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Excitation of poloidal standing Alfvén waves through drift resonance wave-particle interaction

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[1] Drift-resonance wave-particle interaction is a fundamental collisionless plasma process studied extensively in theory. Using cross-spectral analysis of electric field, magnetic field, and ion flux data from the Van Allen Probe (Radiation Belt Storm Probes) spacecraft, we present direct evidence identifying the generation of a fundamental mode standing poloidal wave through drift-resonance interactions in the inner magnetosphere. Intense azimuthal electric field (E_ϕ) oscillations as large as 10mV/m are observed, associated with radial magnetic field (B_r) oscillations in the dawn-noon sector near but south of the magnetic equator at L∼5. The observed wave period, E_ϕ/B_r ratio and the 90° phase lag between B_r and E_ϕ are all consistent with fundamental mode standing Poloidal waves. Phase shifts between particle fluxes and wave electric fields clearly demonstrate a drift resonance with ∼90 keV ring current ions. The estimated earthward gradient of ion phase space density provides a free energy source for wave generation through the drift-resonance instability. A similar drift-resonance process should occur ubiquitously in collisionless plasma systems. One specific example is the "fishbone" instability in fusion plasma devices. In addition, our observations have important implications for the long-standing mysterious origin of Giant Pulsations. **Citation:** Dai, L., et al. (2013), Excitation of poloidal standing Alfvén waves through drift resonance wave-particle interaction, *Geophys. Res. Lett.*, *40*, 4127–4132, doi:10.1002/grl.50800.

1. Introduction

[2] Ultralow frequency (ULF) oscillations of geomagnetic field lines with strong magnetic field perturbations in the radial direction (B_r) and electric field perturbations in the azimuthal direction (E_ϕ) are known as poloidal waves. Charged particles trapped in magnetosphere undergo a longitudinal drift motion around the Earth induced by the magnetic curvature and gradient. The E_ϕ of poloidal waves is aligned with the drift motion of particles, allowing a strong wave-particle resonance interaction. The resonance associated with the drift motion is considered important for dynamics of the ring current [*Southwood*, 1976; *Sibeck et al.*, 2012] and radiation belt particles [*Schulz and Lanzerotti*, 1974; *Elkington et al.*, 2003].

[3] Substantial theoretical work has been devoted to the resonance processes associated with drift motion [*Southwood*, 1976; *Southwood and Kivelson*, 1981; *Chen and Hasegawa*, 1988; *Cheng*, 1991]. The well-known resonance condition is $\omega_{\text{wave}} - m\omega_d = N\omega_b$, where ω_{wave} and m are the wave frequency and azimuthal wave number, respectively, ω_d (ω_b) represents the frequency of particles' drift (bounce) motion, and N is the number of wavelengths across which the particles drift in the wave rest frame during one bounce motion. Drift resonance ($N = 0$) is the special case where the particles drift at the wave propagation velocity and feel steady acceleration or deacceleration by the wave's E_ϕ. Drift resonance ($N = 0$) and bounce resonance ($N = \pm 1$) are shown in theory to be the dominant cases of resonance. The type of resonance that could occur is constrained by the symmetry of the wave E_ϕ with respect to the magnetic equator. As illustrated in Figure 1, drift resonance should occur in association with a fundamental (symmetric) mode while bounce resonance occurs with a second-harmonic (antisymmetric) mode [*Southwood*, 1976; *Southwood and Kivelson*, 1982].

[4] Previous spacecraft observations have overwhelmingly reported excitations of second-harmonic standing Alfvén waves [*Singer et al.*, 1982] and evidence of bounce resonance [*Hughes et al.*, 1978; *Takahashi et al.*, 1990]. Drift-resonance wave-particle interaction with fundamental

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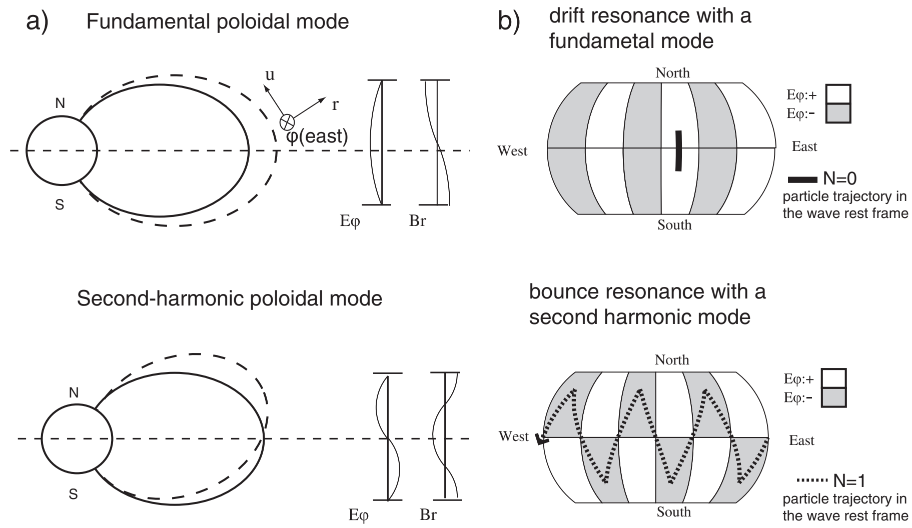

Figure 1. Schematics of standing poloidal Alfvén waves and the resultant wave-particle resonance interactions. Figures are based on *Southwood and Kivelson* [1982] and *Yeoman and Wright* [2001]. (a) Oscillations of geomagnetic field lines in a fundamental mode (upper panel) and second-harmonic (bottom panel) mode of a standing poloidal Alfvén waves in the magnetosphere. (b) Illustrations of resonant particles' trajectory during the drift resonance (upper panel) with a fundamental mode and bounce resonance (bottom panel) with a second-harmonic mode.

mode poloidal waves, however, has never been unambiguously identified in observations. The existence of the fundamental mode of standing poloidal waves was inferred from studies of ground observations of Giant Pulsations [*Green*, 1979; *Thompson and Kivelson*, 2001], which are quasi-monochromatic ULF magnetic pulsations generally believed to result from either symmetric or antisymmetric standing oscillations of geomagnetic field lines. Only recently have observations started to identify the fundamental (symmetric) mode of poloidal waves in space [*Takahashi et al.*, 2011; *Takahashi et al.*, 2013] and reveal their correspondence to Giant Pulsations on the ground [*Glassmeier et al.*, 1999; *Takahashi et al.*, 2011]. An earthward gradient in the phase space density of ring current ions can provide a source of free energy to excite fundamental mode poloidal waves [*Southwood*, 1976]. The density of ring current ions is strongly affected by plasma injections due to convection electric fields [*Wygant et al.*, 1998]. Although an earthward phase space density (PSD) gradient is thought to be unlikely when injections are adiabatic [*Axford*, 1969], there has been no observation investigating this free energy at times when waves are also seen.

[5] Critical for identifying the drift-resonance wave-particle interaction is the measurement of the azimuthal electric field near the magnetic equator in the appropriate region. Measurements of **E** and **B** enable an identification of both the nodal structure in the magnetic equator and the mode of the waves [*Takahashi et al.*, 2011; *Glassmeier et al.*, 1999]. Physically, the drift resonance ($N = 0$) is the interplay between the wave E_ϕ and the particle drift motion mostly near the magnetic equator. At the resonance energy, the particle flux is inphase or exactly antiphase, depending on the sign of the PSD radial gradient, with E_ϕ [*Southwood and Kivelson*, 1981]. Near the resonance energy, particle fluxes have their phase shifted toward +90° or –90° with respect to E_ϕ [*Southwood and Kivelson*, 1981]. These features allow an identification of drift resonance and the proper PSD gradient needed for the instability to grow.

[6] Utilizing measurements from the Van Allen Probes (Radiation Belt Storm Probes (RBSP)) [*Mauk et al.*, 2012], we present direct evidence for the fundamental poloidal mode in drift resonance with ~ 90 keV ring current ions in this paper. In addition, we discuss the connection of our observations to the fishbone instability in lab plasma and to Giant Pulsations detected on the ground.

2. RBSP Observations

[7] The RBSP mission consists of two spacecraft (RBSP-A and RBSP-B) in low inclination, elliptical orbits around the Earth. During our observations, RBSP spacecraft were located near the magnetic equator in the Southern Hemisphere at a radial distance of ~5 Re, near the 5.8 Re apogee. The observations consist of combined measurements from the Electric Field and Waves Suite (EFW) [J. R. Wygant et al., The electric field and waves instruments on the Radiation Belt Storm Probes Mission, *Space Science Reviews*, 2013, in press], Electric and Magnetic Field Instrument Suite and Integrated Science [*Kletzing et al.*, 2013], and Energetic Particle, Composition, and Thermal Plasma Suite [*Blake et al.*, 2013; *Funsten et al.*, 2013; *Spence et al.*, 2013] instruments onboard RBSP.

2.1. Fundamental Mode of Standing Poloidal Waves

[8] Figure 2a shows band-pass waveforms of **E**, **B** and ion fluxes from RBSP-A from 22:00 universal time (UT) to 22:30 UT on 23 October 2012. We identify several important features during this 30 min interval. First, **E** and **B** are highly monochromatic with a dominant poloidal wave component in E_ϕ and B_r. The observations of 21.25 wave cycles in 30 min corresponds to a wave period of ~84 s. We obtain the three dimensional electric field from the **E•B**=0 assumption. This method is good when the angle (~30°–40° in this event) between the magnetic field line and the spacecraft spin plane is larger than 15°. The unusually large amplitude

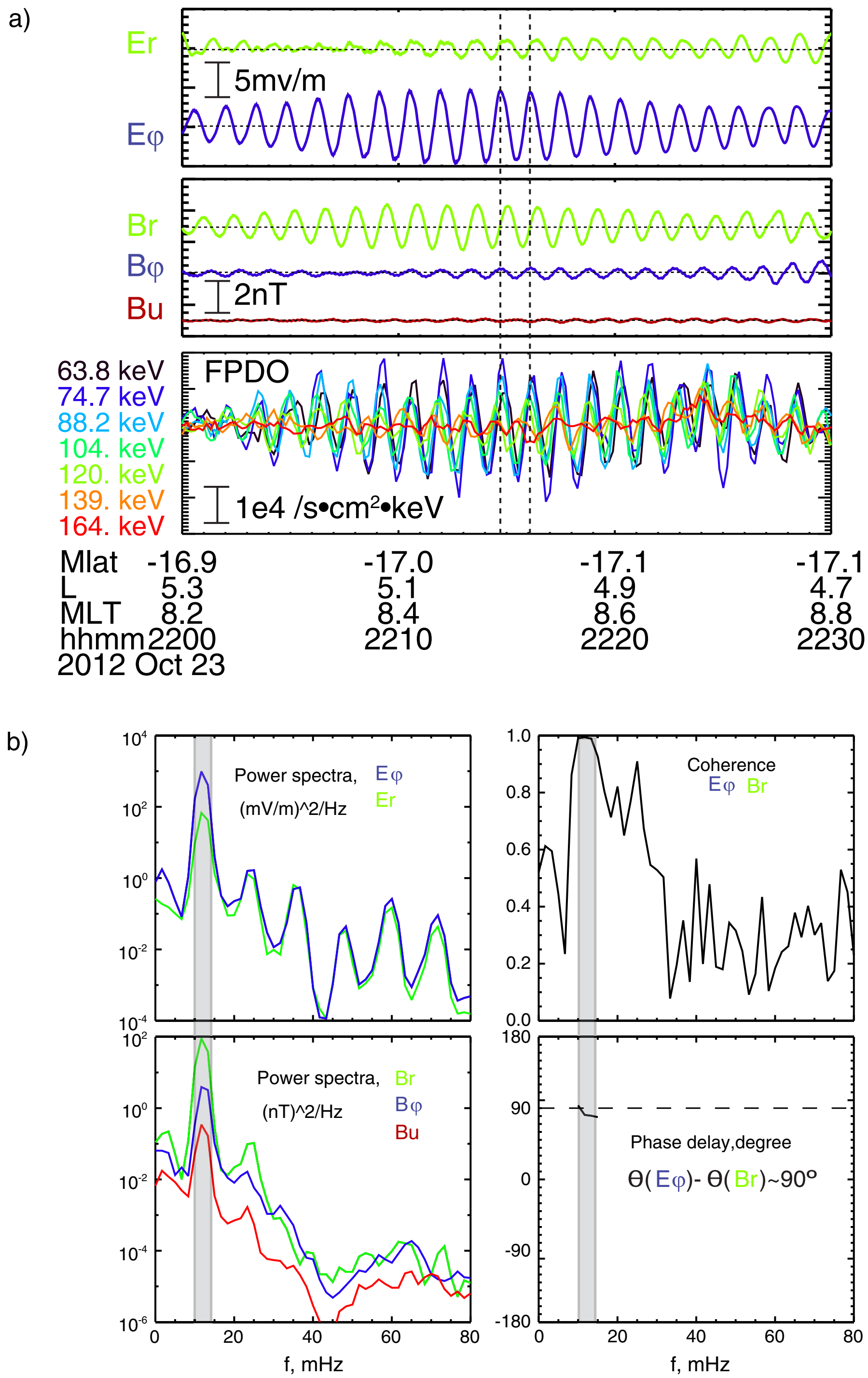

Figure 2. Observations of the electric field, magnetic field, and ion differential fluxes by RBSP-A from 22:00 UT to 22:30 UT on 23 October 2012. (a) Band-pass waveforms (a 22 s running average minus a 600 s running average) of **E**, **B**, and ion differential flux. **E** and **B** are in a magnetic field-aligned coordinate system (see Figure 1a), with ϕ being azimuthally eastward, u being along the 500 s running average magnetic field line, and r completing the orthogonal coordinates and pointing radially outward. (b) Power spectra of wave **E** and **B**, the coherence and phase difference between E_ϕ and B_r, averaged from an ensemble of running windows of 600 s with 200 s overlap between individual windows.

of E_ϕ (10 mV/m) suggests an antinode for E_ϕ in the magnetic equator. Second, the phase of E_ϕ is $\sim 90^\circ$ ahead of B_r, which is generally a signature of standing waves along the geomagnetic field line. Third, RBSP-A also observed small but finite E_r and B_ϕ. This is expected since poloidal waves are coupled to toroidal components when there is finitely small azimuthal wavelength in a radially nonuniform plasma [*Mann and Wright*, 1995]. Finally, the ion fluxes from 63.8 to 164 keV oscillated at the same period as the waves. These fluxes exhibit an energy-dependent phase with respect to E_ϕ. These phase shifts are later shown to be characteristics of drift resonance.

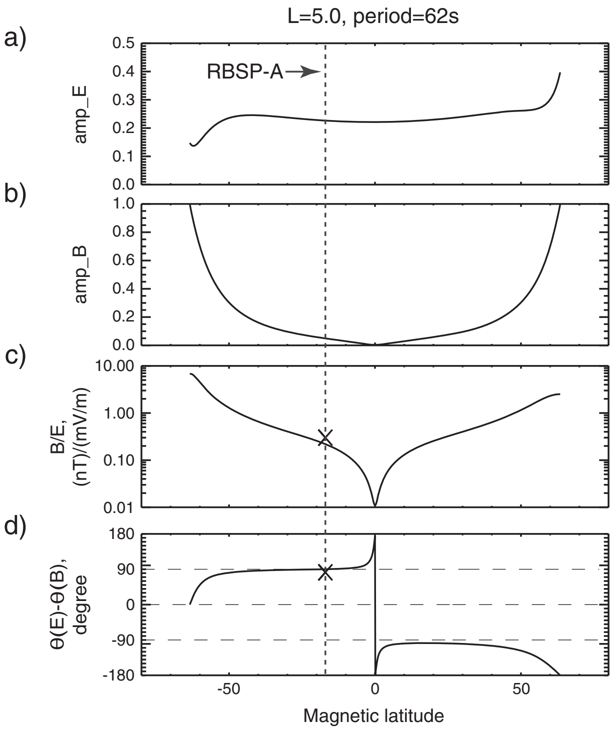

Figure 3. Model results of a fundamental mode standing poloidal wave at the $L = 5$ of the Earth's dipole field. (a) The amplitude of E_ϕ along a geomagnetic field line. (b) The amplitude of B_r along a geomagnetic field line. (c) The ratio B_r/E_ϕ. (d) The phase delay from B_r to E_ϕ, $\theta(E_\phi)$-$\theta(B_r)$

[9] Figure 2b presents the spectral analysis confirming the qualitative inspection of the waveform in Figure 2a. Most of the wave power is concentrated around 12 mHz (~84s). The dominant wave power is in E_ϕ and B_r. E_ϕ is highly coherent with B_r at the frequency of 12 mHz. As expected from inspection of the waveform, E_ϕ led the phase of B_r by about 80°–90°.

[10] All of these wave characteristics are indicative of a fundamental mode standing poloidal wave. We calculated the frequency, amplitude, and relative phase of E_ϕ and B_r of a fundamental poloidal mode using a generalized model of Alfvén standing waves in the magnetosphere [*Cummings et al.*, 1969; *Takahashi et al.*, 2011] with a realistic ionosphere boundary condition described in *Newton et al.* [1978]. We used height-integrated conductivity of 5.4 mho at southern ionosphere and 2.0 mho at northern ionosphere. For the density model, we assumed ions are all protons and adopted a power-law density variation [*Cummings et al.*, 1969] with the power index of 1.0 [*Takahashi and Denton*, 2007] and an equatorial number density of $6.4cm^{-3}$ at $L = 5$. The value of the equatorial density (6.4cm^{-3}) is the mapped value from the density (~7cm^{-3}) inferred from the upper-hybrid resonance line and spacecraft potential at L~5 where the wave amplitude is largest (see Figure S1 in the supporting information).

[11] The model results shown in Figure 3 are entirely consistent with the observations at the magnetic latitude of RBSP-A. The wave period for the fundamental poloidal eigenmode at $L = 5$ is ~62 s, consistent with the observed value 84 s. The model value of wave period is based on a mass density of 100% protons. If we include effects of a small component of heavy ions (O+/H+~0.06 from 25 eV to 2 keV as measured by Helium, Oxygen, Proton, and Electron Mass Spectrometer) or finite pressure gradient, the period is even closer to the observation. The magnetic equator is an antinode of E_ϕ and a node of B_r for the fundamental mode as shown in Figures 3a and 3b. The magnetic latitude of RBSP-A is indicated by a vertical dash line. The observed values are indicated by the symbol "X". The model result of the magnitude ratio $|B_r|/|E_\phi|$ ~0.25 nT/(mV/m) is consistent with the observed value (~0.3 nT/(mV/m)). E_ϕ leads the phase of B_r by ~90° in the Southern Hemisphere in the fundamental mode as illustrated in Figure 3d, exactly as seen in the data (Figure 2). The phase lag between E_ϕ and B_r will be opposite in the case of a second-harmonic standing wave.

2.2. Drift-Resonance Instability

[12] Ring current ions in drift resonance with a fundamental mode of standing poloidal Alfvén waves maintain a steady contact with wave E_ϕ for a finite interaction time. The first adiabatic invariant $\mu \sim v_\perp^2/B$ is conserved in the resonance. Resonant ions encountering westward E_ϕ gain energy from waves and **E**×**B** drift radially inward. Conversely, resonant ions encountering eastward E_ϕ lose energy to waves and **E**×**B** drift radially outward. If there are more particles close to the Earth than farther out, the waves will have a net gain of energy from the particles and grow in magnitude [*McPherron*, 2005]. The behavior of ions in a fundamental mode of standing Alfvén waves has been well investigated in theory [*Southwood and Kivelson*, 1981]. The first and second particle invariants are conserved in the drift resonance [*Southwood and Hughes*, 1983]. From the Liouville's theorem, we have $\delta f = -\frac{\partial f}{\partial L}|_{\mu,J}\delta L$, where δL is the first-order change in the particles' L shell value. Considering the 90° pitch angle ions near the magnetic equator, the particles move in L at a rate of $\dot{L} = \mathbf{E} \times \mathbf{B}/B^2R_E$. Integrating back in time similarly as in *Southwood and Kivelson* [1981], we have $\delta L = iE_\phi/(\omega - m\omega_d)BR_E$ for nonresonant ions and $\delta L = TE_\phi/BR_E$ for resonant ions, where $E_\phi = E_{\phi o}\exp i(m\phi - \omega t)$, positive E_ϕ is eastward and T is the interaction time for particles strictly in resonance. So the resonant ion oscillations are inphase or strictly antiphase with E_ϕ, depending on the sign of the PSD radial gradient [*Southwood and Kivelson*, 1981]. Nonresonant ions close to the resonant energy have their phase shifted toward +90° or –90° with respect to E_ϕ. In the presence of a small wave growth or finite waveband, the transition of the E_ϕ-δf phase relation from the case of resonance (inphase or antiphase) to the case of nonresonance (±90° out of phase) is continuous. These phase relations between oscillating ions and wave E_ϕ are used to identify the drift resonance and infer the corresponding PSD gradient.

[13] To identify the drift resonance, we calculated the coherence and the phase delay between ion fluxes and E_ϕ as shown in Figure 4a. The upper left panel in Figure 4a shows a high coherence (larger than 0.9) between E_ϕ and particle oscillations at the frequency of the waves. The 88 keV ions are closely inphase with E_ϕ. At energies higher than 88 keV, the ion oscillations have an increasing phase shift ahead of the E_ϕ, with 139 and 164 keV ions possessing the highest phase shift of ~ 100°. Below 88 keV, ion oscillations have a negative phase shift as large as –30° from E_ϕ. The pattern of these phase relations can only be explained by a drift

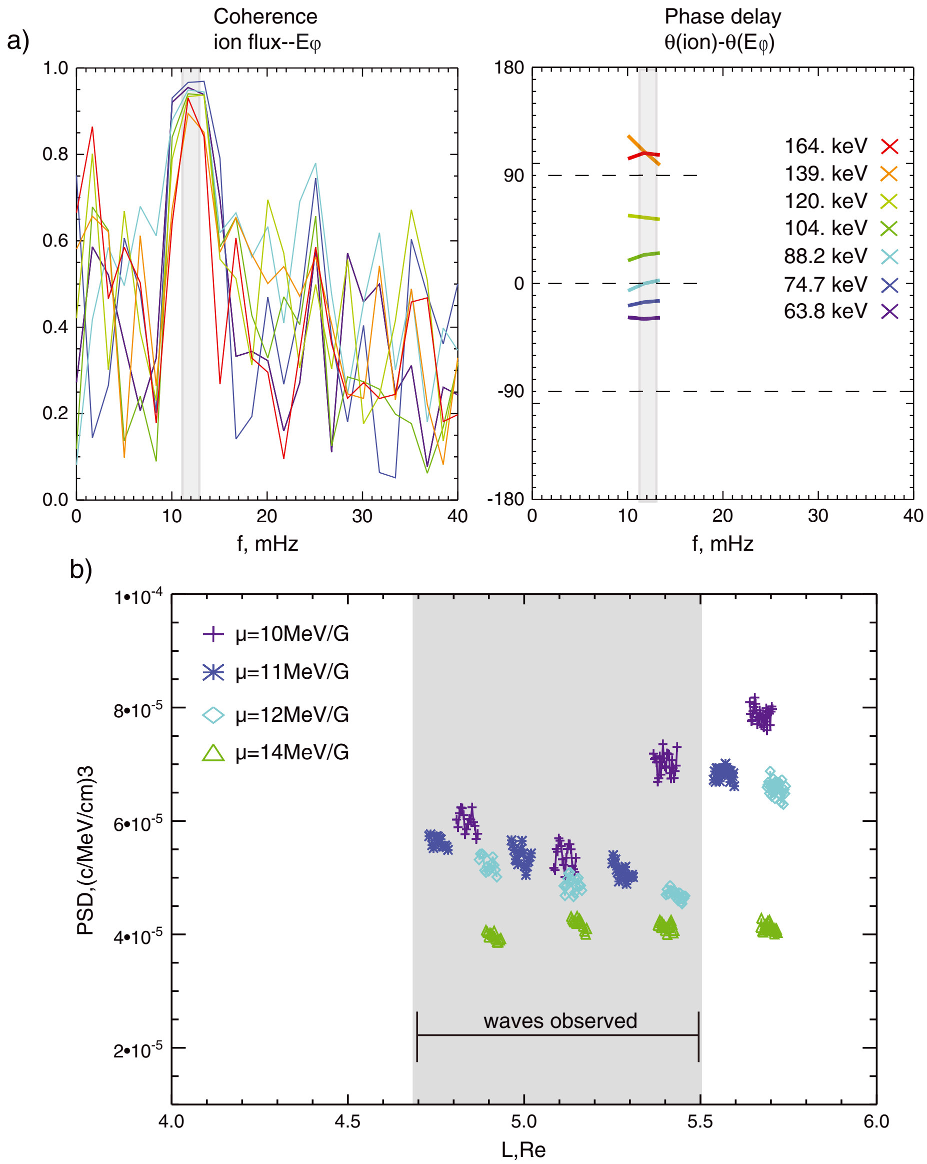

Figure 4. (a) Coherence and phase difference between oscillations of E_ϕ and ion flux in energy bins from 63.8 to 164 keV measured by RBSP-A. (b) PSD of ions from RBSP-A from 21:30 UT to 22:30 UT. The horizontal bar indicates L interval where the wave was observed. A 90° pitch angle is assumed for ions.

resonance at ~88 keV. The resonance with ~88 keV ions cannot be a high N number (e.g., $N = \pm 2, \pm 4...$) drift-bounce resonance (see Figure S2 in the supporting information). Energetic electrons from 20 to 200 keV were also modulated at the wave frequency and behave as nonresonant particles (see Figure S3 in the supporting information). The wave in our observations is expected to propagate at the longitudinal drift velocity (~40 km/s) of 88 keV ions. The m value of the waves inferred from the drift-resonance condition ($\omega_{\text{wave}} = m\omega_d$) is ~ −70 corresponding to a westward propagation. This azimuthal wave number is close to that of the fundamental mode of poloidal wave in a recent THEMIS observation [*Takahashi et al.*, 2013].

[14] The observations of an inphase relation between E_ϕ (positive is eastward) and the resonant ion at ~88 keV indicate an earthward radial gradient in ion PSD ($\partial f/\partial L|_{\mu,J} < 0$) suitable for the drift instability to grow. In addition, we calculated energetic ion PSD as a function of L shown in Figure 4b, assuming their pitch angles are 90°. The first adiabatic invariant μ of the resonant ions is in the range of 11–12 MeV/G. Figure 4b provides evidence in support of an earthward gradient in the resonant ions, assuming that the second adiabatic particle invariant J does not vary much during the event.

3. Conclusions and Discussions

[15] Using cross-spectral analysis of electric field, magnetic field, and ion flux data from RBSP, we have clearly identified the occurrence of the fundamental mode of a standing poloidal Alfvén wave in drift resonance with energetic ions in the inner magnetosphere. The inferred gradient of ion PSD indicated wave generation through the

drift-resonance instability. This instability is expected to absorb energy from the ring current ions and so affect the ring current evolution.

[16] The drift-resonance wave-particle interaction identified in Earth's magnetosphere should ubiquitously occur in planetary, astrophysical, and laboratory plasmas as long as the particles' drift motion applies in a magnetic field with local curvature, such as in the Earth's magnetosphere near the equator. For instance, the drift-resonance instability in the magnetosphere is generically similar to the fishbone instability [*McGuire et al.*, 1983; *Chen et al.*, 1984] in magnetically confined toroidal plasmas in the lab (see supporting information for more details). Here, for the toroidal precessional trapped particles, the resonance condition and the free energy are essentially the same as those in the space plasma.

[17] Our observations have important implications for the origin of Giant Pulsations (Pgs). Pgs are known for their remarkably regular waveforms as observed with ground magnetometers. The mode structure of the pulsations in the magnetosphere and the generation mechanism of the pulsations remain one of the most outstanding questions in magnetospheric ULF wave research. Recent studies have started to reveal a correspondence between Pgs and fundamental mode of standing Alfvén waves [*Takahashi et al.*, 1992; *Takahashi et al.*, 2011; *Glassmeier et al.*, 1999]. The observations here suggest that ring current ion drift-resonance instability may be responsible for Pgs generation.

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