b] observed the concurrent quasi-monochromatic ULF waves and an non-Maxwellian distribution of protons in several keV. They proposed that the drift-bounce resonances of these unstable protons excited the observed ULF waves. The statistical studies by Baddeley et al. [2004] showed that the ring current low-energy protons (10–45 keV) are the dominant non-Maxwellian populations and most likely to be responsible for the generation of small-scale poloidal mode ULF waves. Alternatively, the ULF waves could also be damped and feed energy to the ring current ions via drift-bounce resonances, depending on the distribution function of the resonant particles [Southwood et al., 1969]. That is, for a group of resonant particles, if the distribution function is unstable, i.e., \( df/dW > 0 \), where \( f \) indicates the phase space density and \( W \) denotes the energy, those particles will lose energy and the corresponding waves will grow. On the other hand, if \( df/dW < 0 \), the particles will gain energy and the corresponding waves will be damped [e.g., Southwood et al., 1969; Southwood and Hughes, 1983]. Until now, the in situ observation of the drift-bounce resonances of the ULF waves with the ring current ions has rarely been reported.

[4] Observations of drift resonances of ULF waves with radiation belt electrons have been extensively presented recently. Zong et al. [2007] observed the drift resonances of energetic electrons around 127 keV with the fundamental toroidal-mode Pc5 standing waves by Cluster observations in the inner magnetosphere. Combining the observations from CRRES and GOES satellites, Tan et al. [2004] reported the electron accelerations via drift resonance with the toroidal-mode Pc5 waves accompanied with an interplanetary shock at the geosynchronous orbit. Zong et al. [2009] have demonstrated that the ULF waves induced by a large interplanetary shock as observed by Cluster could energize the energetic electrons via drift resonance. Their survey also showed that the ULF waves, induced by even a small solar wind dynamic pressure pulses, could distinctly modulate the energetic electron fluxes in the inner magnetosphere. On the other hand, Ozeke and Mann [2008] proposed the accelerations of the radiation belt MeV electrons by ring current ion driven ULF waves, although it was derived from model calculation and no relevant observation was presented. In their paradigm, the unstable ring current protons or oxygen ions excited the ULF waves via bounce resonances, and subsequently, the ULF waves feed their energy to the MeV electrons via drift resonances, causing the accelerations of the radiation belt electrons. As another paradigm, it is also possible that the ULF waves, probably excited by the external solar wind source, could simultaneously accelerate the radiation belt energetic electrons via drift resonances and the ring current ions via bounce resonances.

[5] The ion composition variations in the inner magnetosphere could considerably modulate the field line eigenfrequency and structure of the ULF standing waves [see Denton, 2006, and reference therein]. It is believed that the ionospheric upflowing heavy O+ ions could contribute a significant portion to the plasma population in the inner magnetosphere [Horwitz et al., 1984] or the tail plasmasheet region [Ruan et al., 2005]. Takahashi et al. [2006] showed that there was an increase in the average ion mass number density from \( L = 6 \) to 7 with respect to the enhanced geomagnetic activities, suggesting the predominant filling of heavy ions such as O+ ions in the magnetosphere during geomagnetic storms. The heavy ion mass loading in the inner magnetosphere could dramatically decrease the Alfvén eigenfrequencies of the field lines [Fraser et al., 2005]. Lee et al. [2007] observed the global ULF Pc5 standing waves at unusually low L region (\( L = 3.6 \sim 4.3 \)) by ground-based magnetometer array during the great magnetic storm of 24 March 1991. They suggested the reduction of local Alfvén eigenfrequency continuum (\( L = 3.6 \sim 4.3 \)) due to the increase of O+ ions originated from the ionosphere, allowing the penetration of ULF Pc5 wave power to much lower L values than normal. In contrast, the statistical survey of the global ULF wave power distributions by O’Brien et al. [2003] pointed out that the ULF activities dominated at the geosynchronous orbit and beyond. The enhanced O+ ions in the inner magnetosphere during intense storm times, could potentially intrigue the energetic electron accelerations by ULF waves at even lower L region of the radiation belt.

[6] In light of the above developments, we represent the Cluster observations of simultaneous resonant interactions of the same ULF Pc5 standing wave with both the energetic electrons via drift resonances and the thermal ion species (O+ and H+) via bounce resonances. In sections 2 and 3, we describe the data sources and observations, respectively. Discussions are presented in section 4. Finally, we give the conclusions in section 5.

2. Data Sources

[7] The Cluster constellation [Escoubet et al., 2001], which consists of four satellites, is operating on a polar
elliptical orbit with an inclination of 89°. It has a perigee of 4.0 $R_E$ and apogee of 19.6 $R_E$ and orbit period of 57 h.

We use the spin average (4 s resolution) of magnetic field data from the Fluxgate Magnetometer (FGM) \cite{Balogh et al., 2001} and electric field data from the Electric Field and Wave experiment (EFW) \cite{Gustafsson et al., 2001} to analyze the ULF waves. The third component of the electric field which directs along the spin axis is derived from $E \cdot B = 0$ by assuming the ideal hydromagnetic dynamics. In order to analyze the properties of different wave modes, the magnetic and electric field data is projected on the mean field-aligned coordinates \cite[e.g.,][]{Eriksson et al., 2006; Zong et al., 2007}. In this local system, the parallel unit vector $e_p$ is along the 15 min running average of the magnetic field vector, the azimuthal unit vector $e_a$ is along the cross product of $e_p$ and the geocentric radial vector to the spacecraft position, and finally, the radial unit vector $e_r$ completes the triad.

The energetic electron fluxes are obtained from the Research with Adaptive Particle Imaging Detectors (RAPID) \cite{Wilken et al., 2001} onboard Cluster, which is capable of detecting the plasma distribution in the energy range from 20–400 keV for electrons. The Cluster Ion Spectrometry (CIS) \cite{Rème et al., 2001} is utilized to inspect the number densities and the pitch angle distributions of the ions. The CIS experiment is a comprehensive ionic plasma spectrometry package which consists of two sensors, a Hot Ion Analyzer (HIA) and a time-of-flight ion Composition Distribution Function (CODIF). The HIA instrument is capable of obtaining full three-dimensional ion distributions of ions in the energy range of 5 eV/q – 32 keV/q without distinguishing the species. The CODIF instrument measures the full three-dimensional distributions of the major ion species ($H^+$, $O^+$, $He^+$, $He^{2+}$) in the energy range from 20 eV/q to 40 keV/q. In addition, we use the data from the Wind spacecraft for the solar wind observations \cite{Ogilvie et al., 1995}.

3. Observations

An interplanetary shock was observed by the ACE spacecraft which was located at the L1 point at 1615 UT on 21 October 2001. A SSC (Storm Sudden Commencement) occurred on 1700 UT and was followed by a geomagnetic storm with a minimum Dst = −187 nT. During the beginning of the recovery phase of the magnetic storm, the Cluster fleet was traveling outbound in the inner magnetosphere from the Southern to Northern Hemisphere around 0900 MLT near its perigee. Figure 1a shows the trajectories of the satellites during 2300–2400 UT in the XZ plane of the GSM system. The magnetic field configuration is obtained by Tsyganenko T89 Model. The Dst index was about −180 nT during this time interval. The satellite C3 was located at [3.07, −2.98, −0.40] $R_E$ in GSM coordinate at 2340 UT and the relative positions of the four satellites are shown in Figure 1b. As can be seen, C3 was separated with a long distance with the other three satellites. The constellation has a maximum distance of 12300 km and a minimum distance of 940 km. The Cluster configuration during this time interval provides an excellent opportunity to investigate both the azimuthal wave number and radial structure of the ULF standing waves which will be discussed in detail in the following section.

Figure 2 gives an overview of the CODIF and RAPID measurements from 2100 UT, 21 October 2001 to 0200 UT, 22 October 2001. Figure 2b shows the integral fluxes of the energetic electrons (E > 95 keV) from RAPID. Data from different satellites are indicated by the curves.
An overview of the number density of the O\(^+\) and H\(^+\) from C4/CODIF and (b) the integral of A02214 – Ry and constituent in the inner magnetosphere in this event. Wind data for the solar wind condition as well as the Cluster measurements during 2300 UT component of the solar wind velocity. (c) The proton number density. (d) The solar wind dynamic pressure pulse to an average level of \(10 \text{nPa}\) to \(25 \text{nPa}\) within 3 min. The solar wind condition from the Wind spacecraft during 2300–2400 UT are shown in Figure 3. Figures 3a to 3d display the IMF Bz component, the solar wind flow velocity along the Sun–Earth line, the proton number density, and the solar wind dynamic pressure, respectively. The solar wind data is shifted by 8 min to account for the solar wind convection time, according to the distance of the spacecraft (45 \(R_E\)) and the average upstream flow velocity (630 km/s). A dynamic pressure pulse occurs at 2316 UT, with the pressure arising from \(-10 \text{nPa}\) to \(-25 \text{nPa}\) within 3 min. The IMF Bz component increases from \(-25 \text{nT}\) before the pressure pulse to an average level of \(-10 \text{nT}\) in the following 40 min, from which the magnetospheric convection is expected to become weaker. The solar wind velocity \(V_x\) gradually varies from \(-630 \text{ km/s}\) to \(-700 \text{ km/s}\), indicating a still high solar wind flow accompanied with the dynamic pressure pulse. In Figure 3e, the sudden enhancements of the magnetic field magnitudes are observed by C1, C2 and C4 at midlatitude. The magnetic field magnitudes increase about 25 nT within 30 s in response to impact of the dynamic pressure pulse. Whereas, the magnetic field magnitude observed by C3 performs a sudden drop in contrast to the other satellites. This behavior may be attributed to its position at a higher latitude. Figures 3f and 3g show the \(x\) and \(y\) components, respectively, of the electric field in GSE coordinate as observed by C4. The electric field variations are not monochromatic and probably reveal a mixture of several components with different frequencies. In Figure 3h, the energetic electron (E > 95 keV) flux variations during 2300–2400 UT are extracted, showing apparent periodic oscillations especially during 2340–2355 UT. Figure 3i shows the electron flux fluctuations with the background levels taken out. This is performed by calculating the 10 min running average of the flux and subtracting this from the original data. We also applied 40 s sliding average to smooth the electron fluxes, in order to eliminate the high-frequency components. It is found that the apparent flux oscillation beginning at 2316 UT is well correlated with the onset of the dynamic pressure pulse. The L value of each satellite derived from the IGRF model is presented in Figure 3j. For satellites C1, C2 and C4, the amplitudes of the flux oscillations decrease gradually during the first five wave cycles from 2316–2338 UT (marked with green dashed lines). However, the amplitudes reach to a relatively higher level during the subsequent four wave cycles from 2338–2358 UT (marked with red dashed lines). The drift period of 100 keV electrons at \(L = 4.5\) is estimated to be \(-120 \text{ min}\) in a dipole field. Therefore, the flux fluctuations during 2338–2358 UT are not the drift echoes of the waves, but other components with different frequencies. In Figure 3h, the energetic electron (E > 95 keV) flux variations during 2300–2400 UT are extracted, showing apparent periodic oscillations especially during 2340–2355 UT. Figure 3i shows the electron flux fluctuations with the background levels taken out. This is performed by calculating the 10 min running average of the flux and subtracting this from the original data. 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Figure 3

(a) Wind
(b) $V_x$ [km/s]
(c) $N_p$ [cm$^{-3}$]
(d) $P_{sw}$ [pW]
(e) $B_r$ [nT]
(f) $E_x$ [mV/m]
(g) $E_y$ [mV/m]
(h) Electron flux ($E>95$ keV) RAPID
(i) Electron flux ($E>95$ keV)
(j) L [Re]

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The flux amplitude of C3 is much smaller than those observed by the other three satellites before 2330 UT, but quickly reaches to the same level as the others during 2338–2358 UT. As demonstrated in Figure 3j, the L value of C3 is much larger than others before 2330 UT. It is most likely that the flux differences of C3 relative to the others can be attributed to the spatial variations. Nevertheless, the L value of C3 approaches to the other satellites within 1.2 $R_E$ during 2338–2358 UT, although C3 is still located in the Southern Hemisphere while the other three satellites have already entered into the Northern Hemisphere. This implies the energetic electron fluxes are modulated in both the Southern and Northern hemispheres at approximately the same L regions.

The power spectrum density of the original electron fluxes ($E > 95$ keV) during 2300–2400 UT is given in Figure 4a, from which the electron fluxes are confirmed to oscillate with frequencies centered around 3.3 mHz. The magnetic field from Cluster/FGM and the electric field from Cluster/EFW are projected on the mean local field-aligned coordinates (see section 2 for detail). Figures 4b and 4c show the power spectrum density profiles of the azimuthal (poloidal) and radial (toroidal) electric field components, respectively. The compressional mode (i.e., parallel magnetic field perturbation) driven by shock or solar wind dynamic pressure pulse could also contribute to the azimuthal electric field variations [Hudson et al., 1997]. As indicated by Zong et al. [2009], the azimuthally polarized electric field caused by the parallel or radial magnetic field perturbations will have no difference in terms of interacting with charged particles. Therefore, for convenience, we only consider the poloidal mode and toroidal mode in this study. Apparently, the poloidal electric field exhibits two dominant frequencies, with one in 3.3 mHz which is consistent with the electron flux oscillation frequency and the other in 1.8 mHz. Whereas, the peak frequency of the toroidal electric field appears in 2.5 mHz.

Band-pass filtering processes are applied to the poloidal and toroidal wave modes in the main frequencies, and then the phase differences between the magnetic field and electric field components of each wave mode are extracted by performing wavelet coherence analysis [Grinsted et al., 2004], in order to examine whether the waves are standing or propagating. Figure 5 gives the poloidal and toroidal wave components from C4 after band-pass filtering with a bandwidth of 1.0 mHz and the relevant central frequency labeled in Figure 5. The magnetic field and the electric field components are shown as the blue and red lines, respectively. Figure 5a is for the poloidal wave in 3.3 mHz. The corresponding phase difference is shown in Figure 5b. The azimuthal electric field leads the radial magnetic field by $\sim 90$ degrees during 2305–2322 UT when C4 is located in the Southern Hemisphere and subsequently displays $\sim 90$ degree phase lag with respect to the radial magnetic field during 2335–2350 UT when C4 entered into the Northern Hemisphere (see the location of C4 labeled at the
This type of phase difference of the transverse wave modes that reverse from negative 90 degrees to positive 90 degrees across the magnetic equator from south to north has been demonstrated by Singer et al. [1982]. According to their method, the 3.3 mHz poloidal mode appears to be a standing wave with an odd harmonic. However, we cannot find a relatively stable phase difference of 90 degrees between the electric and magnetic field components for the 1.8 mHz poloidal mode, as shown in Figures 5c and 5d. It is most likely that the 1.8 mHz poloidal mode is propagating. Similarly, the 2.5 mHz toroidal mode can also be determined to be propagating, as indicated in Figures 5e and 5f.

We further utilize the wavelet transform [Grinsted et al., 2004] to investigate the coherence between the energetic electron flux and the transverse electric field components [e.g., Zong et al., 2007]. The results are shown in Figure 6.

Figure 5. (a) The poloidal wave in 3.3 mHz, which are obtained by applying a bandpass filter with 1.0 mHz bandwidth. (b) The cross phase of the relevant poloidal magnetic field and electric field components in 3.3 mHz. (c and d) Plane; same as Figures 5a and 5b but for the poloidal wave in 1.8 mHz. (e and f) Plane; same as Figures 5a and 5b but for the toroidal wave in 2.5 mHz.

Figure 6. The squared wavelet coherence of the energetic electron flux with the (top) azimuthal electric field component and (bottom) radial electric field component, respectively. The electron flux and electric field data are from satellite C4.
Figure 6 (top) and Figure 6 (bottom) display the wavelet coherence of the electron flux with the azimuthal electric field component and radial electric field component, respectively. Both the poloidal and toroidal electric field perturbations are well correlated with the energetic electron flux in a rather broad bandwidth during 2310–2325 UT. However, the electron flux appears to be only highly coherent (a coherence of about 0.9 at the period of 300 s) with the poloidal electric field in 3.3 mHz from 2340 UT to 2355 UT, when the electron flux oscillations exhibit relatively large amplitudes. [16] As demonstrated in Figure 3, the apparent flux oscillations beginning at 2316 UT is well correlated with the onset of the dynamic pressure pulse. Zong et al. [2009] have reported the energetic electron flux modulations by the ULF waves induced by solar wind dynamic pressure pulse in the inner magnetosphere. The gradual damping of the flux oscillation amplitude during 2316–2335 UT is similar to the damping of the transverse electric field fluctuations in their study. We speculate that the high coherence of the electron flux with both the poloidal and toroidal modes in a rather broad bandwidth is correlated with the influence of the solar wind pressure pulse. However, the predominant flux modulation by 3.3 mHz poloidal mode during 2340–2355 UT seems to be weakly related to the pressure pulse, since the flux oscillation amplitude enhances dramatically during this time period.

3.1. Drift Resonances of the Energetic Electrons

[17] We focus on the energetic electron flux modulation during 2335–2355 UT, since the flux oscillation during this time period is highly coherent with the 3.3 mHz poloidal standing wave. The azimuthal wave number of this poloidal mode during this time interval can be derived, because the azimuthal distances between C3 and the other three satellites [e.g., Eriksson et al., 2006]. We obtain the cross phases of the 3.3 mHz poloidal magnetic field components between C3 and other satellite as well as the relevant coherence by applying the cross wavelet analysis [Grinsted et al., 2004].

[18] Figure 7a gives the radial magnetic field fluctuations in 3.3 mHz from the four satellites, which are derived from the bandpass filtering process as demonstrated in Figure 5a. In Figure 7b, the cross phases (Δθ) of C1, C2, and C4

Figure 7. (a) The poloidal magnetic field components in 3.3 mHz derived from bandpass filtering process as mentioned in Figure 5a. (b) The cross phases of C1 (black), C2 (red), and C4 (blue) relative to C3. (c) The relevant coherence of C3 with C1, C2, and C4, respectively, in 3.3 mHz. (d) The angular distance (in degree) of C1, C2, and C4 relative to C3 in the azimuthal direction. (e) The values of the azimuthal wave numbers with the relevant coherence larger than 0.85.
relative to C3 are shown as black, red and blue curves, respectively. The phase of radial magnetic field component at C1 (or C2, C4) leads C3 by approximately 135° to 150° and the phase differences appear quiet stable during 2335–2355 UT. The relevant coherences are shown in Figure 7c, in which coherences higher than 0.8 can be found during 2335–2355 UT. Figure 7d shows the corresponding angular distance (Δθ) in the azimuthal direction. The positive values indicate that C3 was eastward of the other satellites. We can deduce that the wave was propagating eastward in the azimuthal direction. Further, the azimuthal wave number can be derived by Takahashi et al. [1985b]:

\[ m = \frac{\Delta \theta}{\Delta \phi} \]

For robustness, m is valid only if the relevant coherence is greater than 0.85 during 2335–2355 UT. The results are shown in Figure 7e. Finally, the azimuthal wave number is around m = 22 ± 3.

Figure 8a shows the differential fluxes of the energetic electrons in different energy channels during 2330–2400 UT. There are small phase differences among different channels, that is, the phases of the higher energies are slightly ahead of the lower ones. This behavior is similar as what has reported by Zong et al. [2007, Figure 3]. They pointed out that the energy-dependent phase shift was not related to the drift dispersion effect but actually attributed to the drift resonant interactions. Zong et al. [2007] derived the resonant energy in which the phase of the flux oscillation was in quadrature with the ULF magnetic field oscillation. The gradual phase shift in other energy channel was speculated to be caused by the spread in wave frequency \( \omega \) or the azimuthal wave number m of the ULF standing wave [e.g., Takahashi et al., 1990].

Due to the mixture of several dominant transverse wave components in this event, it is not appropriate to examine the resonant energy according to the method proposed by Zong et al. [2007]. Instead, we use another way to examine the resonant energy. If the drift resonance occurs in one specific energy band, it is not a surprise that the relevant peak-to-valley ratio of the flux oscillation of this energy will be maximum compared to the adjacent energies. We calculate the maximum peak-to-valley ratio of each energy channel during this time interval. Figure 8b shows the energy dependence of the maximum peak-to-valley ratio from the four satellites. It is obvious that for each satellite, the maximum value appears in the energy channel of 94 keV. The values gradually decline as the energies become lower or higher. This result implies that the drift resonances of the energetic electrons are excited near 94 keV.

[21] The resonant energy can be derived in a dipole field theoretically from equation (2). The bounce frequency of the energetic electrons, with energy of tens of keV and located in the inner magnetosphere, will be much higher than the drift frequency and the Pc5 wave frequency. Thus, the drift-bounce resonance of energetic electrons could only be excited with \( N = 0 \). Then equation (2) is degenerated to the drift resonance condition:

\[ \omega - m\omega_d \approx 0 \]

Based on the wave frequency (3.3 mHz), the L value of the satellites (\( L = 4.5 \)) as well as the azimuthal wave number (m = 22 ± 3), the resonant energy is derived to be 75–99 keV. Thus, the consistency between the theoretical calculations and the observations further confirms drift resonances of the poloidal standing wave with the energetic electrons near 94 keV.

3.2. Bounce Resonances of the Thermal Ion Species

[22] Figure 9 shows the pitch angle distributions of the oxygen ions in different energy channels during 2300–2350 UT from the CODIF instrument. From the top to bottom, the energies decline from ~20 keV to about ~2 keV. In Figure 9a, the O⁺ at 19.4 keV reveals a pancake-like pitch angle distribution. As the energy declines to 11.9 keV, it seems that quasi-periodic field-aligned O⁺ beams appear during 2320–2330 UT, as shown in Figure 9b. Nevertheless, in the energy channel of 7.4 keV, the pancake-like pitch angle distribution appears again from 2300 UT to 2330 UT, and the fluxes in the pitch angle around 90° decrease dramatically in the following 20 min (see Figure 9c). It is very interesting that discernible periodic field-aligned O⁺ beams with periods of ~5 min appear again in the subsequent two energy channels, i.e., 4.5 keV and 2.8 keV. We speculate that the bounce motions of the thermal O⁺ in several specific
energies are modulated by the ULF waves. We should point out that similar signatures did not appear in the pitch angle distributions of H$^+$ in the same energy range. Furthermore, the behaviors of He$^+$ and He$^{2+}$ are not considered here, since the abundances of these two species are negligible.

In order to analyze the frequency properties of the periodic field-aligned O$^+$ beams in detail, we extract the differential flux variations corresponding to the pitch angle of 20°. As shown in Figure 10a, the blue and red curves indicate the fluxes in the energy channels of 2.8 keV and 4.5 keV, respectively. The differential fluxes are smoothed by applying 2 min sliding average to eliminate the high-frequency components. To evaluate the intensity of the flux modulations, we obtain the mean peak-to-valley ratio of the flux at 4.5 keV as 1.2 during 2315–2345 UT, when apparent flux oscillations are observed. In addition, a fast fourier transform (FFT) is performed to the original flux data. The normalized power spectrum density profiles are shown in Figure 10b. The results indicate that the field-aligned O$^+$ beams at 4.5 keV oscillate with frequencies centered around 3.3 mHz. It should be noted that the main frequency (3.0 mHz) of the field-aligned O$^+$ beams at 2.8 keV performs a slight shift with respect to the O$^+$ at 4.5 keV.

The drift-bounce resonance condition of the ions can be figured out theoretically according to equation (2). The angular bounce frequency $\omega_b$ of the ions with energy, $W$, can be determined in a dipole field as [Hamlin et al., 1961; Glassmeier et al., 1999]:

$$\omega_b = \sqrt{\frac{2W/m_i}{L^2 R_E T(\theta)}}$$  \hspace{1cm} (5)

where $L(\theta) = 1.30 – 0.56 \sin\theta$. $m_i$ is the ion mass, $L$ is the McIlwain L-shell value [McIlwain, 1961], $R_E$ is the Earth’s radius, and $\theta$ is the particle’s equatorial pitch angle.

For the ions with energy of several keV bouncing in the field-aligned direction, the drift frequency $\omega_d$ is ignorable, compared to the bounce frequency $\omega_b$ and the Pc5 wave frequency $\omega$. Thus, the equation (2) can be approximately degenerated into bounce resonance condition:

$$\omega \approx N \omega_b$$  \hspace{1cm} (6)

Figure 9. Pitch angle distributions of the oxygen ions in different energy channels as measured by the CODIF instrument from satellite C1. From the top to bottom, the energies decline from $\sim$20 keV to $\sim$2 keV. The energy channels are labeled.
Taking into account the wave frequency as 3.3 mHz, the relation of the particle energy $E$ versus pitch angle $\theta$ can be derived with different integer $N$.

As indicated in Figures 9d and 9e, the pitch angles of the field-aligned $O^+$ beams are constrained within $10^\circ$–$30^\circ$ in the parallel field direction and $150^\circ$–$170^\circ$ in the anti-parallel field direction. Since the satellite C1 is located near the equatorial plane during 2315–2345 UT, when the obvious periodic field aligned $O^+$ beams are observed, we suppose the equatorial pitch angles ($\theta$) of these beams are dominant in the range of $10^\circ$ to $30^\circ$. In this condition, for the oxygen ions, the corresponding resonant energies are estimated to be $18.0$–$13.0$ keV, $4.5$–$3.3$ keV, $2.0$–$1.4$ keV, for the $N = 1, 2, 3$ resonances, respectively. Therefore, we suggest that the $N = 2$ bounce resonance is excited between the 3.3 mHz poloidal standing wave and the oxygen ions with energies around 4.5 keV, producing the periodic field-aligned $O^+$ beams with a regular frequency of 3.3 mHz. Meanwhile, the signature of $N = 1$ bounce resonance could be observed at the energy channel of 11.9 keV (Figure 9b) during 2320–2330 UT, although the feature at this energy is rather faint and probably overwhelmed by the predominant fluxes with the pitch angle around 90 degree. In addition, the resonance will be excited only in one energy band if the Pc5 standing wave is monochromatic. However, a spread in the wave frequency $\omega$ or the azimuthal wave number $m$ is always speculated, resulting in a spread in the resonant energy [e.g., Takahashi et al., 1990; Zong et al., 2007]. The main frequency of the field-aligned $O^+$ beams at 2.8 keV shifts to a relative lower value (3.0 mHz), as shown in Figure 10b, can be attributed to a spread in the wave frequency of the poloidal standing wave.

On the other hand, it should be noted that, with the same energy and equatorial pitch angle, the bounce frequency of $H^+$ should be 4 times larger than $O^+$. The $H^+$ did not show any similar features in the pitch angle distributions as the $O^+$ in the same energy range (20–2 keV), indicating the bounce resonances of the $H^+$ are not excited in this energy range. According to equations (5) and (6), the expected bounce resonance energies for $H^+$ should be 16 times smaller than those of $O^+$. That is, for the $N = 2$ bounce resonance, with the equatorial pitch angle varies from $10^\circ$ to $30^\circ$, the resonant energy of $H^+$ should be in the range of 281–208 eV. Figure 11a shows the pitch angle distribution of the $H^+$ at 280 eV. The flux in each pitch angle channel in the spectrogram is smoothed by a 2 min sliding average. Periodic field-aligned beams can be seen in the spectrogram, although the data is not as apparent as the $O^+$. The differential flux variation corresponding to the pitch angle of $20^\circ$ is shown in Figure 11b. The flux is also smoothed by a 2 min sliding average. The mean peak-to-valley ratio of the flux is estimated to be 1.3 during 2310–2335 UT, when the obvious flux oscillations are observed. This flux modulation intensity is comparable to that of oxygen ions. In Figure 11c, the normalized spectrum density profile (calculated from the original data) indicates that the field-aligned $H^+$ beams in 280 eV also oscillate with frequencies centered around 3.3 mHz, although several high-frequency components appear. This implies the $N = 2$ bounce resonances are also excited between the poloidal standing wave and the protons with energies around 280 eV.

4. Discussion

4.1. Radial Structure of the Poloidal Standing Wave

The radial structure of standing Alfven waves has been extensively studied in theory [Klimushkin et al., 2004], numerical modeling [Mann et al., 1995], ground-based magnetometers at low latitude [Ziesolleck et al., 1993], radar observations at high latitude [Walker et al., 1979], as well as satellite observations [Hughes et al., 1978a; Singer et al., 1982; Mitchell et al., 1990]. Using the ISEE 1 and ISEE 2 satellites, Singer et al. [1982] investigated the radial width of the dayside Pe4, 5 standing Alfven waves and found that they were localized within 0.2–1.6 $R_E$ in the radial extent. The Cluster mission with a large scaled configuration formed by four satellites provides a good opportunity to study the temporal and spatial structures of the poloidal standing waves in the magnetosphere [Schäfer et al., 2007, 2008]. Schäfer et al. [2007] examined a case of spatially localized poloidal standing waves by Cluster observations and identified the radial extent to be about 0.67 $R_E$.

The satellites C1, C2, and C4 traveled across the magnetic equator from south to north during 2300–2400 UT, and they encountered the lowest L-shell at 2320, 2323 and 2325 UT, respectively (see Figure 3). Obviously, they were across the same L-shell regions twice in different hemispheres before and after around 2320–2325 UT. As shown in Figure 7a, it appeared the amplitudes of the 3.3 mHz poloidal magnetic fields were apparently larger during the northern crossing than the southern crossing. This may indicate a temporal evolution of the poloidal standing wave activity...
along the magnetic field lines [e.g., Schäfer et al., 2007, 2008]. The wave packet structure of the poloidal magnetic field in 3.3 mHz observed by C3 was basically identical to the others during 2335–2355 UT, except a phase lag of about 135°–150°. During this time the L value separations between C3 and C1, C2, C4 were less than 1.2 \( R_E \), although C3 was in the Southern Hemisphere and the other three satellites were in the Northern Hemisphere. This demonstrates the spatial variations of the poloidal standing wave along the field lines. The high coherence (>0.8) of the 3.3 mHz poloidal magnetic field oscillations between C3 and the others (see Figure 7c) indicates that the poloidal standing wave are radially localized within a narrow region. If we define that the radial structure of the poloidal standing wave is confined within the region where the coherence between the poloidal modes observed by C3 and each of the other three satellites is higher than 0.8, the radial width of the poloidal standing wave is estimated about 0.58 \( R_E \). This is consistent with the results by previous studies [Schäfer et al., 2007, 2008].

On the other hand, the monochromatic energetic electron fluxes oscillations are observed during 2335–2355 UT, which are confirmed to be predominantly modulated by the 3.3 mHz poloidal standing wave (see Figure 6). The electron integral flux (E > 95 keV) variations during 2330–2400 UT are given in Figure 12a. The four vertical arrows indicate the locations of the peak flux values in the relevant four wave cycles. The peak-peak flux value ratios of C1, C2, C4 relative to C3 are calculated and shown in Figure 12b as solid dots. The black, red and blue dots are correspond to the ratios of the satellite C1, C2 and C4, respectively, as refer to C3. Figure 12c shows the absolute L value differences (\( |\Delta L| \)) of C1, C2, C4 relative to C3. The arrows mark the same locations as in Figure 12a. As indicated by the first black arrow, the \( |\Delta L| \) between C1 and C3 is the smallest. The corresponding peak-peak flux ratio is most close to 1. Similar features are also observed at the other three peaks. That is, the smaller the \( |\Delta L| \) between Ci (i = 1, 2, 4) and C3 is, the closer the peak-peak ratio of Ci relative to C3 is to 1. This suggests the intensities of the electron flux amplitude

Figure 11. (a) The pitch angle distribution of the protons in 280 eV. (b) The differential flux variations corresponding to the pitch angle of 20 degrees in 280 eV. The flux is smoothed by applying 2 min sliding average. (c) The normalized power spectrum density profiles, calculated from the original flux data.
modulations are nearly the same along the same field line in both hemispheres. Those features document a clear spatial evolutions of the electron flux amplitude modulations in the resonant region by the poloidal standing wave. In addition, as an indirect approach, we can quantify the radial structure of the poloidal standing wave by the coincident electron flux modulations. Figure 12d shows the wavelet coherence of the electron flux variations in 3.3 mHz between C3 and C1, C2, and C4, respectively. We still define the regions where the coherence are higher than 0.8 as the limitation of the radial width of the poloidal standing wave. Then we obtain the radial width as $0.59 R_E$. This result is fairly consistent with the one obtained from the high coherence of the poloidal magnetic field variations among the four satellites. Thus, we suggest the coincident monochromatic electron flux oscillations modulated by ULF standing waves could provide another valid approach to evaluate the radial structure of the relevant standing waves.

4.2. Accelerations of the Energetic Electrons

The energy spectra of the energetic electrons are investigated to see whether the electrons are accelerated or decelerated [e.g., Nosé et al., 2000; Zong et al., 2009]. Figure 13a shows the energy spectra of the energetic electrons from C4. The three curves are corresponding to the energy spectra at 2334 (black), 2341 (red), and 2354 (blue) UT, respectively. The relevant times are marked with dashed lines in Figure 8a, which indicate the flux peaks in the relevant wave cycle. The standard deviations of the differential fluxes and the ranges of the energy channels are displayed as vertical and horizontal error bars in Figure 13a. The spectra represent a power law like distribution at t1. A slight increase of the differential fluxes at 50–110 keV appear at t2, which may indicate a slight acceleration of the electrons at these energy band. It is interesting to see a dramatic enhancement of the fluxes at 50–110 keV, especially at the channel of 94 keV (marked by yellowish shadow in Figure 13a). The intensity of the flux in 94 keV at t3 (2354UT) is 2.5 times larger than the magnitude at t1 (2334UT). The spectra variations illustrate a remarkably acceleration of the energetic electrons around the resonant energy (94 keV).

It should be noted that the electrons in the high-energy channel of 244 keV keep on decreasing from t1 to t3. We proposed two possibilities for this variations. On one hand, the drift resonance of Pc5 wave with electrons are not excited at this energy so that the 244 keV electrons may not be energized by the ULF wave. On the other hand, the electrons in this energy band are the constituent of the outer radiation belt relativistic electrons (100 keV to several MeV). The L value of C4 varies from 4.1 to 5.0 monochromatically during 2330–2400 UT. To some extent, the decline of the differential flux at around 244 keV can be attributed to the spatial variation of the relativistic electrons in the outer radiation belt.
As one may note, the acceleration of the electrons could be probably mixed by the adiabatic effect due to the conservation of the first invariant. In order to eliminate this effect, the energy is converted to the magnetic moment by:

\[ M = 100 \frac{E}{B} (\text{MeV/G}) \]

where \( E \) is the electron energy in keV and \( B \) is the magnetic field magnitude in nT from FGM measurement. Here, we assume the pitch angle distribution of the electrons is concentrated around 90 degree, since the electron energization due to ULF wave alone will tend to produce a pancake-like pitch angle distribution, with the conservation of the first and second invariants [Zong et al., 2009]. Figure 13b shows the magnetic moment dependence of electron differential fluxes. The magnetic moment correlated with the energy channel of 94 keV is marked as a yellowish shadow. The result is similar as in Figure 13a, indicating the adiabatic effect has little influence on the energy variations of the electrons. Thus, the energetic electrons around 94 keV are proved to be distinctly accelerated, most likely due to the drift resonances with the ULF waves.

4.3. Implications From the Wave-Particle Interactions

The observed periodic flux oscillations of the energetic electrons in 3.3 mHz are believed to be modulated by the poloidal standing wave with the same frequency. The maximum modulation intensities (peak-to-valley ratio) in the energy channel of 94 keV as measured by all four satellites imply that the drift resonances of the energetic electrons are excited around 94 keV. This is further confirmed by the predictions from the drift-bounce resonance theory [Southwood and Kivelson, 1982], from which the resonant energies are derived to be 75–99 keV. Energy spectra variations of the energetic electrons reveal the accelerations of the electrons at 50–110 keV, most likely due to the drift resonances. Meanwhile, the periodic field-aligned beams of both the O\(^+\) at \( \sim 4.5 \) keV and the H\(^+\) at \( \sim 280 \) eV with the same frequency of 3.3 mHz are also detected. The behaviors of pitch angle distributions of O\(^+\) in different energy channels strongly illustrate that the bounce resonances are excited in some specific energies, although the similar features of the H\(^+\) are not obvious. We suggest the bounce resonances of these two species in different energy channels (O\(^+\) at \( \sim 4.5 \) keV and H\(^+\) at \( \sim 280 \) eV) simultaneously with the observed 3.3 mHz poloidal standing wave. In addition, the modulation intensities of these two species are comparable to each other, indenting they are modulated with no priority. It is interesting to find out that both the drift resonances of the energetic electrons and the bounce resonances of the thermal ion species occur concurrently with the same poloidal standing wave in the inner magnetosphere during storm time.

The field line eigenfrequency is determined by the magnetic field magnitude, the field line length and the plasma mass density distribution along the field line. During the time period of interest, the number density of O\(^+\) is \( \sim 4 \) times larger than that of H\(^+\). The overwhelming O\(^+\) populations in the inner magnetosphere during storm time [e.g., Yau et al., 1984; Hamilton et al., 1988; Fu et al., 2001] can significantly decrease the local field line eigenfrequency [Fraser et al., 2005]. We observed the poloidal Pc5 standing wave with a frequency of 3.3 mHz at \( L = 4.2–5.0 \), which is much lower than the fundamental eigenfrequency (\( \sim 10 \) mHz) as normally expected in this region [e.g., Wild et al., 2005]. The resonant bouncing O\(^+\) ions loading on the magnetic field lines should obviously reduce the local Alfvén eigenfrequency, resulting in the penetration of ULF Pc5 waves to significant lower L values than normal [e.g., Lee et al., 2007]. Subsequently, these penetrated ULF Pc5 standing waves can accelerate the radiation belt electrons in this region via drift resonances, as presented in this study.

5. Summary and Conclusion

During the recovery phase of the geomagnetic storm on 21 October 2001, the Cluster fleet was traveling out-
bound in the inner magnetosphere from south to north near 0900 MLT during 2300–2400 UT. The satellites observed simultaneous periodic modulations in the drifting energetic electrons (~100 keV) and in the bouncing thermal ion species (O\(^+\) at ~4.5 keV and H\(^+\) at ~280 eV) with the same frequency of 3.3 mHz. The magnetic field and electric field measurements showed that the ULF transverse modes revealed a mixture of several dominant wave components, but only the poloidal mode in 3.3 mHz appeared to be a standing wave with an odd harmonic. The Cluster configuration provided an excellent opportunity to investigate the azimuthal wave number m as well as the radial structure of this poloidal standing wave. The 3.3 mHz poloidal standing wave propagated eastward in the azimuthal direction with m = 22 ± 3. The radial extent of this standing wave is about 0.58 R\(_E\), as obtained from the high coherence of the poloidal magnetic field components among the four satellites.

[37] The oscillation periods of the energetic electron fluxes (~100 keV) and the thermal O\(^+\) (~4.5 keV) and H\(^+\) (~280 eV) fluxes are observed at the same time as the period of the poloidal standing wave, strongly indicating the concurrent modulations of the energetic electrons and the thermal ion species by the same wave. Further, we have shown that drifting energetic electrons around 94 keV are satisfied with the drift resonance condition and bouncing thermal O\(^+\) ions around 4.5 keV and H\(^+\) ions around 280 eV are satisfied with the bounce resonance condition. It is confirmed that the energetic electrons around 94 keV are accelerated, most likely due to the drift resonances. To our knowledge, this is the first study to show both energetic particles (radiation belt or ring current population, ~ a few hundreds keV) and thermal ions (background plasma population, ~ a few keV) can be affected by the same ULF standing wave simultaneously in the inner magnetosphere during storm time.

[38] In addition, we observed the supersonic O\(^+\) ions in the inner magnetosphere during this time, of which the number density is ~4 times larger than H\(^+\). This can significantly reduce the local field line eigenfrequency and allow the penetration of ULF Pe5 waves to much lower L region than normally expected. We suggest the supersonic O\(^+\) ion population in the inner magnetosphere during storm time could result in the energetic electron accelerations by the ULF waves in deep region of the radiation belt.

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