Corotating drift-bounce resonance of plasmaspheric electron with poloidal ULF waves

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Abstract: The purpose of this paper is to understand how low energy plasmaspheric electrons respond to ULF waves excited by interplanetary shocks impinging on magnetosphere. It is found that both energy and pitch angle dispersed plasmaspheric electrons with energy of a few eV to tens of eV can be generated simultaneously by the interplanetary shock. The subsequent period of successive dispersion signatures is around 40 s and is consistent with the ULF wave period (third harmonic). By tracing back the energy and pitch angle dispersion signatures, the position of the electron injection region is found to be off-equator at around –32° in the southern hemisphere. This can be explained as the result of injected electrons being accelerated by higher harmonic ULF waves (e.g. third harmonic) which carry a larger amplitude electric field off-equator. The dispersion signatures are due to the flux modulations (or accelerations) of \textquotedblleft local\textquotedblright plasmaspheric electrons rather than electrons from the ionosphere. With the observed wave-borne large electric field excited by the interplanetary shock impact, the kinetic energy can increase to a maximum of 23 percent in one bouncing cycle for plasmaspheric electrons satisfying the drift-bounce resonance condition by taking account of both the corotating drift and bounce motion of the local plasmaspheric electron.

Keywords: drift-bounce resonance; plasmaspheric electron; poloidal mode; ULF wave

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1. Introduction

Sudden plasma density and/or velocity changes in the solar wind, e.g., dynamic pressure pulses or interplanetary shocks will lead to a step-like enhancement of the solar wind dynamic pressure. When such a structure impinges on the Earth’s magnetosphere, the magnetosphere will be suddenly compressed, causing fast magnetosonic mode ULF waves that propagate into the magnetosphere (Wilken et al., 1982; Kepko and Spence, 2003; Hudson et al., 2004; Claudepierre et al., 2009). These fast magnetosonic waves will couple to and thus excite the local standing Alfvén waves through the field line resonance (FLR) process at the day-side magnetosphere around magnetic local noon (Southwood, 1974; Chen L and Hasegawa, 1974; Zhang XY et al., 2010).

It is known that the impingement of interplanetary shocks on Earth’s magnetosphere can trigger/generate various type of waves including harmonic radiations with a few hundreds Hz (Hayashi et al., 1978), fast magnetosonic waves (Wilken et al., 1982; Kepko and Spence, 2003; Hudson et al., 2004; Claudepierre et al., 2009), whistler waves (Park, 1975), EMIC waves (Anderson and Hamilton, 1993), chorus waves (Fu HS et al., 2012), toroidal mode ULF standing waves (Cahill et al., 1990) and both poloidal and toroidal ULF waves (Zong Q-G et al., 2009; Zhang XY et al., 2010) in the geospace. These generated waves can further interact with particles and lead to energetic electron acceleration (Li XL et al., 1993; Zong Q-G et al., 2009; Tan LC et al., 2011) in the radiation belt, and ion acceleration in the ring current region (Zong Q-G et al., 2012).

Nevertheless, the shock-related energetic particle acceleration mechanism is still not fully understood (Baker et al., 2004; Friedel et al., 2002), although very energetic particle acceleration (ions and electrons with energies up to 15 MeV) in the inner magnetosphere due to the impact of an extreme powerful interplanetary shock on 24 March 1991 has been reported (Blake et al., 1992; Vampola and Korth, 1992; Wygant et al., 1994; Looper et al., 1995). In fact, recently, in situ observations of the resonance between energetic electrons and ULF waves (Zong Q-G et al., 2007; Tan LC et al., 2004, 2011) have been reported. Because of the comparable periods between the drift motion of the energetic particles and the ULF oscillations, the drift-bounce resonance interaction (e.g., Southwood and Kivelson, 1981; Hudson et al., 2008; Zong Q-G et al., 2007; Zong Q-G et al., 2009) could be excited to adiabatically accelerate the magnetospheric particles and significantly enhance the radial diffusion coefficient (e.g., Loto‘aniu et al., 2006). An excellent example of the interaction between ULF waves induced by an interplanetary shock and resulting energetic elec-
trons in the magnetosphere has been investigated by Zong Q-G et al., (2009). Zong Q-G et al. (2009) studied the acceleration process of energetic electrons with energy higher than 30 keV in the outer radiation belt November 7, 2004 event. In this case, the acceleration of energetic electrons by poloidal mode ULF waves starts immediately after the interplanetary shock arrival and lasts for at least a few hours. Zong Q-G et al. (2012) also investigated the response of plasma and energetic ions to the interplanetary shock impact, and the contribution to the ion acceleration of both poloidal and toroidal electric fields carried by ULF waves. Furthermore, it is suggested that drift resonance with poloidal ULF waves (Zong Q-G et al., 2009) or compressional poloidal mode ULF waves (Tan LC et al., 2011) induced by interplanetary shock impact will lead to fast electron acceleration and formation of the new radiation belt (Zong Q-G et al., 2011).

Recently, on the other hand, Zong Q-G et al. have reported that low-energy ring current O+ ions (several to tens of keV) may be accelerated or decelerated by ULF standing waves via drift-bounce resonance during storm times (Yang B et al., 2010, 2011a, b; Zong Q-G et al., 2011, 2012). It has also been suggested that the ring current ions (especially H+) having a free energy source can produce ULF waves through drift-bounce resonance in the inner magnetosphere (e.g., Hughes et al., 1978; Glassmeier et al., 1999; Wright et al., 2001; Ozeke and Mann, 2008).

Plasma ion accelerations in the field-align direction due to the interplanetary shocks impact have been addressed by (Olson and Lee, 1983; Yue C et al., 2016). It is shown that the acceleration in the field-align direction can be estimated with the proportional to the power of local magnetic field strength due to the magnetic field compressions caused by the interplanetary shock impinge on the magnetosphere (Yue C et al., 2016). Also, it is noticed that plasma electron can be heated by the interplanetary shock impact, however, this process can not be explained by the $E \times B$ drift and the above mentioned the adiabatic acceleration (Yue C et al., 2016).

A schematic overview of the wave power for various waves (ULF, VLF) and the drift, bounce and gyro frequency of electrons in the inner magnetosphere are shown in Figure 1. Usually lower frequency waves contain more wave power and the wave power scales roughly inversely with the wave frequency (Lanzerotti and Southwood, 1979). The overlap area between the wave frequency and the drift, bounce and gyro frequency of electrons indicates that wave-electron resonance may occur. Figure 1 is just a schematic overview, the details of wave-particle resonant condition should consider the wave frequency and wave vector, wave harmonic number, the location and the particles' pitch angle distribution etc.

In this paper, we shall investigate how plasmaspheric electrons (<100 eV) respond to the interplanetary shock impact and the interactions between plasmaspheric electrons (<100 eV) and poloidal ULF waves in the inner magnetosphere. The observations presented show that poloidal ULF waves excited by interplanetary shock impact can accelerate and heat the plasmaspheric electrons.
al direction $a$ is parallel to the cross product of the $p$ and the spacecraft position vector, and the radial direction $r$ completes the triad. As shown in Figure 2, Cluster satellites lied on the morning side (MLT~10.2) of the magnetosphere ($L$=6.6) at that time and observed ULF waves induced by the interplanetary shock impacting on the magnetosphere, the amplitude of the electric field is ~50 mV/m.

The interplanetary shock arrival time is marked by the vertical dashed line. As shown in Figure 2, the electrons (3 eV to 500 keV) were simultaneously accelerated or heated with the shock arrival, the rapid electron acceleration or heating could be directly correlated with the impact of the interplanetary shock on 25 September.
As reported by Tan LC et al. (2011), during this event, magneto- 
spheric ULF waves have been excited with a wave number \( \approx 3 \) and 
consequently relativistic electrons (up to MeV electrons) are accel-
erated by those ULF waves with a time scale of a few hours. In this 
paper, we shall focus on how the excited ULF waves interact with 
plasmaspheric electrons (<100 eV).

In order to examine how plasmaspheric electrons (<100 eV) in the 
inner magnetosphere response to the interplanetary shock im-
 pact in detail, representative electron pitch angle distributions for 
fourteen energy channels ranging between 5 and 72.5 eV are giv-
en in Figure 3.

As we can see from Figure 3, one outstanding and surprising fea-
ture is electron pitch angle dispersion with the field-aligned (0°) 
electron observed first, and the anti-field-aligned (180°) electron 
observed last immediately after the interplanetary shock arrival. 
Such a pitch angle dispersion can be clearly seen for seven en-
ergy channels from 6 to 19.9 eV. Above 19.9 eV, one can see the 
electron pitch angle oscillate between (0°) and (180°), no clear 
pitch angle dispersion signature can be seen.

The multi dispersions are marked in black dashed lines for easy 
distinguishing. It should be noticed here that the occurring peri-
od of successive dispersion signatures is around 40 s and in con-
sistence with the ULF wave period. Thus, these multi-dispersions 
may be the results of modulation by ULF wave oscillations.

Figure 3. Pitch angle distributions of low energy electron in the inner magnetosphere response to the interplanetary shock impact. From top to 
bottom: representative electrons with pitch angle distributions for fourteen energy channels ranging between 5 and 72.5 eV.
The pitch angle dispersion phenomena is further confirmed by the energy dispersion shown in Figure 4. The multiple energy dispersions appear in the parallel (Figure 4a) and anti-parallel (Figure 4c) direction almost simultaneously after the interplanetary shock arrival at 20:25:10 UT.

With both the pitch angle (Figure 3) and energy (Figure 4) dispersion signatures, the location of the electron injection (possibly acceleration location) can be estimated by using the method of the time of flight (Zong Q-G et al., 2001; Korth et al., 2004). Considering two electrons with different pitch angles at the same energy, the one with smaller pitch angle would precede the one with larger pitch angle. However, it should be noted that particle’s speed along the field line will be changed when the amplitude of the magnetic field changes because of the conservation of the first adiabatic invariant (Zong Q-G et al., 2012).

The energy dispersions in the parallel direction appeared earlier than those in the anti-parallel direction, the first two dispersion signatures lead about 32.6 s and the third signature leads about 30.3 s. The electron with an energy of several eV travels from the equator to its mirroring point (or vice versa) in a quarter of its bounce period. Assuming that the electrons of different energy bounced from the same source region and reached the spacecraft, the reaching time delay can be calculated using the dipole field model (e.g., Roederer, 1970). This is basically consistent with the observed lead time of dispersion (about 35 s). The occurring period of successive dispersion signatures is around 40 s and in consistence with the ULF wave period (third harmonic, see next section), indicating these dispersion signatures were due to the flux modulations (or accelerates) of “local” (plasmaspheric, rather than the electron from the Earth’s ionosphere) electrons by ULF waves. Further analysis shows that electrons with energies of several eV satisfied the drift-bounce resonance condition in this case.

As labeled at the bottom of Figure 2, the Cluster spacecraft were located in the the northern hemisphere (~37.5° MLAT, ~10 MLT). Tracing back both the electron’s pitch angle and energy disper-

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**Figure 4.** Electron energy dispersion. Top panel: electron spectrogram of flux ratio of parallel direction to omni-direction; middle panel: electron spectrogram of flux ratio of perpendicular direction to omni-direction; bottom panel: electron spectrogram of flux ratio of anti-parallel direction to omni-direction. The shock arrival time is marked by the vertical dashed line.
tion signatures, the location of the electron injection can be estimated at around -32° of the southern hemisphere, as can be seen in Table 1. Thus, the acceleration region of the observed plasma electron is located at southern hemisphere of the same $L$-shell.

Table 1. Electron Source Location

| Location(Lat.) | Injection Time (UT) | Interval (sec) |
|----------------|--------------------|----------------|
| Pitch angle dispersion | -29° | 20:25:05 | 46 |
| Energy dispersion | -35.2° | 20:25:11 | 42 |

Different with MeV electrons (Zong Q-G et al., 2009) and ring current ions (Zong Q-G et al., 2012) (for which the acceleration locations are found to be near the equator region), the location of these low energy electrons is estimated at around -32° off the southern hemisphere for both the pitch angle and energy dispersion signatures. The obtained injection time 20:25:08 UT (Table 1) is in agreement with the arrival time of the interplanetary shock.

2.2 The Variation of Electron Spectra

So as to examine the plasmaspheric electron flux variation, electron spectra (Figure 3 and Figure 4) obtained by PEACE instrument with 4 sec time resolution for two different time intervals immediately after the shock arrival (20:25:30 UT, blue), and after the first dispersion signal (20:26:05 UT, red) are given in Figure 5. As we can see from Figure 5, immediately after the interplanetary shock impact at 20:25:30 UT, the electron spectrum was still flat. However, after the first pitch angle and energy dispersion at 20:26:05 UT, there are well developed double-peak structures in the electron spectrum; one peak is between 5 eV and 6 eV, the other peak is between 15 eV and ~20 eV.

As discussed in (Zong Q-G et al., 2012), the energy variation of particles in the inner magnetosphere can be expressed as (Northrop, 1963)

$$\dot{W} = qE_y \cdot v_y + qE_x v_x + \mu \frac{\partial B_z}{\partial t},$$

where $\dot{W}$ is the rate of energy change, $E_x$ is the perpendicular component of electric field, $v_y$ is the gradient and curvature drift velocity, $E_y$ and $E_x$ are the parallel component of electric field and particle velocity, and $B_z$ is the compressional component of the magnetic field.

This equation suggests that the particle energy variation in the inner magnetosphere can be divided into three parts: the first term on the right hand side represents the acceleration of the drifting particles caused by the perpendicular electric field, the second term is due to the effect of parallel electric field, and the third term is the contribution of the compressional component of the magnetic field. The parallel electric field is usually neglected since it can not be built up in a collisionless plasma environment. Thus, when an interplanetary shock impinges on the magnetosphere, the energetic electron (Zong Q-G et al., 2009) and plasma ions (Zong Q-G et al., 2012) can be accelerated by the ULF waves carried electric field.

When an interplanetary shock impinges on the magnetosphere, the magnetosphere will be compressed. Due to the size of the magnetosphere and the Alfvén speed, the interaction time scale is around ~1 min. Thus, it is a reasonable assumption that the first adiabatic invariant is conserved during an interplanetary shock impact (Wilken et al., 1986).

In order to consider the particle acceleration contributed by the compressional component of the magnetic field (the third term of Eq. (1)), the variation of the magnetic field due to the interplanetary shock compression should be considered. The energy change of particles can be estimated by using the third term in Eq. (1) assuming a conserved magnetic moment, the energy change of particles are energy dependent.

As we can see from Figure 2, after the shock compression, all magnetic field components ($B_x$, $B_y$, $B_z$) changed little, the amplitude of magnetic field ($B_z$) even turned to decrease. This leads the $\partial B_z/\partial t$ term was rather small and can be ignored. Thus, the shock compression has a limited effect as reflected on electron spectra both in Figure 5 and Figure 2. This implies that the electric field carried by ULF waves have a major contribution to the plasmaspheric electron heating/acceleration after the interplanetary shock arrival.

3. Discussion and Interpretation

In this paper, we have studied the interaction between low energy electrons (<100 eV) and poloidal ULF waves in the inner magnetosphere or plasmaspheric region and investigated how plasmaspheric electron (<100 eV) in the inner magnetosphere respond to the interplanetary shock impact. The observations presented show that poloidal ULF waves excited by interplanetary shock impact can heat and accelerate low energy electron (<100 eV) in the radiation belt region.

For the particle acceleration in the parallel direction due to the impact of IP shocks (Olson and Lee, 1983; Yue C et al., 2016), performed a study to estimate the magnetic field compressions associated with sudden impulses and have shown that the plasma average energy in the parallel direction is proportional to the power of local magnetic field strength if the first and second adiabatic invariants are conserved (Yue C et al., 2016).
Besides the $E \times B$ drift and adiabatic acceleration, what are the other mechanisms responsible to the electron acceleration? Addressing the above issues would contribute to a better understanding of the responses of the inner magnetosphere to IP shock impacts.

3.1 The Correlation Between the Electron and ULF Waves

To quantify the correlation between observed ULF waves generated by the interplanetary shock impact and plasmaspheric electrons, the wavelet coherence (Grinsted et al., 2004) between the electric field components and the electron flux (the top three panels for poloidal mode, the bottom three panels for toroidal mode) are calculated and shown in Figure 6. The poloidal and toroidal electric field and magnetic fields are obtained by decomposing the Cluster magnetic field and electric field into a MFA coordinate.

Figure 6. Continuous wavelet power spectrum of both ULF poloidal and toroidal electric field and the squared wavelet coherence between the poloidal mode and toroidal mode electric field and parallel (pitch angle <45°) electron flux at 16.335 eV and perpendicular (pitch angle >45°) electron flux.
system (Takahashi et al., 1990).

As shown in Figure 6, the top panel is the continuous wavelet power spectrum of the azimuthal electric field (ULF poloidal mode), Panels 2 and 3 are the squared wavelet coherence between the azimuthal electric field and parallel (pitch angle <45°) electron flux at 16.335 eV and perpendicular (pitch angle >45°) electron flux. Panel 4 is the wavelet power spectrum of the radial electric field (ULF toroidal mode), Panels 5 and 6 are the squared wavelet coherence between the radial electric field and parallel (pitch angle <45°) electron flux at 16.335 eV and perpendicular (pitch angle >45°) electron flux.

Although the poloidal (Panel 1) and toroidal (Panel 4) waves have similar power intensity, the coherences are quite different. Very high coherence (above 0.9) appears in the poloidal mode more significant than the toroidal mode after the shock arrival at 20:25:15 UT. It should be noted here that the ULF wave band which highly correlated with parallel (pitch angle <45°) electron flux is among 32 to 64 s, whereas the ULF wave band which is highly correlated with the perpendicular (pitch angle >45°) electron flux is around 32 s.

The duration of high coherence for the poloidal mode is longer than that for the toroidal mode. In the wavelet coherence analysis of Figure 6, the black arrows pointing to the left and right represent that the phase angles are 180° and 0°, respectively. The phase angles between the poloidal mode electric field and both the parallel (pitch angle <45°) electron flux and the perpendicular electron (pitch angle >45°) flux are nearly 0°, indicating the positive correlation between the poloidal mode ULF waves and the electron flux. However, on the other hand, the phase angles between the toroidal mode electric field and both the parallel (pitch angle <45°) electron flux and the perpendicular (pitch angle >45°) electron flux are around 180°, indicating the anti-correlation between the toroidal mode ULF waves and the electron flux.

These results indicate the strong correlation between both the poloidal ($E_r$) and toroidal ($E_\theta$) mode ULF wave electric field and the plasmaspheric electrons. The close correlation between the ULF wave electric field $E_r$ and $E_\theta$ oscillations and the electron flux suggests that the shock-induced ULF waves had strong heating/ac- celeration effects on the plasmaspheric electrons. The correlation between the observed ULF waves and electrons above 19.9 eV are much weaker comparing to that of electrons at 16.335 eV (not shown here).

### 3.2 Electron-ULF Wave Resonance

The strong correlation between both ULF waves and plasmaspheric electron can be explained by the framework proposed by Southwood and Kivelson (Southwood and Kivelson, 1981; Southwood and Hughes, 1982). In their work, particles experience the electric field carried by ULF waves during their drift-bounce motions in the inner magnetosphere and these particles’ energy can be accordingly changed depending on their paths.

The condition of the resonance between the particle and the ULF waves-the bounce drift resonance can be determined by

$$\Omega - m \cdot \omega_d = N \cdot \omega_b,$$  \hspace{1cm} (2)

where $N$ is an integer (normally ±1, ±2 or 0), $m$ represents the azimuthal wave number of the ULF wave, and $\Omega$, $\omega_d$ and $\omega_b$ are the wave frequency, the drift and bounce frequencies of the particle, respectively. For a particle with given energy in the inner magnetosphere, the drift and bounce frequencies of the particle ($\omega_d$ and $\omega_b$) can be computed at a given L-shell, thus, the resonance energy can be determined if the wave frequency ($\Omega$) and the wave number ($m$) are known.

For a plasmaspheric electron with an energy of a few eV in the inner magnetosphere, the drift frequency of the electron is much less than the bounce frequency ($\omega_d \ll \omega_b$), thus, the bounce-drift resonance between the plasmaspheric electron and the ULF waves becomes the bounce resonance:

$$\Omega = N \cdot \omega_b.$$  \hspace{1cm} (3)

It is worth pointing out that the resonant condition of the bounce resonance is independent of wave number, which implies that plasmaspheric electron could resonant with either poloidal mode or toroidal mode ULF or both. As shown in Figure 6, the flux variations of plasmaspheric electron are indeed correlated with both poloidal mode and toroidal mode ULF waves. The high correlation is mainly in the period range from 30 s to 60 s. Assuming that $L=7$, particle energy is from 6 eV to 20 eV, equatorial pitch angle is 30°, the bounce period is from 69 s to 137 s. The bounce period of the cold electrons is almost two times of the wave period in high correlation, which indicates that these cold electrons satisfy the drift-bounce resonant condition of $N=2$. The toroidal mode has time varying radial electric field and azimuthal magnetic field, and the poloidal mode has azimuthal electric field and radial magnetic field perturbations (Zong Q-G et al., 2009, 2012; Zhang XY et al., 2009), although large-scale compressional waves may also contribute to the azimuthal electric field oscillations to some extent (Hudson et al., 1997). When the geomagnetic field is in the noon-midnight asymmetry under the solar wind impact, the drift velocity of the cold electrons will have a component in the radial direction, but the electron energy will be changed after a drifting period (about 1 day). However, the cold electrons are rapidly accelerated/heated after the drift-bounce resonance with ULF waves in Figure 7, which suggests that the acceleration/heat of the cold electrons are from the interaction with poloidal waves but not toroidal waves.

Figure 7 illustrated a bounce resonant plasmaspheric electron motion in the rest frame of (a) fundamental, (b) second, and (c) third harmonic standing mode wave, the dashed lines represent the electron trajectory. Plasmaspheric electron are moving in the trajectory represent by dashed lines in the wave rest frame, which is the same direction as the electric field $E_r$ carried by the poloidal ULF waves. Therefore, the negative (positive) $E_r$ would accelerate (decelerate) plasmaspheric electron when it is resonant with ULF waves, which agrees with our observations (Figure 3 and Figure 4) very well.

It should be noted that for most plasmaspheric electrons, the acceleration and deceleration processes would cancel out the energy gain within one wave period. As we can see from Figure 7, electron resonant with fundamental mode would cancel out the
energy gain within one wave period, only those plasmaspheric electrons resonant second or third harmonic ULF waves can gain energy very efficiently. The energy change of resonant particles with ULF waves can be expressed as

\[
\frac{dw}{dt} = qE_a V_d;
\]

where \( \frac{dw}{dt} \), \( E_a \), and \( V_d \) are the rate of the particle energy, the poloidal wave azimuthal electric field, and the particle velocity in the wave frame respectively.

More and more observations have revealed the importance of ULF waves in the dynamics of radiation belt electrons and ring current ions. This study reports that cold plasmaspheric electrons also could be accelerated/heated through the drift-bounce resonance with ULF waves, which provides a new acceleration mechanism for the low energy plasmaspheric electrons and may also explain the thinning of the plasmasphere. In another ongoing work, we found that low-energy (15 eV-200 eV) plasmaspheric electron fluxes could be enhanced up to several times by ULF waves at the plasmaspheric boundary layer using Van Allen Probes data, and implied that colder electrons (~eV), out of the measurements of Van Allen Probes, also can be affected by ULF waves. This new mechanism provides a new way to understand the plasmaspheric electron acceleration and heating.

4. Conclusion

The objective of this paper is to understand how plasmaspheric electrons response to the ULF waves excited by the impinge on magnetosphere of interplanetary shocks. Main results obtained in this paper can be summarized as fellows:

(1) Both plasmaspheric electron energy and pitch dispersion signatures generated by the interplanetary shock impinge on the magnetosphere are observed.

(2) Tracing back signatures from both energy and pitch dispersion, the position of the electron injection region is found to be off-equator-at around -32° of the southern hemisphere. This can be explained as that these injected electrons are accelerated by higher harmonic ULF waves (e.g. third harmonic) which having larger amplitude electric field off-equator. This is different with MeV electrons (Zong Q-G et al., 2009) and ring current ions (Zong Q-G et al., 2012) (which acceleration locations are found to be around the equator region).

(3) The occurring period of successive dispersion signatures is around 40 s and in consistence with the ULF wave period (third harmonic), indicating these dispersion signatures were due to the

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**Figure 7.** Illustration of the bounce resonance (after Southwood and Kivelson (1982)) for (a) fundamental, (b) second, and (c) third harmonic standing mode. The dashed lines represent the electron motion in the rest frame of the wave.
flux modulations (or accelerations) of “local” (plasmaspheric, rather than the electron from the Earth’s ionosphere) electrons by ULF waves.

(4) The duration of high coherence for the poloidal mode is longer than that for the toroidal mode. The phase angles between the poloidal mode electric field and both the parallel (pitch angle <45°) electron flux and the perpendicular (pitch angle >45°) electron flux are nearly 0°, indicating the positive correlation between the poloidal mode ULF waves and the electron flux. On the other hand, the phase angles between the toroidal mode electric field and both the parallel (pitch angle <45°) electron flux and the perpendicular (pitch angle >45°) electron flux are nearly 180°, indicating the anti-correlation between the toroidal mode ULF waves and the electron flux. The close correlation between the ULF wave electric field $E$ and $E_r$ oscillations and the electron flux suggests that the shock-induced ULF waves had strong heating/acceleration modulations on the plasmaspheric electrons.

In summary, plasmaspheric electron in the inner magnetosphere can be accelerated by ULF waves excited by an interplanetary shock impinging on Earth’s magnetosphere. This mechanism requires that plasmaspheric electron satisfies the bounce resonance condition with poloidal mode ULF waves. Both observations and calculations show that plasmaspheric electron (~10 eV) can be accelerated very efficiently mainly by poloidal mode ULF waves.

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