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ABSTRACT

Cold ions of the ionospheric origin mainly contribute to the ion population in the Earth's magnetosphere. These cold ions can be modulated by Pc5 ultralow frequency waves or wake electric fields in the dayside outer magnetosphere, through which their energy can increase to hundreds of eV. Using measurements of Magnetospheric Multiscale mission, this paper reports a new finding of the cold ion modulation process, occurring at a timescale of several seconds. This modulation is identified to be mainly controlled by large-amplitude electromagnetic ion cyclotron (EMIC) waves through the wave-induced electric field drift. This study also gives distinct observational features in the cold ion modulation processes associated with EMIC waves and wake electric fields.

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I. INTRODUCTION

Cold ions are mainly responsible for the ion density and ion flux in the Earth's magnetosphere.¹ These cold ions can escape from the ionosphere in the polar cap and the equator and then enter the Earth's magnetotail and magnetopause.^{2–7} Their dynamics have attracted much attention in the space physics community. For example, as the cold ion gyroradius is comparable with the electron inertial length, cold ions can considerably affect the dynamics in the magnetic reconnection near the boundary of the outer magnetosphere^{8–16} and can also modify the Hall physics therein.^{17,18}

Due to the sunlit-induced photoelectron emission in the dayside outer magnetosphere, the spacecraft is positively charged to a few to tens of volts, and consequently, the cold ions (a few eV) are prevented from reaching the onboard detectors.¹ However, an *in situ* spacecraft often measures ions with energies around hundreds of eV in the outer magnetosphere. Moreover, these cold ions sometimes exhibit periodic variations in the ion energy spectrogram.^{19–21} The modulation of cold ions is caused by ultralow frequency (ULF) waves in the Pc5 band ($\sim$ a few mHz).^{19–22} ULF waves are common in the Earth's magnetosphere and can efficiently transfer energy with energized particles.^{23–31} Recently, the ULF wave-induced cold ion enhancements are clearly explored from Magnetospheric Multiscale (MMS) mission.^{20,21} Through the $E \times B$ drift resulting from ULF waves, low-energy cold

ions (a few eV) are converted to ions with energy exceeding the minimum energy threshold of the MMS plasma instrument, which induces these hidden cold ions reaching the onboard detector.^{20,21} Also, ULF waves can naturally produce periodic variations of energy of cold ions due to their electric fluctuations. Furthermore, besides the $E \times B$ drift, Liu *et al.*²¹ found that the ULF wave-induced polarization drift can dominate the modulation of cold heavy ions (e.g., O^+), where the energy resulting from the polarization drift can be 9 times larger than the energy associated with the $E \times B$ drift.

In this study, using data from the MMS spacecraft, we find a new modulation behavior of cold ions in the dayside outer magnetosphere, that is, ions with periodic variations around several seconds as seen in the energy spectrogram. This timescale is much smaller than the timescale in the modulation of cold ions relating to Pc5 ULF waves.^{20,21} Accompanying cold ions, there exists large-amplitude electromagnetic ion cyclotron (EMIC) waves having a frequency of ~ 0.2 Hz. Through analyzing the dynamical relationship between EMIC waves and cold ions, we propose that the EMIC wave-induced the $E \times B$ drift is mainly responsible for such short-timescale cold ion modulation.

II. DATA SET

The cold ion and wave activity are analyzed by using plasma and electromagnetic data from the MMS mission. The Fast Plasma

Investigation (FPI) provides plasma data with a temporal resolution of 4.5 s in fast mode and 150 ms for ions and 30 ms for electrons in burst mode.³² Since the Dual Ion Spectrometer (DIS) in FPI cannot distinguish protons from other kinds of ion species, ions are assumed to be protons in our analysis. Magnetic field data from the FluxGate Magnetometer (FGM) have a temporal resolution of 16 samples/s in survey mode,³³ and the Electric Double Probes (EDPs) give the electric field data with a sample rate of 32 Hz.^{34,35}

III. EVENT OVERVIEW

Figure 1 shows an overview of the event on 7 January 2019. Figure 1(a) gives the ion differential energy flux E_i , and Fig. 1(b) presents the magnetic field B_{GSE} in Geocentric Solar Ecliptic (GSE) coordinates. From Figs. 1(a) and 1(b), we find that MMS 1 stays in the Earth's magnetosheath during a time interval of $\sim 19:00:00\text{UT} - 19:03:00\text{UT}$ and a short-time interval of $\sim 19:21:50\text{UT} - 19:22:10\text{UT}$, when E_i is enhanced near 1 keV, and magnetic fields are strongly disturbed. While MMS 1 moves into the magnetosphere, both high-energy ($E_i \gtrsim 10$ keV) and low-energy ($E_i \sim 1 - 100$ eV) components are found in E_i . Moreover, there are magnetic fluctuations having a period of ~ 5 min, which correspond to Pc5 ULF waves. The interaction between ULF waves and cold ions has been recently studied in Refs. 20 and 21. Here, clear evidence for ULF wave-modulated cold ions is illustrated in Figs. 1(c)–1(g), which provides a zoomed view of 20:28:00UT – 20:43:50UT. Figure 1(c) presents ion and electron number densities using the fast mode data of FPI. The ion number density increases from $\sim 1\text{ cm}^{-3}$ up to $\sim 2 - 3\text{ cm}^{-3}$, whereas the electron number density remains stable $\sim 1\text{ cm}^{-3}$. This ion number density enhancement agrees with the appearance of cold ions with $E_i \sim 1 - 100$ eV as shown in Fig. 1(d). From Figs. 1(e)–1(g), we find ULF waves with the magnetic field amplitude ~ 4 nT and the electric field amplitude ~ 3 mV/m. To show the cold ion modulation by ULF waves, the $\mathbf{E} \times \mathbf{B}$ drift ion energy $W_E = m_p V_E^2/2$ and the total drift energy $W_T = m_p (V_E + V_P)^2/2$ are also overlaid in Fig. 1(d), where $V_E = \mathbf{E} \times \mathbf{B}/B^2$ and $V_P = m_p d_i E/eB^2$ are the electric field drift and the polarization drift, respectively. Here, V_E and V_P are sampled at the temporal resolution of the fast mode of FPI. W_E is nearly as same as W_T , indicating that V_E is the main contribution to the cold ion modulation. Comparing W_E to E_i , we find that W_E closely follows the variation of the cold ion energy. Hence, we conclude that these cold ions are modulated by ULF waves.^{20,21}

Figure 2 presents the ion energy spectra in different directions from measurements of FPI/DIS. The spectra are made in the Despun Body Coordinate System (DBCS), which nearly match with GSE coordinates due to the small angle between the positive spin axis of MMS and the ecliptic normal around 3° . In Fig. 2, the differential energy flux E_i in each energy bin is averaged over particles with the DBCS flow direction within 45° of each axis. Comparing Figs. 2(a) and 2(b), the E_i values of cold ions (below 100 eV) near $+x$ and $-x$ are asymmetric, and this asymmetry is nearly in agreement with the appearance of V_E at $+x$ and $-x$ directions in Fig. 2(c). Also, the asymmetry of E_i near $+y/-y$ [Figs. 2(d) and 2(e)] and near $+z/-z$ [Figs. 2(g) and 2(h)] is nearly consistent with variances of V_E at $+y/-y$ [Fig. 2(f)] and $+z/-z$ [Fig. 2(i)]. Therefore, the modulation of cold ions by ULF waves is again identified by Fig. 2.

Besides Pc5 (~ 5 min) ULF waves, cold ions are also observed in accompany with EMIC waves. Figure 3 presents the polarization analysis by using the singular value decomposition method.³⁶ From top to bottom panels, we give the power spectral density of the perpendicular magnetic field, the power spectral density of the perpendicular electric field, the wave normal angle (θ), the degree of polarization (DOP), the ellipticity, and the parallel Poynting flux $S_{\parallel}$ normalized by $|S|$. In Fig. 3, the proton cyclotron frequency f_{cp} and the helium cyclotron frequency f_{CH^+} are overlaid. Clear signatures of quasi-monochromatic waves between 0.1 and 0.5 Hz (H^+ -band waves) can be seen. These waves have small normal angles ($\lesssim 30^\circ$) and strong DOP ($\gtrsim 0.7$). Moreover, most of the waves have the ellipticity smaller than -0.7 and $S_{\parallel} < 0$. Therefore, these features indicate the presence of EMIC waves propagating against the magnetic field.

The MMS has high-temporal resolution (burst mode) measurements during 20:39:24UT – 20:41:23UT (the region between two vertical dashed lines in Figs. 1–3), when EMIC waves have considerable electromagnetic fluctuations, and these measurements are in favor of studying the modulation of cold ions by EMIC waves.

IV. MODULATION OF IONOSPHERIC OUTFLOW IONS BY EMIC WAVES

More detailed properties of EMIC waves are presented in Fig. 4, where Figs. 4(a)–4(d) plot B_{GSE} and E_{GSE} in GSE coordinates during the burst time interval of 20:39:24UT – 20:41:23UT. Before 20:40:50UT, there exist quasi-monochromatic EMIC waves with the period of approximately 5 s and having the maximum strength at $\sim 20:40:30\text{UT}$. The peak-to-peak amplitudes are $\delta B \sim 4$ nT and $\delta E \sim 3$ mV/m. In comparison to the ambient magnetic field $B_0 \sim 47$ nT, the relative magnetic amplitude is nearly 0.09. Note that during 20:40:25UT – 20:40:35UT when EMIC waves are the strongest, the distribution of E_z contains several dipolar structures where the E_z direction rapidly changes [Fig. 4(d)]. In addition, high-frequency electrostatic fluctuations between f_{cp} and $0.1f_{ce}$ are also observed.

Figures 4(e)–4(g) present the ion velocity V_{iGSE} in GSE coordinates from the burst mode data of FPI. The $\mathbf{E} \times \mathbf{B}$ drift velocity V_E (sampled at the temporal resolution of the burst mode of FPI) is also overlaid in Figs. 4(e)–4(g). V_E is in good agreement with V_{iGSE} , especially for the $\mathbf{E} \times \mathbf{B}$ drift velocity resulting from EMIC waves. Therefore, we conclude that the short-timescale ion velocity fluctuation is dominated by the EMIC wave-induced $\mathbf{E} \times \mathbf{B}$ drift.

Figures 4(h)–4(k) further present the time series of magnetic field fluctuations $B_{\perp}$ and ion velocity fluctuations $V_{\perp}$ perpendicular to the background magnetic field B_0 . To obtain $B_{\perp}$ and $V_{\perp}$, we choose B_0 through averaging the magnetic field over 20 s and then transform B_{GSE} and V_{iGSE} to the field-aligned coordinates (FAC). From the distribution of $B_{\perp}$ in Fig. 4(h), we see that the phase $B_{\perp 1}$ is nearly behind of $B_{\perp 2}$ by $\pi/2$, indicating the left-hand polarization for EMIC waves. For the strong EMIC waves in $\sim 20:40:20\text{UT} - 20:40:35\text{UT}$, the phase difference between $B_{\perp 1}$ and $B_{\perp 2}$ is near 0 or π , and the amplitude of $B_{\perp 1}$ is much smaller than that of $B_{\perp 2}$. The phase difference of $V_{\perp 1}$ and $V_{\perp 2}$ in Fig. 4(i) nearly retains $\pi/2$ during the whole EMIC time interval. Moreover, for the strongest EMIC waves, the amplitude of $V_{\perp 1}$ is smaller than that of $V_{\perp 2}$. Furthermore, Figs. 4(j) and 4(k) compare $B_{\perp}$ (normalized by B_0) to $V_{\perp}$ (normalized by the Alfvén speed V_A). In the EMIC wave time interval, we find $B_{\perp}/B_0 \simeq V_{\perp}/V_A$. This positive correlation relation indicates the EMIC wave propagating

FIG. 2. Ion energy spectra E_i at different directions: (a) and (b) E_i near $+x$ and $-x$ directions in Despun Body Coordinate System (DBCS); (d) and (e) E_i near $+y$ and $-y$ directions in DBCS; and (g) and (h) E_i near $+z$ and $-z$ directions in DBCS. Electric field drift velocities V_E at different directions: (c) x , (f) y , and (i) z in GSE coordinates. The red and blue lines in panels (c), (f), and (i) represent the drift velocity along and against each axis. Since the positive spin axis of MMS retains within around 3° from ecliptic normal, DBCS is nearly in accordance with GSE coordinates.

$V_A = B_0 / \sqrt{\mu_0 m_i n} \simeq 458$ km/s, as computed from $B_0 \simeq 47$ nT and $n \simeq 5$ cm $^{-3}$, is much larger than the ion bulk flow speed $V_{\text{flow}} \simeq 47$ km/s, the Doppler shift is negligible, and the wave frequency $f \sim 0.2$ Hz in the spacecraft frame is nearly the same as that in the plasma frame.

Due to the V_E induced by ULF and EMIC waves, the ion energy can exceed the lowest energy channel in the FPI instrument. The details of the short-timescale modulation of cold ions by EMIC waves, based on burst mode data, are shown in Fig. 5. Figure 5(a) presents ion and electron number densities, where the ion number density

behaves as a periodic variation between $n_i \sim 1$ cm $^{-3}$ and ~ 5 cm $^{-3}$, but the electron number density nearly remains constant $n_e \sim 1$ cm $^{-3}$. Comparing Fig. 5(a) with Fig. 1(c), we see that the ion density measured in the fast mode ($\sim 1 - 3$ cm $^{-3}$) actually underestimates the cold ion density. Figure 5(b) shows the ion energy spectrogram and the $\mathbf{E} \times \mathbf{B}$ drift energy W_E . The cold ion energy E_i is consistent with the theoretical prediction of W_E . The modulation of cold ions is explored by Figs. 5(c)–5(f) in detail, which shows the ion pitch angle spectrogram for $2.2 \text{ eV} \leq E_i \leq 153.4 \text{ eV}$ [Fig. 5(c)], the normalized differences $\frac{\text{PSD}_{\text{para}} - \text{PSD}_{\text{perp}}}{\text{PSD}_{\text{para}} + \text{PSD}_{\text{perp}}}$ between the ion parallel and perpendicular PSDs

FIG. 3. Polarization analysis. (a) Power spectral density of the perpendicular magnetic field. (b) Power spectral density of the perpendicular electric field. (c) Wave normal angle (θ). (d) Degree of polarization (DOP). (e) Ellipticity. (f) The parallel Poynting flux $S_{\parallel}$ normalized by $|S|$. Three solid lines represent the proton cyclotron f_{cp} , helium cyclotron f_{ch+} , and oxygen cyclotron f_{co+} frequencies, respectively.

[Fig. 5(d)], the normalized differences $\frac{PSD_{anti} - PSD_{perp}}{PSD_{anti} + PSD_{perp}}$ between the ion anti-parallel and perpendicular PSDs [Fig. 5(e)], and the distribution of the magnitude of the $\mathbf{E} \times \mathbf{B}$ drift velocity $|V_E|$ [Fig. 5(f)]. Figures 5(c)–5(f) show that at the minima of $|V_E|$ induced by EMIC waves (vertical dashed lines), both parallel and antiparallel PSDs are larger than perpendicular PSDs, indicating that cold ions come from the ionospheric outflow.²¹ At the times of the maxima of $|V_E|$, the pitch angle of cold ions is around 90° , which corresponds to the position of the strongest $\mathbf{E} \times \mathbf{B}$ drift.

Figure 6 shows the ion energy spectrum E_i in different directions during the burst time interval. It explores the asymmetric distribution of E_i at a short timescale of ~ 5 s. Similarly, the asymmetric E_i is consistent with the variance of the $\mathbf{E} \times \mathbf{B}$ drift velocity at different

directions. Therefore, we demonstrate again the modulation of cold ions by EMIC waves.

V. DISCUSSION AND SUMMARY

Based on the MMS measurements of high resolution plasma and field data, this paper reports for the first time the modulation of cold ions by EMIC waves. The $\mathbf{E} \times \mathbf{B}$ drift of EMIC waves can increase the energy of cold ions up to $E_i \sim 100$ eV and consequently make them detectable by the onboard plasma instrument. Due to the EMIC wave-induced $\mathbf{E} \times \mathbf{B}$ drift, the energy of cold ions has periodic variations at a short-timescale of ~ 5 s. Moreover, our results indicate the drift of cold ions is dominated by $\mathbf{E} \times \mathbf{B}$ drift instead of the polarization and diamagnetic drifts. The polarization drift becomes important as the parallel

FIG. 4. (a)–(g) Electromagnetic field and ion velocity during the burst time interval of 20:39:24UT – 20:41:23UT. (l) and (m) Power spectral densities of magnetic and electric fields. (a) The total magnetic field $|B|$. (b) Magnetic field B_{GSE} in GSE coordinates. (c) and (d) Electric field E_{GSE} in GSE coordinates. (e), (f), and (g) Ion velocity V_{GSE} in GSE coordinates, where the $E \times B$ drift velocity V_E is overlaid. (h) Perpendicular magnetic field components $B_{\perp}$ in field-aligned coordinates (FAC) coordinates. (i) Perpendicular ion velocity components $V_{\perp}$ in FAC coordinates. (j) and (k) Correlation relation between $B_{\perp}$ and $V_{\perp}$ during the burst time interval. (l) B power spectral density. (m) E power spectral density. $B_{\perp}$ and $V_{\perp}$ fluctuations are filtered in the range of 0.1 Hz – 0.5 Hz. All plasma data come from the burst mode data of FPI.

wavelength approaches the ion inertial length $\lambda_i = \sqrt{m_p / \mu_0 n e^2} \simeq 9.5$ km, where the plasma density is given as $n = 5 \text{ cm}^{-3}$. The diamagnetic drift takes part in the wave dynamics as the perpendicular wavelength is of the order of the ion gyroradius or the finite ion

gyroradius. In our event, the ion gyroradius ρ_i for cold ions ($E_i \sim 1 - 100$ eV) is nearly 3.1 – 31 km, and the finite ion gyroradius ρ_s at an electron temperature $T_e \sim 389$ eV is around 62 km, where T_e is the averaged electron temperature in the burst

FIG. 5. Modulation of cold ions by EMIC waves. (a) Ion and electron number density. (b) Ion energy spectrogram, and the solid line denotes the $E \times B$ drift energy W_E . (c) Ion pitch angle spectrogram for ions with $2.2 \text{ eV} \leq E_i \leq 153.4 \text{ eV}$. (d) Normalized difference between the parallel ion PSD (pitch angle, $\sim 0^\circ - 20^\circ$) and perpendicular PSD (pitch angle, $\sim 80^\circ - 100^\circ$). (e) Normalized difference between the antiparallel PSD (pitch angle, $\sim 160^\circ - 180^\circ$) and perpendicular PSD (pitch angle, $\sim 80^\circ - 100^\circ$). (f) The $E \times B$ drift velocity V_E . The vertical dashed lines in figures (a)–(f) represent minimum V_E . All plasma data come from the burst mode data of FPI.

time interval. The wavenumbers in FAC are given as $k_{\perp 1} \simeq 1.4 \times 10^{-3} \pm 0.3 \times 10^{-3} \text{ km}^{-1}$, $k_{\perp 2} \simeq 3.65 \times 10^{-4} \pm 0.05 \times 10^{-4} \text{ km}^{-1}$, and $k_{\parallel} \simeq -2.45 \times 10^{-3} \pm 0.05 \times 10^{-3} \text{ km}^{-1}$ by using the phase difference method⁴⁰ for the magnetic envelop in one wave period during 20:39:39UT–20:39:44UT. Since $(\lambda_i k_{\parallel}, \rho_i k_{\perp}, \rho_s k_{\perp}) \ll 1$, both the polarization and diamagnetic velocity drifts weakly affect the cold ion drift.

Previous statistical surveys have shown that H^+ -band EMIC waves are common in the dayside region of the outer magnetosphere.^{41,42} Also, highly disturbed geomagnetic conditions can yield high occurrence rates of EMIC waves in the afternoon sector, and strong dynamic pressure in the solar wind can yield high occurrence rates in the dayside outer magnetosphere. Considering that the

duration of these waves is usually a few minutes to a few hours,^{41,42} therefore, the EMIC wave-induced cold ion modulation may frequently arise in the outer magnetosphere. However, the identification of these phenomena requires plasma measurements of high-temporal resolution, and the MMS spacecraft in the burst mode can make such observations possible.

This paper also identifies the modulation of ionospheric outflow cold ions by Pc5 ULF waves. This mechanism results in the modulation of cold ions at a timescale of ~ 5 min in the ion energy spectrogram, and our results are consistent with the recent results in Refs. 20 and 21. Besides cold ions modulated by ULF waves and EMIC waves, Toledo-Redondo *et al.*⁴³ recently proposed that the cold ion density exhibits a periodic fluctuation due to wake electric fields. This

FIG. 6. Ion energy spectra E_i at different directions during the burst time interval. (a) and (b) E_i near +x and -x directions in DBCS. (d) and (e) E_i near +y and -y directions in DBCS. (g) and (h) E_i near +z and -z directions in DBCS. Drift velocities of electric field V_E at different directions in GSE coordinates: (c) x, (f) y, and (i) z. The red and blue lines in panels (c), (f), and (i) represent the velocity along and against each axis.

modulation period is approximately 5 s, that is, a quarter of the MMS spin period of ~ 20 s. In order to explore the difference between short-timescale cold ion modulations by EMIC waves and by wake electric fields, Fig. 7 compares the detailed plasma and electromagnetic distributions in the EMIC wave-induced event and in wake electric field-induced events.

Figure 7(a) presents another event of cold ions modulated by EMIC waves, labeled as EMIC Event II. The timescale in this event is about 2 s, which is different from the timescale ~ 5 s in the cold ion event in Sec. III. It clearly shows that the EMIC wave determines the timescale of the variance in the cold ion energy spectrogram. Figures

7(b) and 7(c) give two wake electric field events analyzed in the study by Toledo-Redondo *et al.*⁴³ In Wake Event I [Fig. 7(b)], wake electric fields (i.e., the periodic spikes in E_x and E_y distributions) arise when the Active Spacecraft Potential Control (ASPOC) instrument is not in operation. In Wake Event II [Fig. 7(c)] where the ASPOC is on, wake electric fields appear.⁴³ It should be noted that for a medium cold ion density (several particles in cm^{-3}), wake electric fields will be removed as the ASPOC instrument is in operation.⁴³

Comparing EMIC wave-induced events in Figs. 4, 5, and 7(a) to weak electric field-induced events in Figs. 7(b) and 7(c), we can see many differences between these two kinds of cold ion modulations.

FIG. 7. The cold ion modulation by EMIC waves VS. by wake electric fields. (a) EMIC wave-modulated cold ion event on 5 January 2019, labeled as EMIC Event II. (b) Wake electric field-modulated cold ion event on 28 December 2016, labeled as Wake Event I, where the ASPoC instrument is not in operation. (c) Wake electric field-modulated cold ion event on 27 January 2017, labeled as Wake Event II, where the ASPoC instrument is in operation. From top to bottom panels, ion and electron densities (top panels), ion energy spectrogram (second panels), the magnetic field in GSE coordinates, the total magnetic field (third panels), the electric field in GSE coordinates (fourth panels), the ion velocity V_{GSE} , and the $\mathbf{E} \times \mathbf{B}$ drift velocity $\mathbf{V}_E$ in GSE coordinates (fifth, sixth, and seventh panels), and the perpendicular magnetic field $\mathbf{B}_\perp$ and ion velocity $\mathbf{V}_\perp$ in FAC coordinates (eighth and bottom panels). $\mathbf{B}_\perp$ and $\mathbf{V}_\perp$ are filtered in the range of 0.1 Hz – 1 Hz. The solid lines in the second row denote the $\mathbf{E} \times \mathbf{B}$ drift energy W_E .

First, the magnetic fields behave sinusoidal/cosinusoidal fluctuations in EMIC wave-induced events, but wake electric field-induced events have no magnetic fluctuations. Second, both electric fluctuations E_x and E_y have a sinusoidal/cosinusoidal envelop in EMIC wave-induced events, but in wake electric field-induced events, E_x and E_y are spike-like and anti-correlated. Moreover, since our two EMIC wave-induced events contain medium cold ion densities ($\lesssim 5 \text{ cm}^{-3}$) and the ASPoC instrument is on, wake electric fields can be canceled out.⁴³ Third, in EMIC wave-induced events, ion velocity fluctuations are in accord with the $\mathbf{E} \times \mathbf{B}$ drift velocity, but the measured ion velocities deviate from the $\mathbf{E} \times \mathbf{B}$ drift velocity in wake electric field-induced events. Fourth, in EMIC wave-induced events, the relationship between magnetic fluctuations and velocity fluctuations is consistent with the theoretical prediction,^{37,38} i.e., $\mathbf{B}_\perp/B_0 \simeq \mathbf{V}_\perp/V_A$, but this relationship does not exist in wake electric field-induced events.

Finally, based on the unidirectional propagation of EMIC waves antiparallel to the magnetic field, we propose that these waves are not locally generated. This conclusion is supported by the kinetic instability analysis. To distinguish the cold and hot particle components in our event, we use the following procedures: based on the maximum ion density near 5 cm^{-3} as shown in Fig. 5, the ambient ion number density is assumed as $n_i = 5 \text{ cm}^{-3}$. Suppose that the ion population is composed of the hot component ($E_i \gtrsim 160 \text{ eV}$) and cold component ($E_i \lesssim 160 \text{ eV}$). The plasma parameters of hot ions are thus obtained by averaging the part-moments data from FPI measurements: $n_{i1} = 0.53 \text{ cm}^{-3}$, $T_{i1\parallel} = 5.9 \text{ keV}$, and $T_{i1\perp} = 7.7 \text{ keV}$. For cold ions, the number density is given as $n_{i2} = n_i - n_{i1} = 4.47 \text{ cm}^{-3}$, and the temperature is assumed as $T_{i2\parallel} = T_{i2\perp} = 1 \text{ eV}$. Similar to ions, the electron population is assumed to be contributed by hot and cold components. The averaged plasma parameters of hot electrons are directly given by FPI measurements: $n_{e1} = 1.06 \text{ cm}^{-3}$, $T_{e1\parallel} = 368 \text{ eV}$, and

$T_{e\perp 1} = 326$ eV. For the cold electron population, we assume the isotropic temperature $T_{e\parallel 2} = T_{e\perp 2} = 0.001$ eV, and the number density is obtained as $n_{e2} = n_i - n_{e1} = 3.94 \text{ cm}^{-3}$ based on the quasi-neutrality condition. Using these plasma parameters, we find that the temperature anisotropy ($T_{i\perp 1} > T_{i\parallel 1}$) of hot ions induces unstable EMIC waves with the maximum growth rate near 0.0027 s^{-1} . However, this growth rate is too weak to result in an effective amplification of EMIC waves. Note that this result is found to be almost independent of the cold ion and electron temperatures. The source region of these EMIC waves may be off-equator magnetic field minimum in the Earth's outer magnetosphere.⁴⁴ After the waves escape from the source region, they can continually interact with cold ions along the propagation trajectory. Since the source of large-amplitude EMIC waves is still not fully explored, we will study this problem in the future.

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