
Whistler wave generation by electron temperature anisotropy during magnetic reconnection at the magnetopause

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ABSTRACT

Two magnetopause reconnection events of the Magnetospheric Multiscale mission with whistler wave activity are presented. The whistler mode around half of the electron cyclotron frequency is excited near the magnetospheric separatrix. In both events, there are positive correlations between the whistler wave and the lower hybrid drift instability (LHDI) activities, indicating a possible role of LHDI in the whistler wave generation. A sudden change in the electron pitch angle distribution (PAD) function of energetic electrons is observed right after intense LHDI activity. This change in the PAD leads to temperature anisotropy in energetic electrons which is responsible for the whistler wave excitation. The measured dispersion relation demonstrates that the whistler wave propagates toward the X line nearly parallel to the background magnetic field. Finally, a linear analysis with the measured distribution function verifies that the whistler mode is excited by the temperature anisotropy in energetic electrons.

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I. INTRODUCTION

Magnetic reconnection, a topological rearrangement of magnetic field lines, plays an important role in explosive phenomena in magnetized plasmas such as solar flares and substorms.1,2 Magnetic reconnection converts magnetic energy efficiently to plasma particles, and the reconnection site has many free energy sources for waves.3 The waves generated by free energy sources potentially impact reconnection dynamics via wave-particle interactions.

Observations of waves in space have been increasing since NASA’s Magnetospheric Multiscale (MMS) was launched in 2014. The unprecedented temporal resolution in both particle and field measurements has provided opportunities for studying waves quantitatively in space. In particular, whistler waves have been widely observed near the magnetospheric separatrix4–7 as well as near the electron diffusion region8 during asymmetric reconnection at the dayside magnetopause.

Recently, Yoo et al.7 have demonstrated that whistler waves near the magnetospheric separatrix are excited by temperature anisotropy in tail electrons and propagate toward the X line mostly parallel to the background magnetic field. The dispersion relation of the anisotropy-driven whistler waves was measured by using the correlations among magnetic field data from four MMS satellites. The temperature anisotropy of energetic electrons is demonstrated with the 2D electron distribution function, which is unstable to the whistler wave generation. Moreover, the enhanced transport of electrons with a high parallel speed by the turbulence driven by the lower hybrid drift instability (LHDI) was suggested as the fundamental reason for the observed anisotropy. Although correlation between whistler and LHDI activities both in space and laboratory data provides circumstantial evidence for this hypothesis, further research is required to confirm the role of LHDI in the whistler wave excitation near the magnetospheric separatrix with an active X line.

Here, another MMS event with the similar whistler wave activity is analyzed and compared with the event reported by Yoo et al.7 to have better insight into the role of LHDI in the whistler wave generation. In Sec. II, the overview of two MMS events with clear whistler wave activity is presented. In Sec. III, dispersion relations of the
whistler mode are demonstrated. In Sec. IV, the measured electron distribution functions are shown, and it is verified that these distribution functions are unstable to the observed whistler mode by a linear analysis. Finally, in Sec. V, the possible role of LHDI in the whistler wave generation is discussed.

II. OVERVIEW OF TWO MMS EVENTS

High-resolution burst mode data from two MMS events are analyzed to understand excitation mechanisms and propagation characteristics of the whistler wave near the magnetospheric separatrix during asymmetric reconnection at the dayside magnetopause. The first one is a well-known MMS event where MMS encountered the electron diffusion region at the magnetopause on 16 October 2015. The other event occurred on 19 September 2015, when MMS crossed the magnetopause near an active X line. More details of these magnetopause events including the MMS trajectory can be found in the studies by Burch et al. and Wang et al. Whistler wave activity appeared near the magnetospheric separatrix about 10–15 \( \delta_i \) away from the X line for both events. Here, \( \delta_i = c/\omega_{pe} \) is the ion skin depth and \( \omega_{pi} \) is the ion (angular) plasma frequency.

Electron distribution functions are measured using a Fast Plasma Instrument (FPI). The magnetic field is measured using a Search-Coil Magnetometer (SCM) and a FluxGate Magnetometer (FGM), while the electric field is measured using an Electric field Double Probe (EDP).

The coordinate system in this study is \( LMN \), with \( L \) along the reconnecting field component, \( M \) along the out-of-plane direction, and \( N \) normal to the current sheet. For the first event, we follow the transformation matrix given in the study by Burch et al., which transforms the geocentric-solar-ecliptic (GSE) coordinates to the \( LMN \) coordinates. For the second event, the matrix is obtained by a minimum variance analysis of the magnetic field during the current sheet crossing around 07:41:22 on 19 September 2015; the unit vector along \( L, M, \) and \( N \) is \((0.244, 0.011, 0.970), (0.567, −0.813, −0.133), \) and \((0.787, 0.582, −0.205) \) in GSE, respectively.

Figure 1 demonstrates the location where the whistler wave is observed by MMS. Both events occurred at the dayside magnetopause—the boundary between the magnetosphere (left side) and the magnetosheath (right side). Since plasma parameters and magnetic field strength in the magnetosphere are significantly different from those in the magnetosheath, the reconnection at the magnetopause is inherently asymmetric. For example, the plasma density in the magnetopause \((0.1–1 \text{ cm}^{-3})\) is one or two orders of magnitude smaller than the density in the magnetosheath \((10–100 \text{ cm}^{-3})\). Due to this large density asymmetry, steep density gradients build up near the magnetospheric separatrix, leading to the development of LHDI-driven turbulence. The LHDI-driven turbulence is characterized by strong, broadband electric field fluctuations whose energy is concentrated mostly below the lower hybrid frequency \( (f_{LH}) \). This LHDI-driven turbulence obscures the location of the magnetospheric separatrix; the separatrix becomes an electron mixing region where some electrons from the exhaust region are transported to the magnetospheric side occasionally and vice versa. As illustrated in Fig. 1 with a red circle, MMS spacecraft was in the electron mixing region (orange color) when it observed the whistler wave together with LHDI. The whistler wave disappears in the exhaust region (pink color).

Figure 2(a) shows a power spectrogram of the magnetic field from a wavelet analysis. The magenta solid line indicates half of the local electron cyclotron frequency, \( 0.5f_{ce} \), while the black solid line represents the local lower hybrid frequency, \( f_{LH} \). There is clear whistler wave activity near \( 0.5f_{ce} \) until MMS3 enters the exhaust region at 13:05:43, which is indicated by the red vertical dashed line. There are four features that suggest that MMS3 moves from the electron mixing region to the exhaust region. First, there is strong LHDI-driven turbulence, as shown in Figs. 2(a) and 2(c). This enhanced LHDI activity near the separatrix has been observed consistently during asymmetric magnetic reconnection. Second, a sharp increase in the electron density exists, as shown in Fig. 2(d). Third, there is a decrease in the reconnecting magnetic field component, as presented in Fig. 2(e). Finally, the electron temperature decreases due to the increased...
population of the cold plasma in the exhaust that is from the cold magnetosheath. All these features occur around 13:05:43.

Figure 2(b)–2(d) show a time evolution of the power in the whistler wave, $P_{\text{WS}} (0.25 f_{\text{ce}} < f < 0.75 f_{\text{ce}})$, the power in LHD, $P_{\text{LHD}} (0.3 f_{\text{ce}} < f < 1.4 f_{\text{ce}})$, and electron density, $n_e$. As shown in Fig. 2(d), the local electron density starts to increase around 13:05:26.5 and 13:05:33, which is indicated by two magenta dashed lines. This density increase is caused by the transport of electrons from the exhaust region by LHDI. Furthermore, the correlation between $P_{\text{LHD}}$ and $n_e$ also supports the transport of magnetosheath electrons by LHDI; as shown in Figs. 2(c) and 2(d), the local density increase follows peaks in $P_{\text{LHD}}$. For reference, the unper- turbated density of the magnetosphere for this event is about 0.3 cm$^{-3}$.

The observation of cold electrons from the exhaust region with occasional LHDI activity provides convincing evidence that MMS3 was in the electron mixing region when it observed the whistler wave. The whistler wave activity also correlates with both $P_{\text{LHD}}$ and $n_e$. As shown in Fig. 2(b), $P_{\text{WS}}$ significantly increases right after $P_{\text{LHD}}$ and $n_e$ start to increase.

Figure 2(e) shows a time profile of the magnetic field, measured by FGM. Compared to $B_L$, both $B_{\parallel}$ and $B_{\perp}$ components are negligible, which means that the guide field is negligible and MMS3 is not really far from the X line (estimated about 10d, away). The strength of $B_L$ on the magnetosphere side is about 40 nT. The electron flow profile is shown in Fig. 2(f). It is worth noting that there is a sizable electron flow toward the X line (positive $V_{\parallel}$).

The electron temperature profile shown in Fig. 2(g) shows a general trend of $T_{\parallel} > T_{\perp}$ near the separatrix, which is due to the trapped particle dynamics with the acceleration potential. Both parallel and perpendicular temperatures decrease significantly in the exhaust region where the electron population from the cold magnetosheath dominates.

Finally, the pitch angle distributions (PADs) of middle-energy (200–2000 eV) and high-energy (2–30 keV) electrons are shown in Figs. 2(h) and 2(i), respectively. For middle-energy electrons, electrons with a pitch angle $\phi$ close to 0° or 180° (parallel or antiparallel to the field line) are dominant over electrons with $\phi$ close to 90° (perpendicular to the field line), which means that $T_{\parallel} < T_{\perp}$ for these electrons. For high-energy electrons, on the other hand, PAD shows the opposite trend—electrons with $\phi$ close to 90° are dominant. This means that $T_{\parallel} > T_{\perp}$ for energetic electrons. This temperature anisotropy in tail electrons exists together with the whistler mode activity [Fig. 2(a)], until MMS3 enters the exhaust region at 13:05:43.

**B. Event on 19 September 2015**

Similar whistler activity is found in another MMS event on 19 September 2015. As shown in Fig. 3(a), the whistler mode around $f = 0.5 f_{\text{ce}}$ is strong from 07:40:40 to 07:41:08. MMS4 enters the exhaust region around 07:41:08, which is supported by the increase in LHDI activity in Fig. 3(c), the large increase in the electron density $n_e$ in Fig. 3(d), and the decrease in $B_L$ in Fig. 3(e).

There is also an interesting correlation among $P_{\text{WS}}$, $P_{\text{LHD}}$, and $n_e$ in this event. As shown in Figs. 3(a) and 3(c), there is an enhanced LHDI activity from 07:40:37 to 07:40:43. At the same time, the local electron density ($n_e$) increases significantly from about 0.2 cm$^{-3}$ to 1 cm$^{-3}$, as shown in Fig. 3(d). In addition, there is a sharp decrease in $T_{\parallel}$ from about 200 eV to about 30 eV. Again, this is due to the LHDI-driven turbulent transport of cold electrons in the exhaust region to the magnetosphere side. Right after the intense LHDI activity, strong whistler wave activity starts, as shown in Figs. 3(a) and 3(b), which supports the causality between LHDI and the whistler mode.
electrons with $\phi^\circ \sim 90^\circ$. It is important to see that the anisotropy is caused by a sudden "loss" of electrons with a dominant parallel velocity after the LHDI activity. This indicates that LHDI may be responsible for the loss of electrons with a dominant parallel velocity, which will be discussed in Sec. V. The temperature anisotropy of $T_e > T_i$ in energetic electrons is the required condition for the anisotropy-driven whistler wave in this region.\textsuperscript{25} This anisotropic PAD continues until MMS4 enters the exhaust region around 07:41:08. It is worth noting that the period where the anisotropic PAD exists coincides with the strong whistler wave activity. The LHDI activity and local density increase support that MMS4 was in the electron mixing region when it observed the whistler wave.

The middle-energy (200–2000 eV) electrons show the opposite PAD, where the phase space density of electrons with $\phi$ close to 0° or 180° is larger than that of electrons with $\phi$ close to 90°, as shown in Fig. 3(h). This means that the cold electrons from the exhaust region have been accelerated by the parallel electric field, which exists near the magnetospheric separatrix.\textsuperscript{27}

**III. MEASUREMENTS OF THE DISPERSION RELATION**

The measurement of the dispersion relation is important for identifying the wave mode and understanding the wave propagation. It also provides important information on the wave excitation mechanism. Yoo et al.\textsuperscript{7} provide the first clear measurement of the whistler wave dispersion near the reconnection site in space by using the maximum likelihood method.\textsuperscript{27} The method requires correlations between data from each measurement point. Since the separation of MMS for the event on 16 October 2015, it is about 10 km that is smaller than the wavelength of about 40 km, whistler wave signals from each MMS correlate with each other. Thus, the spectral power as a function of $\omega$ and $k$, $P(\omega, k)$, from the maximum likelihood method demonstrates the wave dispersion, as shown in Fig. 4.

Figure 4(a) shows the maximum likelihood spectral power, $P(\omega, k_L)$ with $k_M = k_N = 0$. SCM data from 13:05:26.6 to 13:05:27 are used to obtain $P(\omega, k)$. As presented in Fig. 2(e), the magnetic field during the given time period has a dominating $B_z$ component, such that $k_L$ represents $k_z$. The magenta dashed line indicates the cold plasma dispersion with $\theta = 0$, where $\theta$ is the angle between $k$ and the magnetic field. The sold red line is the dispersion from a linear dispersion solver, WHAMP (waves in homogeneous, anisotropic, and multicomponent plasmas\textsuperscript{28}), which agrees with the measured dispersion relation.

Figures 4(b) and 4(c) show $P(k_L, k_M)$ with $k_N = 0$ and $P(k_L, k_N)$ with $k_M = 0$. The wave vector with the highest power at $\omega = 3921$ rad/s is $k = (1.76, -0.16, -0.45) \times 10^7$ m. In this case, $\theta$ is about 19°. Since MMS passed through the southern part of the X line structure,\textsuperscript{7} the relatively small $\theta$ and positive $k_z$ mean that whistler waves propagate toward the X line almost parallel to the magnetic field, which agrees with the previous research.\textsuperscript{27}

The phase velocity of the whistler mode is estimated to be about $2 \times 10^7$ m/s. The polarization of the wave from the singular value decomposition (SVD) analysis\textsuperscript{27} is right-handed. The observed characteristics of the whistler wave such as the dominant $k_z$ and high phase velocity are consistent with anisotropy-driven whistlers.\textsuperscript{25,27,18}

For the event on 19 September 2015, the maximum likelihood method cannot be used, as the separation between spacecraft (≈100 km) is larger than the wavelength (≈30 km) of the whistler mode. In this case, two methods for single spacecraft data can be used.
The first method is the SVD analysis by Santol et al.\textsuperscript{29} The basic idea of the SVD analysis is to create a real matrix equation equivalent to Eq. (1), which is solved by the singular value decomposition method to find the best estimate of the wave number vector $\mathbf{k}$. Here, the best estimate means a solution that minimizes errors from noise. The details on the SVD analysis can be found in the study by Santol et al.\textsuperscript{29}

The second method is based on the hodogram analysis, which is mathematically less rigorous than the SVD analysis. With the given $\delta \mathbf{B}$, the direction of $\mathbf{k}$ is determined from the condition $\mathbf{k} \cdot \Re(\delta \mathbf{B}) = 0$ and $\mathbf{k} \cdot \Im(\delta \mathbf{B}) = 0$, which is from Maxwell’s equation $\nabla \times \mathbf{B} = 0$. Here, $\Re()$ and $\Im()$ mean the real and imaginary part of a complex quantity, respectively. Therefore, $\mathbf{k}$ is either parallel or antiparallel to the direction of $\Re(\delta \mathbf{B}) \times \Im(\delta \mathbf{B})$. This ambiguity can be removed by using the condition $\mathbf{k} \cdot \delta \mathbf{S} > 0$\textsuperscript{30}, where $\delta \mathbf{S} = \Re(\delta \mathbf{E} \times \delta \mathbf{B})/\mu_0$ is the Poynting vector. This condition means that the phase velocity of a wave is generally close to the Poynting vector direction. Once the direction of $\mathbf{k}$ is determined, its magnitude can be obtained from the real part of Eq. (1).

Figure 5 shows the measured dispersion relations by both methods with MMS4 data from 07:40:46.5 to 07:40:47.5. These are power-weighted ($P(\omega, k)$) histograms to demonstrate the dispersion relation of the whistler wave. In all panels, the cyan dashed line indicates 0.5$P(\omega, k)$ with $\omega$ = 0, which means that it propagates toward the X line for a given $\omega$ and possibly due to errors in the electric field measurement.
weighted $|\delta\mathbf{B}|^2$ histograms of $\omega$ and $k_\parallel$ or $k_\perp$. First, SCM data are partitioned into many segments with 512 data points. Then, the fast Fourier transform is conducted for each segment to obtain $\delta E(\omega, \mathbf{k})$ and $\delta B(\omega, \mathbf{k})$, which are used to obtain $k(\omega)$ using the two methods. Each result is weighted by power in the magnetic field $|\delta\mathbf{B}|^2$ and added up over every segment to generate histograms in Fig. 5.

Figures 5(a) and 5(c) show the dispersion relation from the SVD analysis. The magenta dashed line represents the cold plasma dispersion relation with $\theta = 15^\circ$, $k_d = \sqrt{\omega}/(\alpha_e \cos \theta - \omega)$, where $d_e = c \alpha_e$ is the electron skin depth and $\alpha_e$ is the electron cyclotron frequency. The cyan dashed line indicates $0.5 \alpha_e$. The measured dispersion relation shows $k_\parallel > k_\perp$ and is in relatively good agreement with the cold plasma dispersion relation. However, the SVD analysis generally underestimates $k_\parallel$, which is mostly caused by the violation of the assumption of a unique $k$ for a given $\omega$ and possibly by the errors in the electric field measurements.

Figures 5(b) and 5(d) show the dispersion relation from the hodogram analysis, which is similar to that from the SVD analysis. The main difference is that the SVD analysis has smaller variance in the power distribution; histograms from the SVD analysis show a higher power concentration near the average value of $k$. This means that the average result is the same for both methods, but the SVD analysis, which is mathematically more rigorous, requires a lower number of segments to identify the dispersion relation. The hodogram analysis, on the other hand, is simpler and faster.

The measured dispersion relation for the second MMS event also shows similar features of the whistler mode in the first event; $k_\parallel > k_\perp$, positive $k_\parallel$ (propagating toward the X line), and the phase velocity ($\sim 10^7$ m/s) exceeding the electron thermal velocity. This agreement proves that the whistler wave is excited by the same mechanism for both events—temperature anisotropy in tail electrons.

IV. ELECTRON DISTRIBUTION FUNCTION

For better understanding of the whistler wave generation mechanism, the 2D electron distribution function during the same time period of the dispersion relation measurement is presented in Fig. 6(a).

The measured distribution function shows interesting temperature anisotropy, which depends on the electron energy. The black dashed semicircles indicate the sample contours with an isotropic electron distribution function. For electrons with a high speed ($v_e < 3 v_{th,e}$), $v_e$ is the electron speed; $v_{th,e} \sim 4 \times 10^7$ m/s, contours of the phase space density ($f_e$) are elongated along the parallel direction, indicating $T_\parallel > T_\perp$ for these electrons. This anisotropy is consistent with trapped particle dynamics under an acceleration potential.\textsuperscript{23} The magenta dashed lines denote the boundaries between trapped and passing electrons, based on the anticipated acceleration potential and magnitude of the magnetic field far from the reconnection region; electrons between the lines are trapped due to the parallel electric field and magnetic mirror force. For tail electrons ($v_e > 3 v_{th,e}$), however, the trend is reversed; contours are elongated along the perpendicular direction. These tail electrons with $T_\perp > T_\parallel$ excite the whistler mode.\textsuperscript{26,31}

To confirm this argument, WHAMP has been employed to obtain the dispersion relation and the growth rate. Due to the constraint in the solver, the local 2D electron distribution function must be modeled as a sum of bi-Maxwellian distribution functions. Figure 6(b) shows the modeled electron distribution function, which has the same key features as the measured distribution function. The combined electron density and parallel flow velocity ($\sim 270$ km/s) also match with the measured values.

Figure 6(d) shows the dispersion relation computed by WHAMP for $k_\parallel > 0$ (blue solid line) and for $k_\parallel < 0$ (red solid line). Two lines are slightly different, which is caused by the effect from the local electron flow (positive $V_{el}$). The blue dashed line indicates the dispersion relation in a cold plasma, which is different from the blue solid line.

![Fig. 6.](image-url)
especially for $\omega > 0.5\omega_{ce}$. This discrepancy is mostly due to effects from thermal and energetic electrons.

Figure 6(e) shows the growth rate ($\gamma$) for $\theta = 0$ computed by WHAMP. WHAMP expects a positive growth rate for $0.5\omega_{ce} \leq \omega \leq 0.6\omega_{ce}$ for $k_j > 0$, which agrees with measurements. The whistler mode with $k_j < 0$, on the other hand, is marginally stable ($\gamma = 0$, not shown) due to the larger phase space density of resonant electrons with $|v_j| \gg v_e$.

To understand the difference, it is important to understand the interaction of the wave with resonant electrons. The electrons are resonant with the wave when its parallel velocity satisfies the following cyclotron resonance condition: $\omega - v_j k_j = \omega_{ce}$. In other words, the resonance occurs when the Doppler-shifted frequency of the wave is the same as electron cyclotron frequency. This resonant condition indicates that the whistler mode with $k_j < 0$ is resonant with electrons with a parallel velocity, since $\omega = 0.5\omega_{ce}$, while the mode with $k_j > 0$ is resonant with electrons with a negative parallel velocity. Resonant electrons with a dominant parallel velocity ($|v_j| \gg v_e$) damp the whistler wave, while resonant electrons with a dominant perpendicular velocity ($v_j \gg |v_j|$) excite the whistler wave.

Figure 6(c) clearly shows that the phase space density of electrons with resonant velocity ($|V_{res}| \approx 2 - 3 \times 10^8$ m/s) with $\phi = 0$ (blue asterisks, resonant with whistlers with $k_j < 0$) is higher than that with $\phi = 180^\circ$ (green asterisks, resonant with whistlers with $k_j > 0$).

There is a shoulder near the phase velocity of whistlers ($\sim 2 \times 10^7$ m/s) in $f_\phi(\phi = 0^\circ)$ [blue line in Fig. 6(c)], which has been observed together with whistler waves.5,6 It should be mentioned that this shoulder structure is not an electron beam exciting the whistler mode. As mentioned earlier, these electrons are resonant with the whistler mode with $k_j < 0$, not the mode with $k_j > 0$. The reason why these electrons have a parallel velocity similar to the phase velocity of whistlers with $k_j > 0$ is that the wave frequency is $0.5\omega_{ce}$. Since the whistler wave with $k_j < 0$ is marginally stable, it is more reasonable to say that the shoulder structure results from damping of waves: WHAMP calculations without the shoulder structure show that the growth rate of the whistler waves with $k_j < 0$ becomes positive. This shoulder structure leads to the aforementioned larger phase space density of resonant electrons with $|v_j| \gg v_e$, making the whistler mode with $k_j < 0$ marginally stable.

For reference, the electron distribution function in the magnetosphere away from the reconnection region has been examined. It is measured by MMS3 from UT10:56:00 to 10:56:02 on 16 October 2015. Near this time, there are minimal changes over time in the magnetic field, electron density, and electron velocity. As an example, the electron density profile is shown in Fig. 7(a). The electron density remains around $0.3$ cm$^{-3}$, indicating that MMS is away from the reconnection region or the magnetostrictive separatrix where LHDI creates rapid changes in the density, as shown in both Figs. 2(d) and 3(d).

In this region, the 2D distribution function is much more isotropic, as shown in Fig. 7(b). A WHAMP analysis shows that it is also marginally stable to the whistler mode. There is a possibility that the loss of energetic electrons with a high parallel velocity along the open magnetic field line in the magnetosphere excites whistler waves. However, if there is no fast change in the magnetic geometry, the wave particle interaction makes the distribution function marginally stable to the wave mode. The shoulder structure around $v \sim 9 \times 10^8$ m/s for both $\phi = 0$ and $180^\circ$ in Fig. 7(b) is evidence of the interaction between the whistler mode and electrons. The small temperature anisotropy in the electron tail excites the whistler wave whose phase velocity parallel to the field is about $9 \times 10^8$ m/s. Then, it is damped by resonance electrons, creating a shoulder structure and making the whistler mode marginally stable. This means that the loss cone distribution by the open field line in the magnetosphere is not responsible for the whistler wave excitation near the separatrix region; we need fast dynamic changes in the magnetic field topology, associated with magnetic reconnection.

Compared to the distribution functions in the magnetosphere [red lines in Fig. 7(e)], those near the magnetostrictive separatrix [blue lines in Fig. 7(c)] show that there is a significant reduction in the phase space density of energetic electrons with $\phi \sim 0$ and $\phi \sim 180^\circ$. As
mentioned before, this loss of electrons with a dominant parallel velocity is responsible for the whistler wave generation. This change in the phase space density of electrons mostly parallel or antiparallel to the field line cannot be explained by the trapped particle dynamics that only expects the reduction of the phase space density with $\phi \sim 90^\circ$. In Sec. V, the possible role of the turbulent transport by LHDI in the loss of energetic electrons with a dominant parallel velocity is discussed. As mentioned in Sec. II, the increase in the phase space density for lower energy electrons near the magnetospheric separatrix is caused by electrons from the exhaust region which are transported by LHDI-driven turbulence.

V. DISCUSSION AND SUMMARY

The correlated behavior between activities of LHDI and the whistler mode in both events suggests that LHDI may lead to the dynamic change in the electron distribution function. The local electron density increase followed by the LHDI activity in Figs. 2 and 3 prove that LHDI initiates the electron mixing process near the magnetospheric separatrix. On the other hand, Fig. 3(i) suggests that LHDI produces a preferential loss of electrons with a high parallel velocity, causing the temperature anisotropy in tail electrons which excites the observed whistler wave.

The turbulent transport process by LHDI is caused by the $\mathbf{E} \times \mathbf{B}$ motion from strong fluctuations in the electric field. The magnitude of electric field fluctuations by LHDI exceeds that of the reconnection electric field, which means that the particle drift motion near the magnetospheric separatrix is dominated by the strong electric field fluctuation. This $\mathbf{E} \times \mathbf{B}$ drift motion does not depend on the parallel velocity. Thus, to understand the difference, more detailed analysis on the particle motion is required.

The key difference between electrons with a dominant parallel velocity and those with a dominant perpendicular velocity is the ability to move into the exhaust region by a velocity kick from the turbulent electric field fluctuation. When electrons with a high parallel velocity see the magnetic field in the exhaust region by a kick from LHDI, they travel quickly along the magnetic field in the exhaust region and do not come back to the magnetosphere side. An example motion for this group of electrons is illustrated by a blue path in Fig. 1. However, electrons with a dominant perpendicular velocity can remain in the mixing zone longer due to their large gyro radius, moving back and forth by the fluctuating electric field. An example of the guiding center motion for this group of electrons is illustrated by a green line in Fig. 1. This picture can explain the sudden change in PAD of energetic electrons right after the intense LHDI activity, as presented in Fig. 3(i). This argument can be verified by running test particles near the magnetospheric separatrix under the LHDI-driven turbulence, which is a potential future research topic.

It should be mentioned that the exact mechanism for the observed anisotropy in tail electrons requires further investigation. Besides LHDI, there is a possibility that the observed 2D electron distribution is explained by a model based on the double adiabatic theory. The measurement location is away from the X-line, such that there is no significant change in the local magnetic field strength during the whistler wave activity; the local flux tube has not been expanded. The part of the flux tube, on the other hand, may be stretched as the tube approaches the X-line, resulting in the decrease in the average density in the flux tube. In this case, the electrons with a high parallel velocity can be dominantly cooled. However, this mechanism cannot explain the increase in the local electron density observed around UT13:05:27, which is caused by the low-energy electrons from the magnetosheath. The density increase indicates that the part of the flux tube has been already affected by the electron mixing process via LHDI-driven turbulence.

In summary, two MMS reconnection events at the dayside magnetopause with whistler wave activity near $0.5T_m$ are analyzed. The whistler wave exists in the electron mixing region near the magnetospheric separatrix. In both events, the correlation between LHDI and the whistler mode is observed. The anisotropy in energetic electrons is caused by the loss of tail electrons with a dominant parallel velocity. This anisotropy in the tail electrons results in the excitation of the observed whistler mode. The measured dispersion relations of the whistler mode show that the whistler wave propagates toward the X-line mostly parallel to the magnetic field ($0 < 20^\circ$). The 2D electron distribution function demonstrates the temperature anisotropy in low energy electrons ($T_i > T_e$) as well as that in high-energy electrons ($T_i < T_e$). A linear analysis verifies that the observed 2D distribution is unstable to the whistler mode.

Finally, a possible explanation of the observed temperature anisotropy by the preferential loss of electrons with a high parallel velocity due to the turbulent transport process by LHDI is proposed.

This whistler wave around $0.5T_m$ shows that there is an active X line nearby. Moreover, the whistler mode can help determine the location of spacecraft because it is an important indicator of the electron mixing region near the magnetospheric separatrix. The impact of the whistler wave on magnetic reconnection requires further investigation, as current research is limited to the wave near the magnetospheric separatrix. Because the whistler mode can also be excited near the X line, it is important to study the excitation mechanism near the X line and to address possible role of the whistler wave in magnetic reconnection.

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