

Ultrafast field-particle energy transfer during chorus emissions in space

Corresponding Author: Dr Chengming Liu

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Referee #1

(Remarks to the Author)

This paper reports an observation of chorus emissions in the neutral sheet of the Earth's magnetotail at 25 earth radii. The observation is a new finding that the chorus emissions, usually observed in the inner magnetosphere, can also be generated in a magnetic dip (MD) showing a weak decrease of local magnetic field strength in the neutral sheet. The finding is significant implying the nonlinear wave-particle interaction chorus emissions with frequency variation can take place anywhere in space plasma where certain conditions are met. The paper shows detailed analysis of the linear dispersion relation of whistler-mode waves and linear growth rates based on the observed wave and energetic particle data with high-time resolution of the MSS spacecraft. The methods of the data analyses are described properly, and they are reasonable and useful. Some of the energetic particle data analyses are insufficient for claiming observation of electron holes in the velocity phase space, and they should be clarified before publication of the paper. More specific comments are the followings.

(1) Figure 5: Electron distribution in the phase space chorus waves. a-d: The time series F, G, H, I in Figure 4 shows evolution of an rising-tone chorus element, while the electron holes are indicated on both sides of the resonance velocity indicated by the dashed magenta line.

As the frequency increases the resonance velocity decreases. Some of the depletions in the velocity phase space do not correspond to the electron holes generating the rising-tone chorus element. The rising-tone frequency varies from 0.1 fce to 0.5 fce. Which frequency is assumed for the calculation of the resonance velocity? As we find in the frequency spectra in Figures 3a and 3b, the wave fields consist of several waves. In the computation of the relative phase angle ζ , the wave phase of the rising-tone element should be used to identify the electron hole. How is the wave phase calculated? It is not easy to extract a wave phase at a specific frequency of the rising-tone chorus element from the observed wave forms.

(2) Figure 4f2: A depletion is indicated at the resonance velocity. Similar depletions are found in other parallel velocities. The 2D cuts of the 3D distribution function do not show the depletion in the velocity phase space clearly. A plot of distribution function $f(v_{\text{parallel}}, v_{\text{perp}})$ after integration over gyro-phases would be more useful for identifying possible depletions.

(3) Lines 157-158: In the cut of the 3D distribution function, the gradient of the VDF cannot be recognized properly. The gradient is for the linear growth rate, but the deformation of the VDF is due to coherent nonlinear wave-particle interaction. The nonlinear growth rate does not depend on the gradient. It is due to the bunching of gyro-phases. It is not appropriate to discuss the gradient of the VDF in the nonlinear stage of the interaction.

(4) Lines 164-167: The crucial role played by electron holes in the generation of whistler mode waves has been verified by Kitamura et al. [Nature Communications, 2022].

(5) Figure 3h: What is the frequency range of positive linear growth rate? It is not easy to read it from the 3D plot. A simple plot of the linear growth rate as a function of frequency in the parallel direction, and a plot of the linear growth rates in the 2D wavenumber space would be better. It is also interesting to show that the chorus wave is growing even in a frequency range of negative linear growth rate. Obviously, the wave growth process is due to formation of electron hole and frequency chirping through nonlinear wave-particle interaction triggered by a coherent wave growing due to the linear growth rate.

(6) Figure 3f: The wave propagation angle varies from 0 to 20 degrees as we find in Figure 3d. The linear dispersion relation for 20 degrees may well be plotted in addition to 0 degree. What is the ratio of the electron plasma frequency to the electron cyclotron frequency assumed? It determines the shape of the linear dispersion relation of whistler-mode waves.

Minor points:

(7) Figure 6: Labeling of plots are wrong (abdddf -> abcdef).

(8) Line 208: "resonance velocity" is better than "resonant velocity" used in other parts of the paper. "velocity" is not resonant with the wave, while "electrons" are resonant.

Referee #2

(Remarks to the Author)

Review of the paper by Liu et al submitted to Nature

This paper reports a new observation of whistler mode chorus waves in the tail region of the magnetosphere, which to my knowledge has never been observed before. It includes particle and wave observations with exceptionally high time resolution and proceeds to test some of the theories on the generation of chorus waves. This is Nature material, but subject to my comments below.

The paper states correctly that chorus is usually seen on magnetic field lines that are dipolar, and that according to theory the gradient in the magnetic field plays an important role in the generation. These observations of chorus are not on dipolar field lines – they are some 25 Re down tail. The discussion suggests that the theory needs to be revised. However, their own data shows that there are gradients in the magnetic field where they observe chorus, so they cannot rule out the importance of density gradients. The authors need to do more tests to see if it is consistent with second order resonance as given in the theory.

The authors use the data to calculate the linear instability and find evidence for locally growing waves. This confirms local generation. They also show energy transfer from particles into the waves which supports local generation. However, I think the most important part of the paper is their search for electron depletions or holes in the electron phase space density. The generation of chorus is highly nonlinear and evidence for electron holes is key to testing the theory. My concern here is the statistics. For example, in Figure 4 the evidence for phase bunching is not very strong, the contours are noisy and are not convincing. Some statistical analysis is required giving for example 95% confidence levels. The same is true for Figure 5. There are dashed circles around electron "holes" on the right near the dashed red line indicating the parallel phase velocity – but there are similar "holes" on the left of the figure near $V_z = -4$ which are not even mentioned. The statistical significance of these observations needs to be quantified.

Also I do not understand why the phase space density has units of s^2, m^{-5} , it should be $s^3 m^{-6}$. Same question applies to Figure 4. Also, something seems strange in figure 3 – panels c, d and e have the same envelope as a and b, but they cut off just below 10 Hz, instead of near 1 Hz. It looks like they have been shifted in frequency on the axes, and does not seem right. This must be addressed and explained. Also there are two panels labelled f in Figure 4 – perhaps more care is needed. This does not inspire confidence.

Line 206 onwards. The authors make a point that the resonant energy is much smaller than the speed of light and that relativistic effects are not critical for generation. But it is well known that the dominant interaction is with electrons of 1-50 keV maybe 100 keV electrons for wave generation and that MeV electrons don't play much role in wave generation. The point is that the relativistic resonance condition extends to MeV energies and the waves resonate with electrons at all these energies at the same time. The lower energy electrons give rise to wave growth and the waves then transfer energy to accelerate a fraction of the electrons to relativistic energies. This is explained in Horne et al., JGR, 2005.

In summary I cannot recommend the paper as it stands. If the authors can provide convincing evidence that the observations of the electron holes are statistically significant, and address the others points above about the gradient, and modify the discussion about the acceleration, then I think this paper would be suitable for Nature.

Version 1:

Reviewer comments:

Referee #1

(Remarks to the Author)

The manuscript has been improved properly based on the comments by the referees. The confirmation of the nonlinear characteristics by calculating the inhomogeneity factor from the MMS spacecraft data makes the paper more significant and convincing. The paper is an important contribution from the observation to the study of nonlinear wave-particle interaction as the generation mechanism of chorus emissions.

Referee #2

(Remarks to the Author)

The authors have addressed all the points I have raised and I am happy with their reply - except, they need to include some more of this information in the text of the paper as well. Specifically, I had asked that they provide some statistical analysis giving 95% confidence levels. They have stated in their reply that "For all the velocity distributions functions (VDF), we have set 95% confidence levels and removed data beyond the confidence interval". But they need to state this in the text of the paper - otherwise other readers may ask the same question.

I am happy to recommend publication provided they include this statement.

I think this is an important paper.

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Overall response:

We would like to express our sincere gratitude to the referees for your constructive comments and valuable suggestions, all of which we have comprehensively addressed in this revision. Below, we provide a point-by-point response.

Both referees raised concerns regarding the electron hole signal, which ultimately depends on the electron measurements. In addition to implementing the improvements you suggested, we have conducted two more calculations independent of the electron measurements: one is the inhomogeneous factor S in the second-order resonance equation, which is the cause of the electron hole, and the other is the resonance current J_{Bwave} antiparallel to the wave magnetic field, which is the consequence of the electron hole. Results from both calculations are in line with the presence of the electron hole (please see more details in our reply below). Hence, the combined data analyses, especially the newly-added J_{Bwave} which can directly cause the frequency chirping, provide solid evidence for the nonlinear theory of chorus waves.

We believe that the revisions made have significantly improved the manuscript, and we hope that these changes meet your expectations.

Thank you once again for your time, effort, and involvement.

Best regards,

Chengming Liu, Jinbin Cao, Christopher Russell, Craig Pollock, Boning Zhao, Xining Xing, Yangyang Liu, Per Arne Linqvist, James Burch

Reply to Referee1:

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[Thank you for highlighting the significance of this study and providing the](#)

constructive review. Based on your suggestions and comments, we have managed to strengthen our results. Please see our reply below.

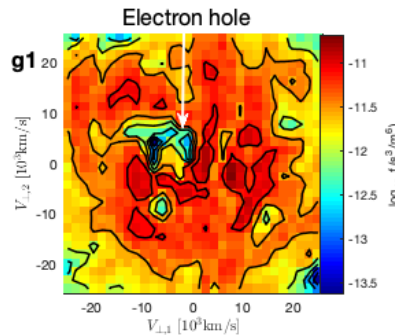
(1) Figure 5: Electron distribution in the phase space chorus waves. a-d: The time series F, G, H, I in Figure 4 shows evolution of an rising-tone chorus element, while the electron holes are indicated on both sides of the resonance velocity indicated by the dashed magenta line.

As the frequency increases the resonance velocity decreases. Some of the depletions in the velocity phase space do not correspond to the electron holes generating the rising-tone chorus element. The rising-tone frequency varies from $0.1 f_{ce}$ to $0.5 f_{ce}$. Which frequency is assumed for the calculation of the resonance velocity? As we find in the frequency spectra in Figures 3a and 3b, the wave fields consist of several waves. In the computation of the relative phase angle zeta, the wave phase of the rising-tone element should be used to identify the electron hole. How is the wave phase calculated? It is not easy to extract a wave phase at a specific frequency of the rising-tone chorus element from the observed wave forms.

Here the wave frequency used for the previous calculation is $0.15 f_{ce}$, corresponding to the maximum wave power during the whole period. In the previous calculation, we assumed that the frequency variation ($0.1-0.3 f_{ce}$) for the time series is not significant and used a constant $0.15 f_{ce}$ for simplicity. This may cause potential confusion.

Now we take the frequency variation into account, and select the wave frequency f_p based on the maximum wave power at each time and then calculate the resonance speed, as shown by the magenta lines in Figure 4.

To calculate the relative phase angle, we first obtain the wave magnetic field $\mathbf{B}_{wave}$ by bandpass filtering between $[f_l, f_u]$, where f_l and f_u are the lower and upper frequencies corresponding to half the maximum wave power, and then we calculate the angle between $\mathbf{B}_{wave}$ and $\mathbf{V}_{perp}$ at each time, without directly resolving the wave phase. To illustrate in more detail, now we use $\mathbf{b}_{wave}$ (normed vector of $\mathbf{B}_{wave}$) as $\mathbf{V}_{\perp 1}$ in the 2D ($V_{\perp 1} - V_{\perp 2}$) cut of the 3D distribution, where the cutting range is close to the resonance speed $[0.5V_r, 2V_r]$. The electron hole now can be clearly identified in the cyclotron plane (e.g., Figure 4g1 below).



Electron hole in the 2D ($V_{\perp 1} - V_{\perp 2}$) cut. Here the $V_{\perp 1}$ is aligned with $\mathbf{B}_{wave}$.

The identified electron hole has two main features that are consistent with the nonlinear theoretical expectations: 1) it locates in the $-V_{\perp 1}$ region, thus can lead to resonant current antiparallel to $\mathbf{b}_{wave}$, which has been predicted to directly cause the

frequency rising of chorus (Omura et al., 2011). 2) its center region corresponds to a perpendicular speed of $\sim 10^4$ km/s, which leads to an inhomogeneous factor of ~ -0.51 (please see *the inhomogeneous factor* in Methods), close to the predicted value (-0.41) which yields the maximum energy transfer condition.

In addition, we have confirmed the J_{Bwave} from a different perspective, i.e., calculating the resonant current using the Ampere's law which resolves the current density from the magnetic field curvature (without involvement of electron data), as shown in Figure 5e.

The consistence of these calculations suggests that the signal of electron hole can be well resolved by our procedure. We have included more statements in the text to clarify this, **please see lines 154-185, and 203-214.**

(2) Figure 4f2: A depletion is indicated at the resonance velocity. Similar depletions are found in other parallel velocities. The 2D cuts of the 3D distribution function do not show the depletion in the velocity phase space clearly. A plot of distribution function $f(v_{parallel}, v_{perp})$ after integration over gyro-phases would be more useful for identifying possible depletions.

Thanks for your suggestion. We have plotted the distribution function $f(\mathbf{V}_{\parallel}, \mathbf{V}_{\perp})$, as shown in Figure 4. f1-f4, where the hole signature does not become clearer. The integration over gyro-phases seems not better, considering that the depletions are both weak and local in the velocity space. Electron hole can more easily fade into the thermal background when its center speed moves closer to the thermal speed. We find that even in the PIC simulations, depletions are also hard to find directly in $f(\mathbf{V}_{\parallel}, \mathbf{V}_{\perp})$ (e.g., Katoh and omura, 2007, doi: 10.1029/2007GL029758; Wang et al., 2024, doi: 10.1029/2023GL108000). Recent simulations often use a so-called δf method, which subtracts the initial VDFs to show the hole clearer. Such subtractions cannot be done in observations, since the initial VDFs are unknown for the real data. Discussing the hole's presence in the $f(\mathbf{V}_{\parallel}, \mathbf{V}_{\perp})$, therefore, might be inappropriate, we have **deleted related discussions in the text.**

(3) Lines 157-158: In the cut of the 3D distribution function, the gradient of the VDF cannot be recognized properly. The gradient is for the linear growth rate, but the deformation of the VDF is due to coherent nonlinear wave-particle interaction. The nonlinear growth rate does not depend on the gradient. It is due to the bunching of gyro-phases. It is not appropriate to discuss the gradient of the VDF in the nonlinear stage of the interaction.

Yes, we agree that the nonlinear wave growth is not related to the gradients of the VDFs. In the previous discussion, we intended to mean that the existence of electron holes may cause gradients near the resonance velocity, which now seems not clearly supported by the data. To remove possible confusion, **we have deleted related discussions about the gradients in the text.**

(4) Lines 164-167: The crucial role played by electron holes in the generation of whistler mode waves has been verified by Kitamura et al. [Nature Communications,

2022].

The motioned paper focused on lion roars (without frequency chirping) in the magnetosheath, which we think does not influence our statement regarding chorus here. We had included a statement to clarify this, **please see line 175**.

(5) Figure 3h: What is the frequency range of positive linear growth rate? It is not easy to read it from the 3D plot. A simple plot of the linear growth rate as a function of frequency in the parallel direction, and a plot of the linear growth rates in the 2D wavenumber space would be better. It is also interesting to show that the chorus wave is growing even in a frequency range of negative linear growth rate. Obviously, the wave growth process is due to formation of electron hole and frequency chirping through nonlinear wave-particle interaction triggered by a coherent wave growing due to the linear growth rate.

Thanks for such a great suggestion! Now we have replotted the dispersion relation in Figure 3, including a line plot of linear growth rate as a function of frequency (range for positive growth rate, $[0.05, 0.2] f_{ce}$), and a 2D plot of growth rate in the wave number space. As you suggested above, we can find that the largest frequency with positive linear growth rate is clearly lower than the chorus' maximum frequency which approaches $0.5 f_{ce}$. Hence, the chorus growth should be ascribed to nonlinear wave-particle interaction which can yield higher-frequency triggering emissions (e.g., Omura et al. 2008, *JGR*).

We have added related discussions in the text, **please see line 134-138**.

(6) Figure 3f: The wave propagation angle varies from 0 to 20 degrees as we find in Figure 3d. The linear dispersion relation for 20 degrees may well be plotted in addition to 0 degree. What is the ratio of the electron plasma frequency to the electron cyclotron frequency assumed? It determines the shape of the linear dispersion relation of whistler-mode waves.

Following your suggestion, we have added the linear dispersion relation lines for both 0 and 20 degrees in Figure 3g (blues and black dashed lines). The ratio of electron plasma frequency to the electron frequency in this case is ~ 25 , obtained from local magnetic field strength (4 nT) and density (0.1 cm^{-3}). We have specified this value in the text, **please see Figs. 3g-3i**.

Minor points:

(7) Figure 6: Labeling of plots are wrong (abdddf $\rightarrow$ abcdef).

Thanks for your reminding, we have revised the labels in Figure 5 (which is the original Figure 6).

(8) Line 208: "resonance velocity" is better than "resonant velocity" used in other parts of the paper. "velocity" is not resonant with the wave, while "electrons" are resonant.

Yes, we agree. We have revised this phrase throughout the text.

Reply to Referee2:

This paper reports a new observation of whistler mode chorus waves in the tail region of the magnetosphere, which to my knowledge has never been observed before. It includes particle and wave observations with exceptionally high time resolution and proceeds to test some of the theories on the generation of chorus waves. This is Nature material, but subject to my comments below.

Thank you for endorsing the significance of this study and providing the constructive review. We have thoroughly revised the manuscript according to your suggestions and comments. Please see our reply below.

The paper states correctly that chorus is usually seen on magnetic field lines that are dipolar, and that according to theory the gradient in the magnetic field plays an important role in the generation. These observations of chorus are not on dipolar field lines – they are some 25 Re down tail. The discussion suggests that the theory needs to be revised. However, their own data shows that there are gradients in the magnetic field where they observe chorus, so they cannot rule out the importance of density gradients. The authors need to do more tests to see if it is consistent with second order resonance as given in the theory.

Following your suggestion, we have carried out more tests to check the importance of magnetic field gradient in the second-order resonance condition. We directly calculate the inhomogeneous factor S in second-order resonance equation:

$$\frac{d^2\zeta}{dt^2} = \omega_{tr}(\sin \zeta + S)$$

where is ζ the relative phase angle and ω_{tr} is the trapping frequency. For the rising-tone chorus generation, that requires S to be in the range $[-1,0]$ (e.g., Omura et al., 2008, JGR). S is contributed by two terms, the nonlinear term R_1 and field gradient term R_2 :

$$S = R_1 + R_2 = \frac{-1}{s_0\omega\Omega_w} s_1 \frac{\partial\omega}{\partial t} + \frac{-1}{s_0\omega\Omega_w} c s_2 \frac{\partial\Omega_e}{\partial h}$$

These parameters can be directly calculated using the MMS observations (please see more detail in *the inhomogeneous factor* in Methods). In particular, we use the four-point measurement of magnetic field to calculate the magnetic field gradient along the magnetic field line, yielding $\sim 1.5 \text{ pT km}^{-1}$. Using $V_{\perp} \sim 10^4 \text{ km/s}$ obtained from the electron hole signal in the distribution function (please see reply below), we have:

$$S = R_1 + R_2 = -0.46 - 0.05 = -0.51$$

which suggests: 1) the second order resonance condition for the rising-tone chorus is satisfied, and the value is close to -0.41 which theoretically corresponds to the maximum energy transfer condition; 2) $R_2/R_1 \sim 0.1$, i.e., the field gradient term is not important in the present case.

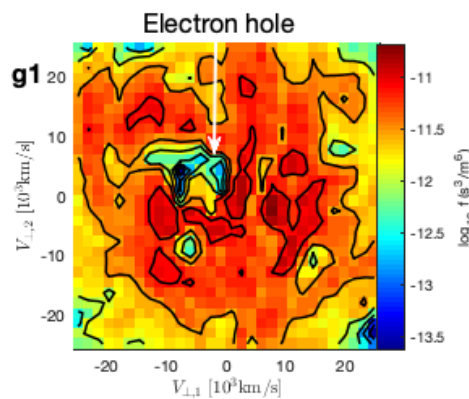
We have added related content in the text, **please see lines 227-235.**

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transfer from particles into the waves which supports local generation. However, I think the most important part of the paper is their search for electron depletions or holes in the electron phase space density. The generation of chorus is highly nonlinear and evidence for electron holes is key to testing the theory. My concern here is the statistics. For example, in Figure 4 the evidence for phase bunching is not very strong, the contours are noisy and are not convincing. Some statistical analysis is required giving for example 95% confidence levels. The same is true for Figure 5. There are dashed circles around electron “holes” on the right near the dashed red line indicating the parallel phase velocity – but there are similar “holes” on the left of the figure near $V_z = -4$ which are not even mentioned. The statistical significance of these observations needs to be quantified.

Thanks for your suggestion. The value of the inhomogeneous factor obtained above suggests the presence of electron hole. For all the velocity distribution functions (VDFs), we have set 95% confidence levels and removed data beyond the confidence interval. In addition, we have made more changes to clarify the issue, including:

- 1) we have removed the measurement error and one-count level of the FPI instrument (Pollock et al., 2016, SSR).
- 2) we have used $\mathbf{b}_{\text{wave}}$ (normed vector of $\mathbf{B}_{\text{wave}}$) as $V_{\perp 1}$ direction in the 2D ($V_{\perp 1}$, $V_{\perp 2}$) cuts of VDFs and limited the speed range along the out-of-plane direction (near the resonance speed V_r , $V_r \cdot [0.5, 2]$). Now the electron hole is more clearly identified in the cyclotron plane, e.g., Figure 4g1 below.

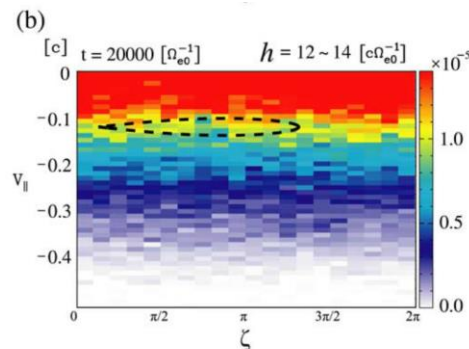


Electron hole in the 2D ($V_{\perp 1} - V_{\perp 2}$) cut. Here the $V_{\perp 1}$ corresponds to $\mathbf{B}_{\text{wave}}$.

The identified electron hole has two main features that are consistent with the nonlinear theoretical expectations: 1) it locates in the $-V_{\perp 1}$ region, thus can lead to resonant current antiparallel to $\mathbf{B}_{\text{wave}}$, which has been predicted to directly cause the frequency rising of chorus (Omura et al., 2011). 2) its center region corresponds to a perpendicular speed of $\sim 10^4$ km/s, which leads to an inhomogeneous factor of ~ -0.51 (as we replied above), close to the predicted value (-0.41) which yields the maximum energy transfer condition.

3) most importantly, we have also calculated the resonance current antiparallel to the wave magnetic field, via the Curlometer method (widely used for MMS data, Dunlop et al. 1998, ASR), which resolves electric current density based on Ampere’s law (uses only magnetic field data and calculates its curvature). This is another advantage

of the MMS mission. Consistent with the electron hole feature, we find locally-enhanced electric current antiparallel to the wave magnetic field (please see Figure 5d), as predicted by the nonlinear theory. This current directly leads to the frequency rising of chorus (Omura et al., 2011, JGR).



Signal of electron hole in simulations (Figure 8b in Omura et al., 2008, JGR). We also would like to note that due to its weak nature, electron hole is typically hard to be clearly identified in the VDFs even in PIC simulations (e.g., Figure 8b in Omura et al., 2008, JGR). Electron hole can more easily fade into thermal background when its center speed moves closer to thermal speed. This is the reason why recent PIC simulations often use a so-called δf method, which subtracts the initial VDFs to the make the hole clearer. Such subtractions cannot be done in observations since the initial distribution is unknown for real data. Therefore, checking the resonant current using magnetic field curvature is necessary and more reliable in practice (for MMS mission), with electron data used as an auxiliary proof. We have included more statements in the text to clarify this, **please see lines 154-185, and 203-214.**

Also I do not understand why the phase space density has units of s², m⁻⁵, it should be s³ m⁻⁶. Same question applies to Figure 4. Also, something seems strange in figure 3 – panels c, d and e have the same envelope as a and b, but they cut off just below 10 Hz, instead of near 1 Hz. It looks like they have been shifted in frequency on the axes, and does not seem right. This must be addressed and explained. Also there are two panels labelled f in Figure 4 – perhaps more care is needed. This does not inspire confidence.

Thanks for your patience for noting these possible errors. We have corrected all the labels and units in the figures. For the frequency cutoff in panels c, d, and e, it is because during the SVD analysis, the spectral matrices are averaged over 8 wave periods to get smooth results. This may cause confusion. Now we replot the figure without doing the average to make the frequency in all planes consistent. **Please see figures 3 and 4.**

Line 206 onwards. The authors make a point that the resonant energy is much smaller than the speed of light and that relativistic effects are not critical for generation. But it is well known that the dominant interaction is with electrons of 1-50 keV maybe 100 keV electrons for wave generation and that MeV electrons don't play much role in

wave generation. The point is that the relativistic resonance condition extends to MeV energies and the waves resonate with electrons at all these energies at the same time. The lower energy electrons give rise to wave growth and the waves then transfer energy to accelerate a fraction of the electrons to relativistic energies. This is explained in Horne et al., JGR, 2005.

We agree that the relativistic resonance condition extends to MeV energies and the waves resonate with electrons at all energies simultaneously. As you suggested, the lower energy electrons cause the wave growth and the waves then transfer energy to accelerate a small fraction of high-energy electrons to relativistic energies. We have revised our discussions in the text, based on the detailed explanations in Horne et al., JGR, 2005. **Please see lines 236-242.**

In summary I cannot recommend the paper as it stands. If the authors can provide convincing evidence that the observations of the electron holes are statistically significant, and address the others points above about the gradient, and modify the discussion about the acceleration, then I think this paper would be suitable for Nature. Thanks for your constructive comments and valuable suggestions. We have carefully addressed the issues you mentioned above, and hope these revisions are satisfactory.

Reply to Referee1:

The manuscript has been improved properly based on the comments by the referees. The confirmation of the nonlinear characteristics by calculating the inhomogeneity factor from the MMS spacecraft data makes the paper more significant and convincing. The paper is an important contribution from the observation to the study of nonlinear wave-particle interaction as the generation mechanism of chorus emissions.

[Thanks for highlighting the significance of this study and endorsing its publication.](#)

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I am happy to recommend publication provided they include this statement.

I think this is an important paper

[Thanks for the recommendation. We have included this statement in line 143.](#)