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Energetic electron loss process associating with oblique chorus emissions in the outer radiation belt

Yikai Hsieh and Yoshiharu Omura

Research Institute for Sustainable Humanosphere, Kyoto University

Purposes:

1. To verify the precipitation process caused by chorus emissions by simulation.
2. To check if wave normal angles of chorus emissions contribute to electron loss in the outer radiation belt.

Oblique whistler mode waves are usually detected by satellites

- Several studies reported the relation between parallel propagating chorus waves and EEP.

  Ex: [Rosenberg et al. (1990)], [Hikishima et al.(2010)], [Saito et al. (2012)], [Chen et al. (2020)],[Miyoshi et al. (2021)]

- Obliquely propagating (wave normal angle $\theta \neq 0°$) chorus waves lead to effective pitch angle scattering. Even a small θ makes the WPI different from parallel cases. [Hsieh & Omura (2017, 2018)]

- In observations, there are many chorus events with oblique wave normal angles. Therefore, we cannot ignore the oblique effects in wave-particle interactions.

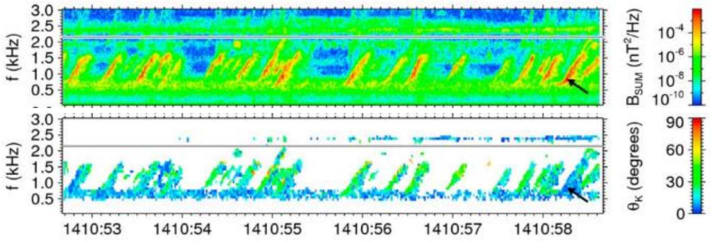
Observations from Van Allen Probes:

Lower-band chorus

[Santolik et al., *GRL*, 2014]

B spectrum

Wave normal angle

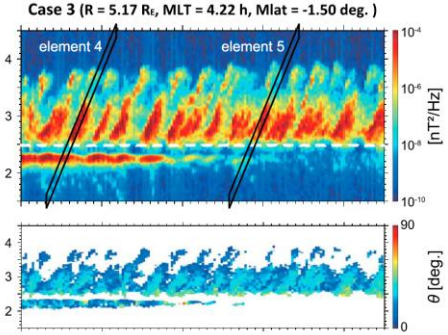


Upper-band chorus

[Kubota et al., *JGR*, 2018]

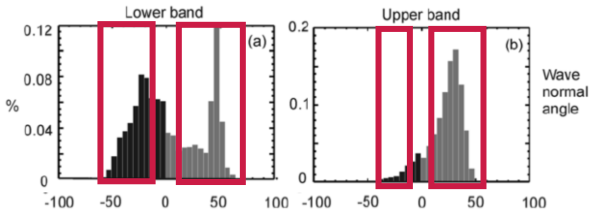
B spectrum

Wave normal angle



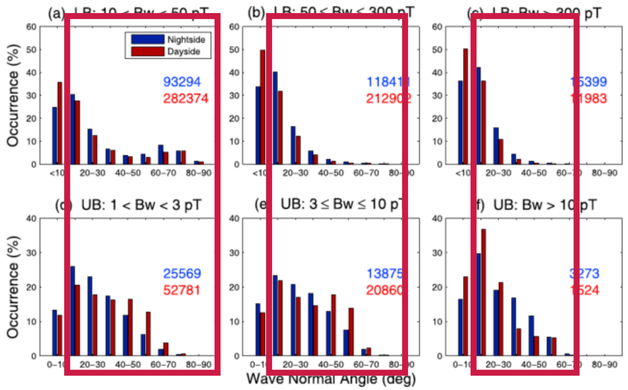
Statistical results of chorus wave normal angles:

Cluster



[Breneman et al., *JGR*, 2009]

THEMIS



[Li et al., *JGR*, 2011]

: Oblique chorus; others: (Quasi) parallel chorus

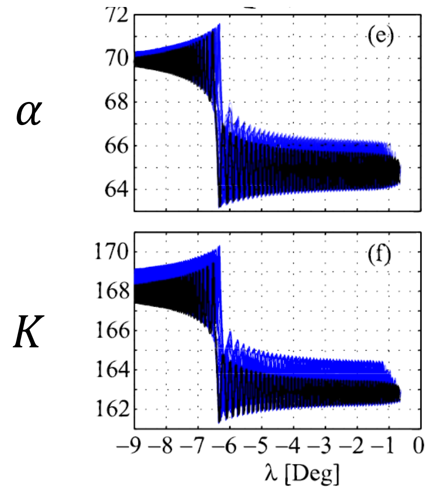
There are more oblique events than parallel events

Scattering tendencies of nonlinear wave-particle interactions

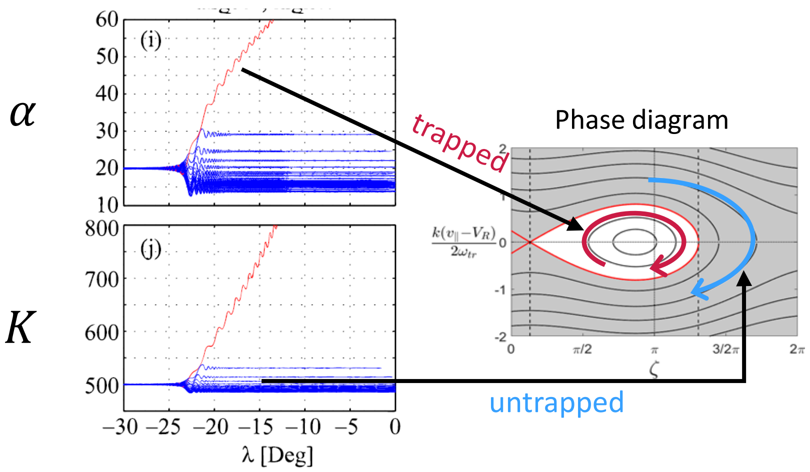
Electron tendencies after nonlinear WPI:

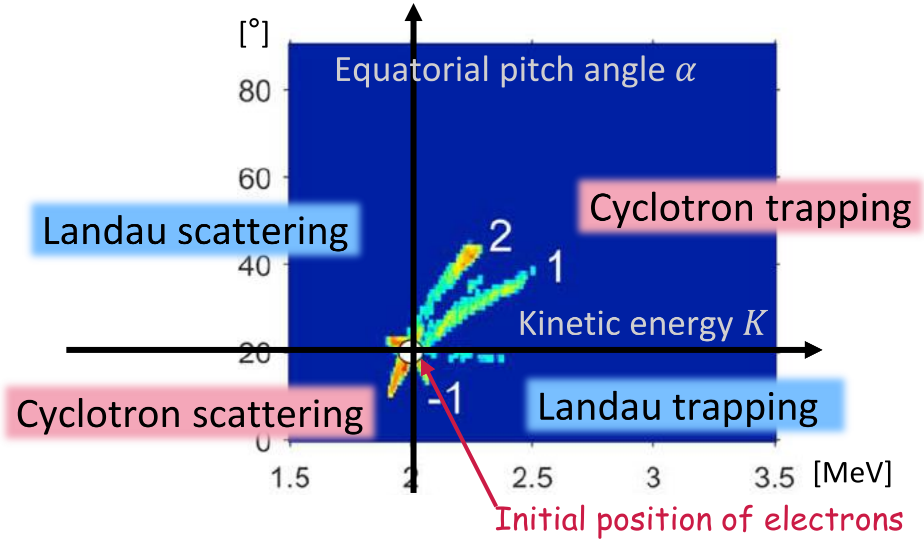
[Bortnik et al., *GRL*, 2008; Saito et al., *JGR*, 2016]

(1) Nonlinear scattering (Phase-bunching, dislocation)



(2) Nonlinear trapping (Phase-trapping)





***In case the wave propagating away from the equator:**

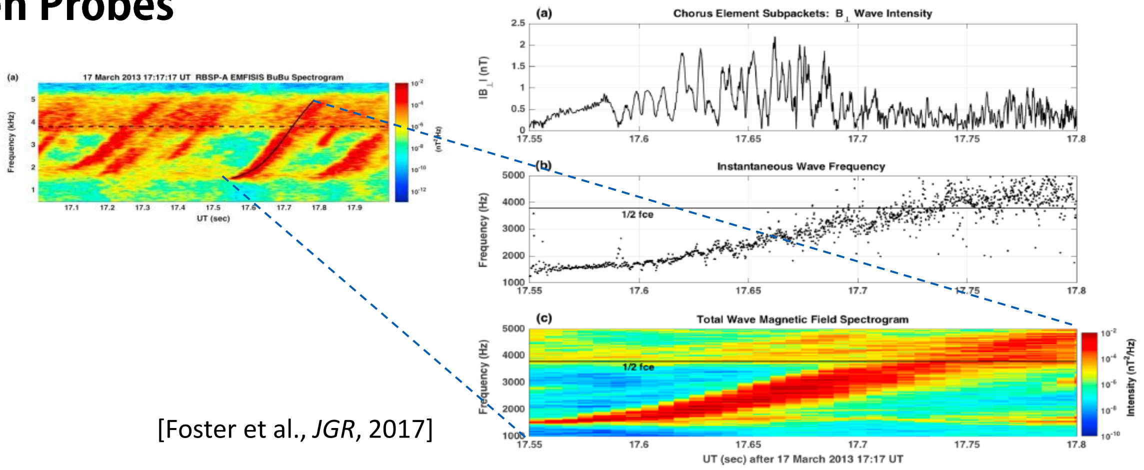
Resonance	Nonlinear interaction	Equatorial pitch angle	Kinetic energy
Cyclotron	Scattering	↘	↘
	Trapping	↗	↗
Landau	Scattering	↗	↘
	Trapping	↘	↗

- Tendencies of n < 0 are as Landau resonance.
- Tendencies of n > 1 are as cyclotron resonance.
- For electrons at high α & K, the tendency for cyclotron resonance appears like Landau resonance.

- Of course, there should be diffusion as well. Because diffusion does not contribute to effective precipitation, so we only discuss nonlinear processes in this study.

Whistler mode chorus wave model

Wave observed by Van Allen Probes



[Foster et al., *JGR*, 2017]

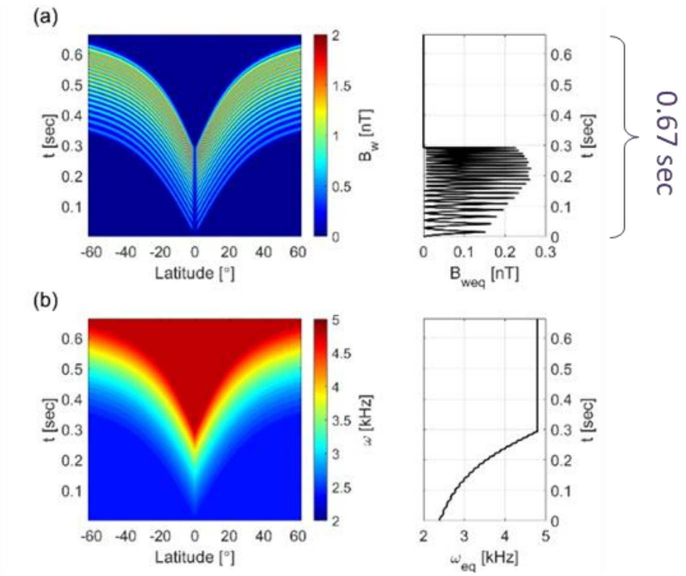
Subpacket structure

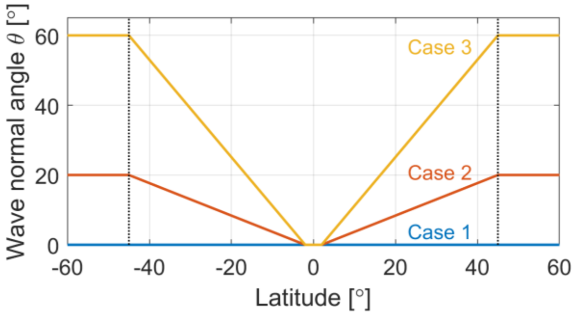
Rising-tone frequency

Wave model profile for a chorus element in simulations

1. Wave amplitude: <u>subpacket structure</u> ($B_{max} = 2.1$nT)
2. Wave frequency: <u>rising-tone lower-band</u> ($0.25 - 0.5\Omega_{eq}$)
3. Wave normal angles:
   Case 1: purely parallel
   Case 2: slightly oblique with $\theta_{max} = 20°$
   Case 3: moderated oblique with $\theta_{max} = 60°$

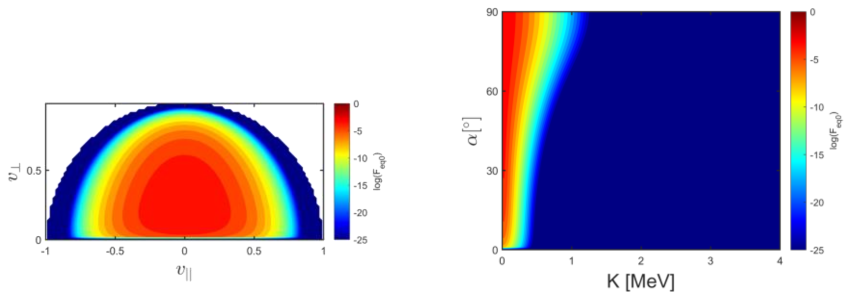
*In this study we did not try very oblique wave normal angles.





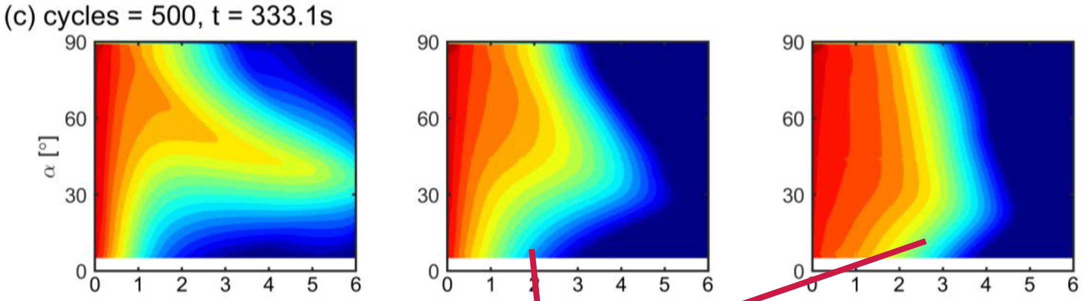
Compare precipitations between oblique and parallel chorus emissions

- Initial distribution function: **Subtracted Maxwellian Dist.**

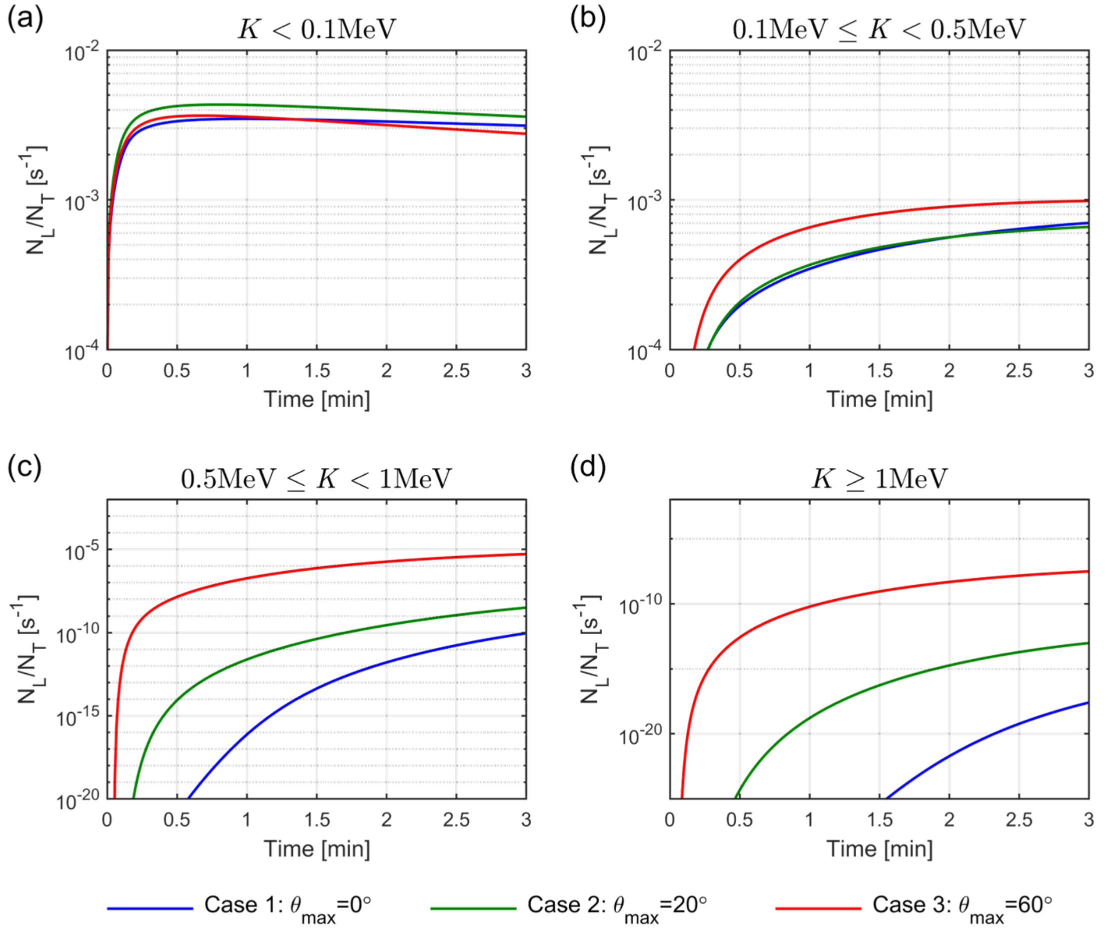


- Normalized total fluxes: 1 m^{-2}

- After interacting with 500 consecutive chorus emissions:



Oblique waves accelerate more electrons than parallel waves at low α

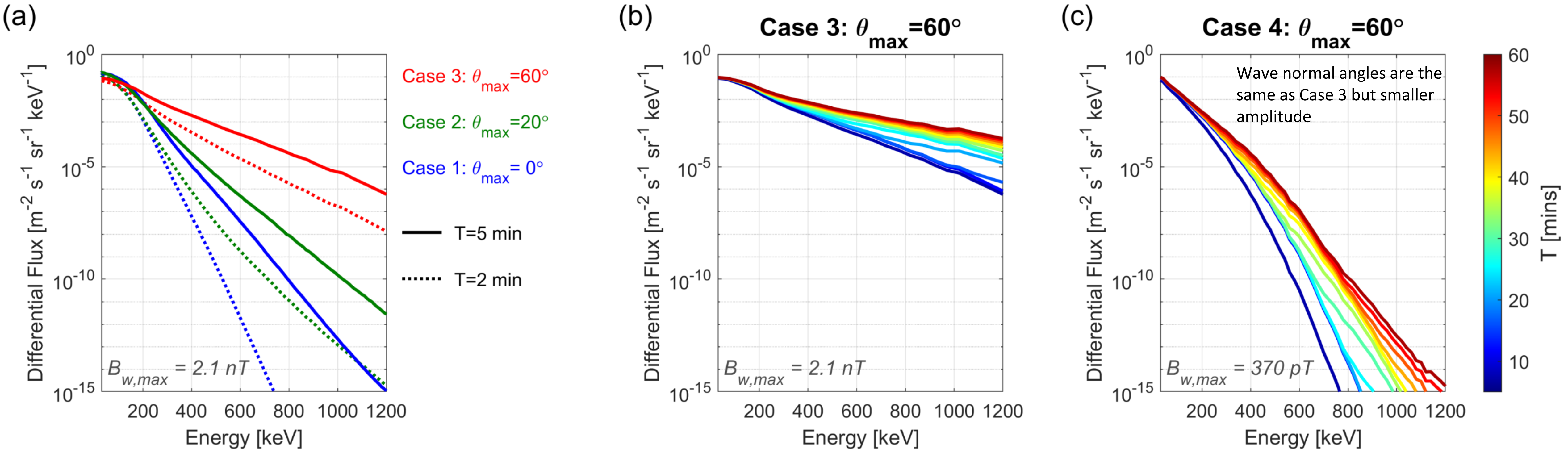


N_L: Loss particles

N_T: Total particles over all energy ranges

- At E < 100 keV, slightly oblique chorus emissions lead to the largest amount of precipitation.
- For sub-relativistic/relativistic electrons, larger wave normal angle causes greater amount of precipitation.

Precipitation fluxes

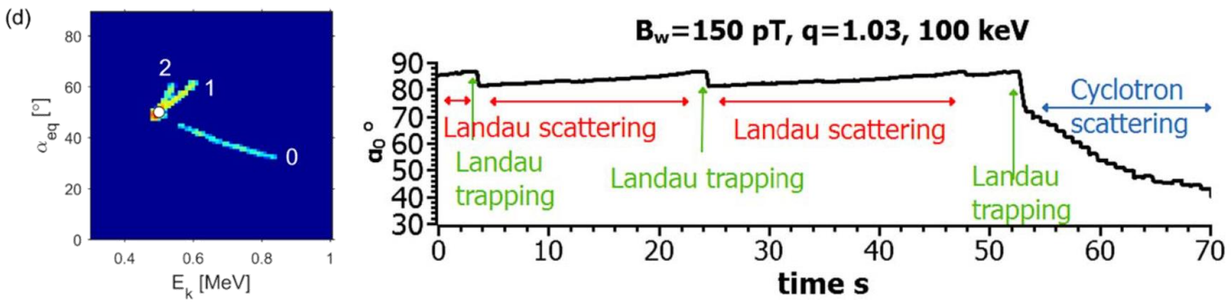


- Precipitation fluxes are stronger in the oblique cases than the purely parallel case at energy greater than 100 keV, especially in the MeV part.
- Wave amplitude highly affects the precipitation rate, especially for relativistic electrons. Still, precipitation fluxes at about 1 MeV of Case 4 increases when the number of interaction cycle increases.
- Electrons are accelerated from tens of keV to 1 MeV and precipitate into loss cone after interactions with many chorus wave packets.
- Electron precipitation at about 1 MeV induced by oblique chorus emissions is stronger than that induced by purely parallel chorus emissions if both oblique and parallel chorus have the same amplitude.

2-step precipitation process

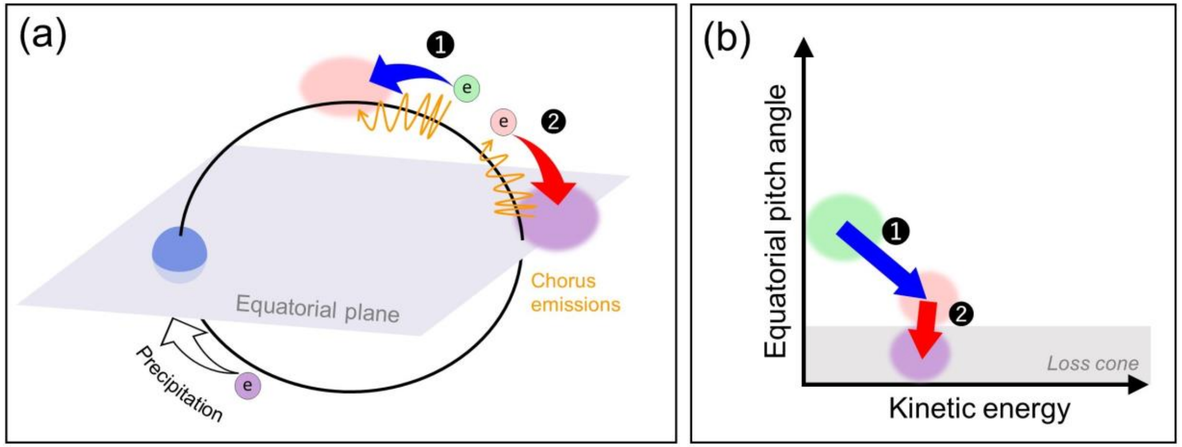
- Why oblique chorus emissions cause higher precipitation rate than parallel chorus emissions?

Very oblique chorus wave [Mourenas et al., *JGR*, 2016]



i. Nonlinear trapping via Landau resonance can lower equatorial pitch angles.

ii. Electrons may keep undergoing cyclotron resonance or Landau resonance with chorus subpackets for several wave cycles and then be transported into the loss cone rapidly.



❶ Via nonlinear trapping of Landau resonance, electrons at high pitch angles are effectively accelerated in the parallel direction, and their pitch angles become lower.

❷ The electrons bounce back toward the equator, and they are pushed into loss cone through nonlinear scattering due to cyclotron resonance with another chorus emission.

Precipitation at the opposite hemisphere.

The 2-step precipitation process is the reason why oblique chorus contributes to more precipitation than parallel chorus

If you have any questions or comments,
mail to Yikai Hsieh: yikai_hsieh@rish.kyoto-u.ac.jp

*Find this study in *JGR Space Physics:*

Hsieh, Y.-K., Omura, Y., & Kubota, Y. (2022). Energetic electron precipitation induced by oblique whistler mode chorus emissions. *Journal of Geophysical Research: Space Physics, 127*, e2021JA029583. https://doi.org/10.1029/2021JA029583

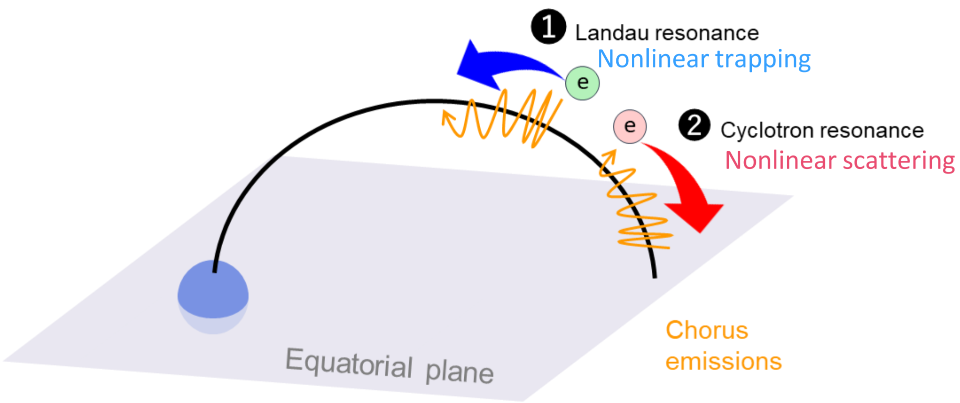
Summary

1. Electron precipitation induced by parallel and oblique chorus are simulated.

2. **We verified the electron loss processes**:

   - Nonlinear scattering by cyclotron resonance is the main process that directly pushes electrons into the loss cone.
   - Obliquely propagating chorus causes more energetic electron precipitation than parallel propagating chorus (especially in MeV level) because of combination of **nonlinear trapping via Landau resonance** and **nonlinear scattering via cyclotron resonance.**

3. We propose a 2-step precipitation process to describe the loss process in oblique whistler mode wave-particle interaction.



Appendix: Multiple resonances in oblique MPI

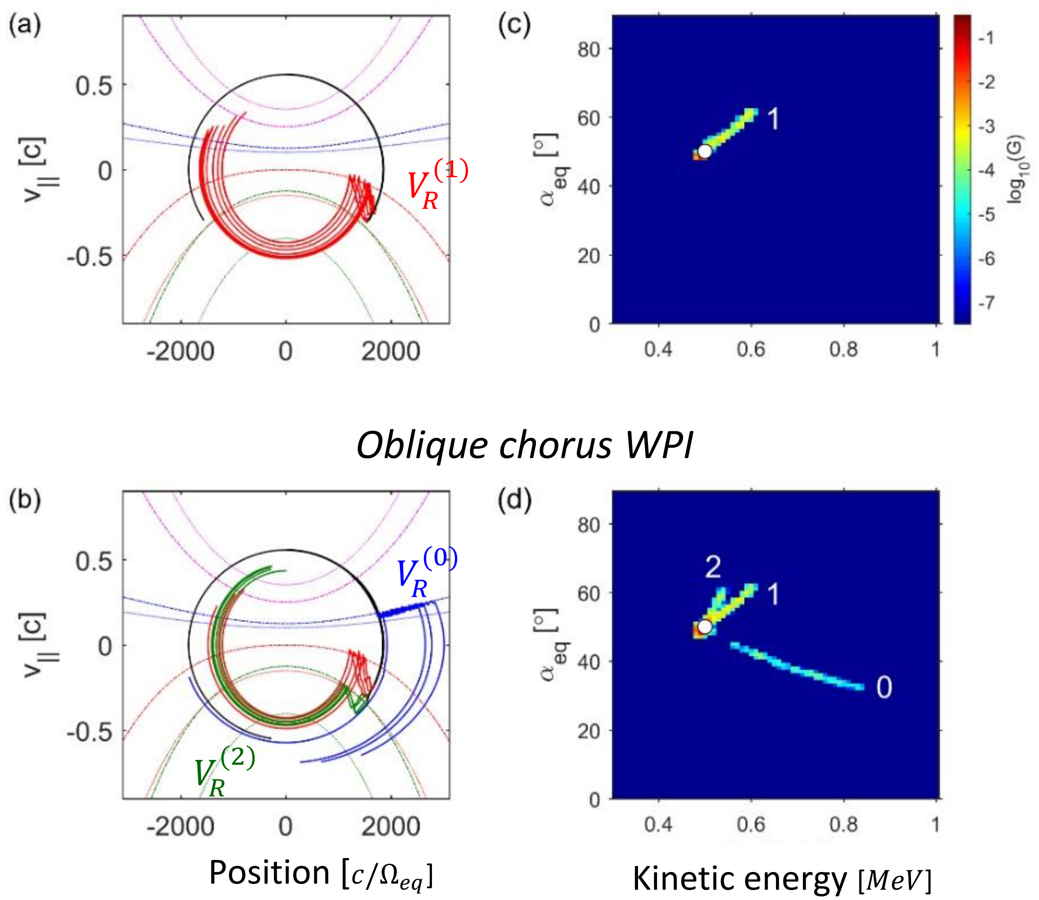
- When an electron undergoing *n*-th resonance, its parallel velocity $v_\parallel$ follows resonance velocity

$$V_R^{(n)} = \frac{1}{k_\parallel}\left(\omega - \frac{n\Omega_e}{\gamma}\right)$$

- We can recognize an electron undergoing a certain resonance by tracing the electron trajectory in position-$v_\parallel$ plot.
- In <u>parallel chorus wave-particle interactions</u>, only 1st order cyclotron resonance occurs.
- In <u>oblique chorus wave-particle interactions</u>, not only n=1 cyclotron resonance but also n=0 Landau resonance and higher order cyclotron harmonic resonances occur.

Parallel chorus WPI

Oblique chorus WPI

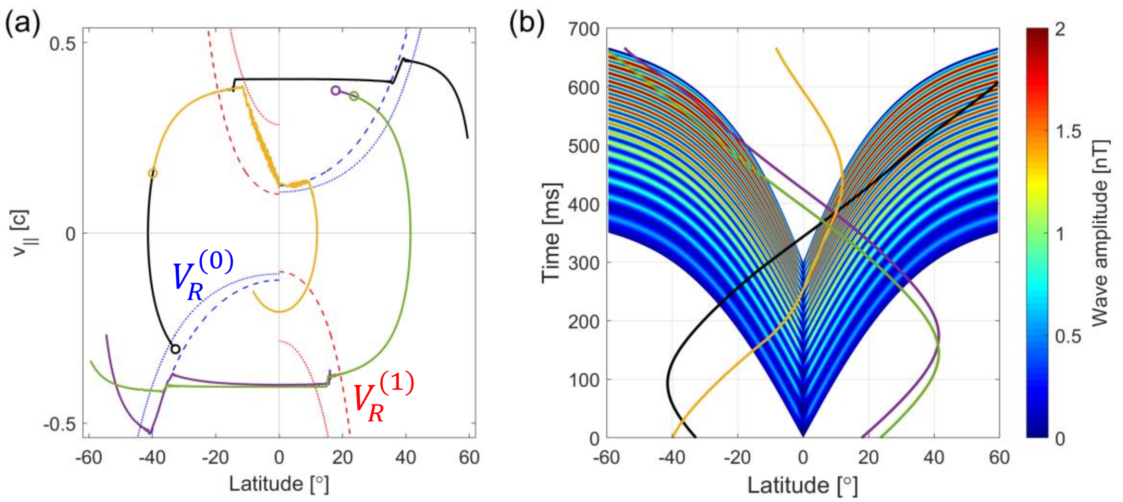


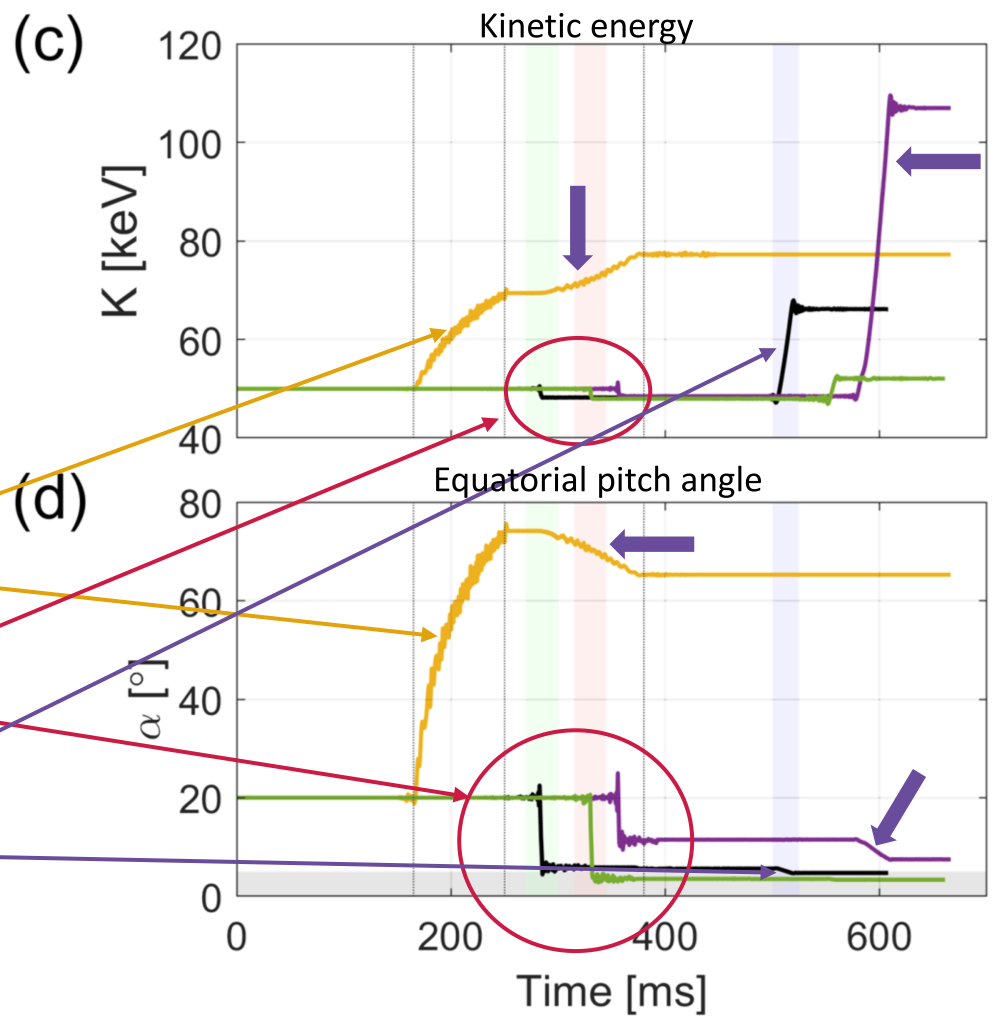
[Hsieh and Omura., *JGR*, 2017]

Cyclotron resonance

Cyclotron resonance+
Landau resonance +
Higher order cyclotron harmonic resonances

Appendix: trajectories of nonlinear wave-particle interactions





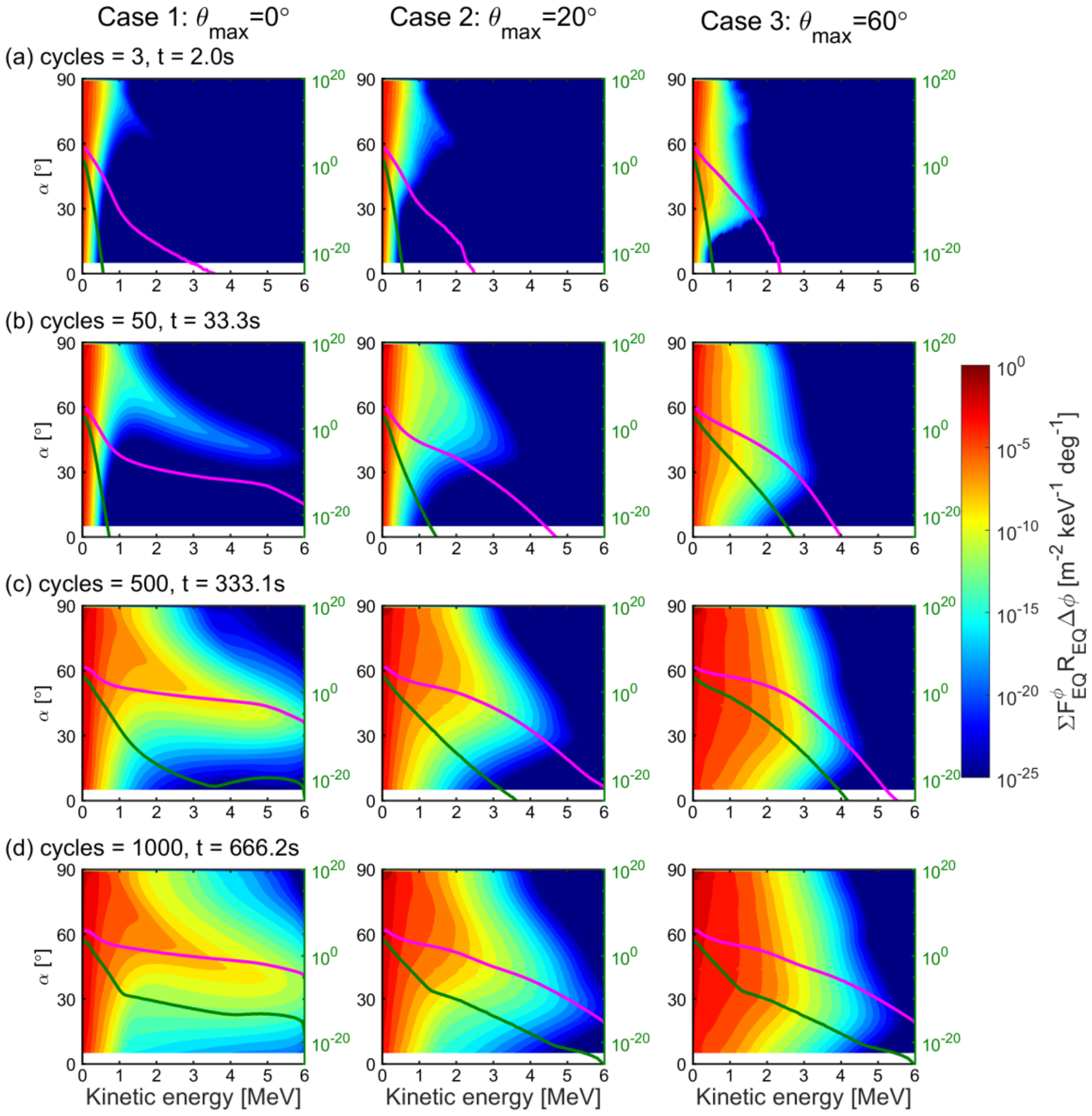
Nonlinear trapping by n=1 cyclotron resonance

Nonlinear scattering by n=1 cyclotron resonance

Nonlinear trapping by n=0 Landau resonance
(rare for precipitation)

- Nonlinear scattering by n=1 cyclotron resonance is the main process that pushes electrons into the loss cone.
- Nonlinear trapping by n=0 Landau resonance also contribute the precipitation. (But rare)

Appendix: Formation process & loss process



Electron flux trapped by magnetic field

Electron flux inside loss cone

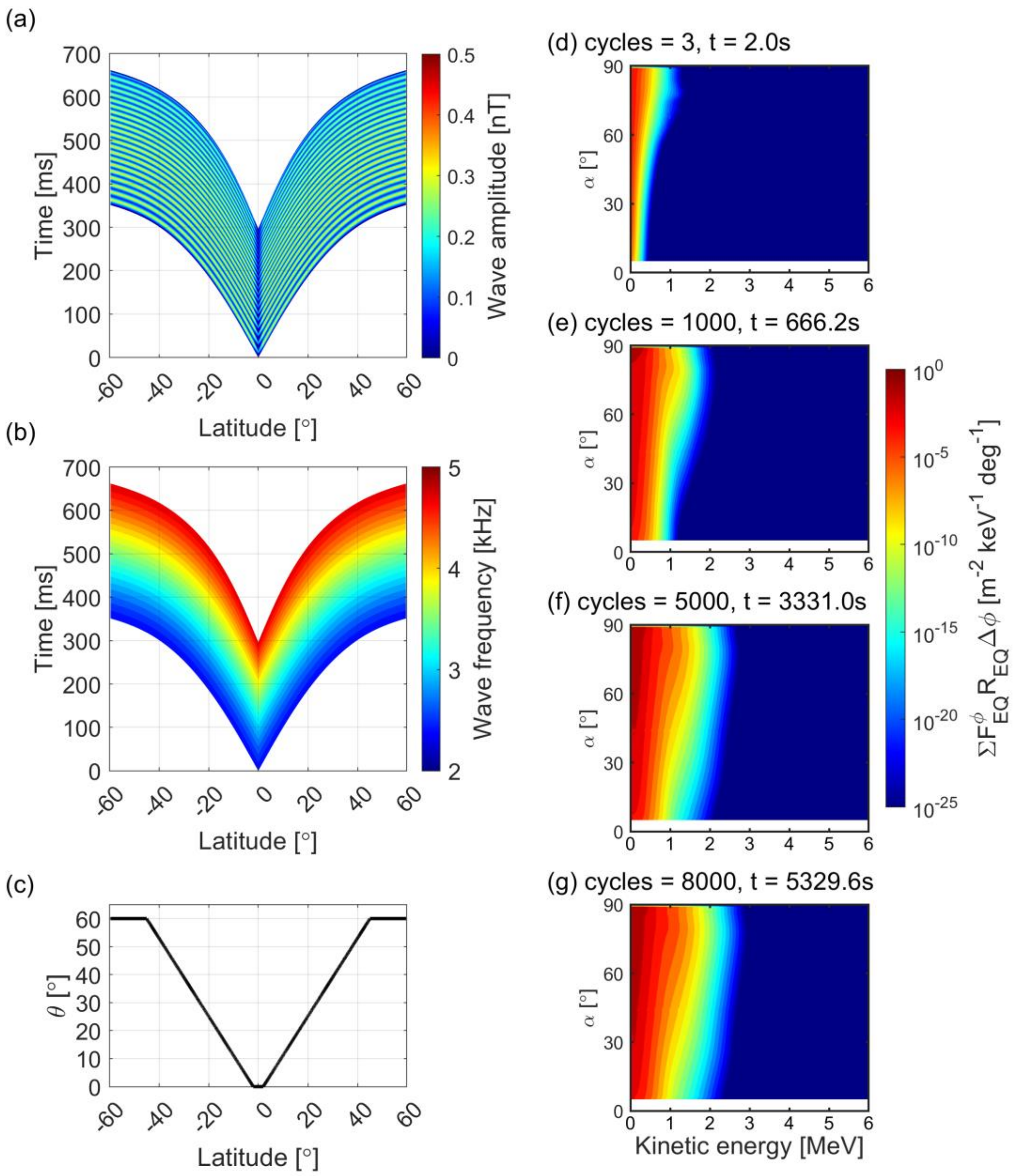
Formation process

- Contributed by nonlinear trapping of cyclotron resonance and Landau resonance.
- Parallel waves contribute to acceleration in high α, while oblique waves contribute to effective acceleration in **wide range of α**, especially at low α.
- Oblique chorus emissions energize keV electrons to about 1 MeV rapidly within several emissions (few secs), which is much faster than the parallel chorus acceleration. However, the prompt acceleration slows down after reaching 2 MeV.
- After long-time evolutions (few mins), the parallel chorus emissions can accelerate electrons to energies higher than 6 MeV.

Loss process

- Directly contributed by nonlinear scattering of cyclotron resonance.
- Oblique chorus emissions contribute to more precipitation than that induced by parallel chorus emissions.

Appendix: Case 4

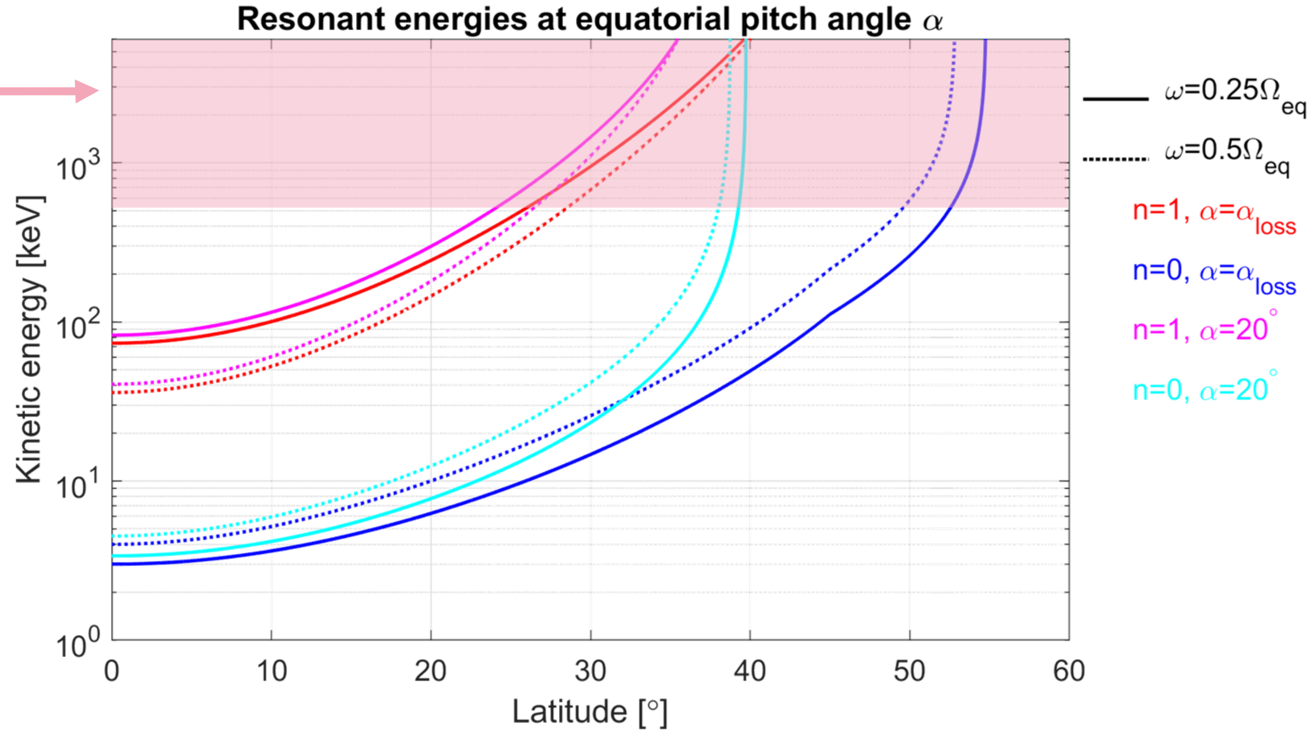


Wave model profile for a chorus element in simulations

1. Wave amplitude: subpacket structure ($B_{max} = 370\text{pT}$)
2. Wave frequency: rising-tone lower-band ($0.25 - 0.5\Omega_{eq}$)
3. Wave normal angles:
   The same as Case 3: moderated oblique with $\theta_{max} = 60°$

- Acceleration effect of Case 4 is not as strong as that of Case 3 because wave amplitude highly affects the nonlinear interactions.
- the smaller amplitude still can accelerate electrons to more than 1 MeV in 10 minutes, indicating that the nonlinear interactions happen in this amplitude level (~ 370 pT) since the acceleration time scale for quasi-linear theory is much longer.
- Acceleration occurs in all α rather than in a certain range of α.
- For nonlinear trapping of Landau resonance, a larger wave amplitude leads to a longer interaction time for one emission because it corresponds to a wider $|S| < 1$ range, and longer interaction time results in a larger $\Delta\alpha$ and a larger acceleration rate. For the nonlinear scattering of cyclotron resonance, a larger amplitude also causes a larger $\Delta\alpha$. Consequently, a larger amplitude leads to a higher precipitation rate.

Appendix: Resonant energies



- For relativistic/sub-relativistic and low equatorial pitch angle electrons, they are difficult to interact with n=0 Landau resonances.
- **Reason**: For these electrons, Landau resonances occurs in higher latitudes, where the inhomogeneity factor $|S_0|$is too large for the nonlinear resonance.

➡ **MeV electrons cannot be pushed into the loss cone by Landau resonance.**

Inhomogeneity factor:

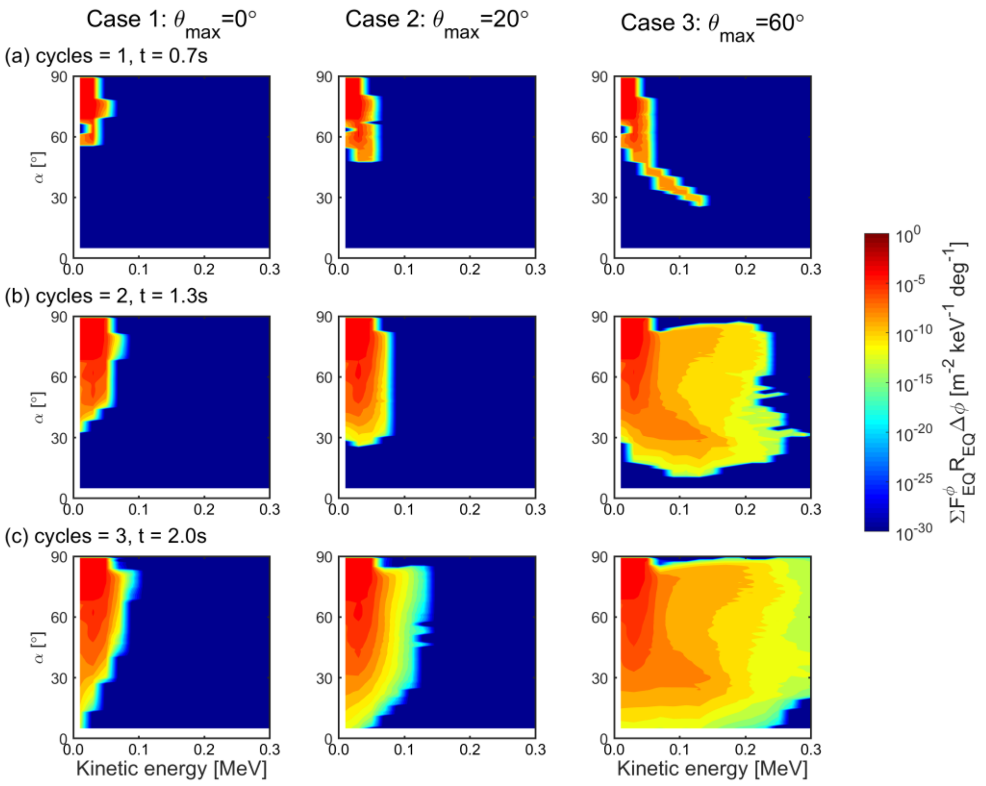
$$S_n = -\frac{1}{\Omega_{t,n}^2}\left\{\left(1-\frac{V_R}{V_{g\|}}\right)^2\frac{\partial\omega}{\partial t}+\left[\frac{\omega v_\perp^2}{2\Omega_e V_{p\|}}-\frac{n}{\gamma}V_R\left(1+\frac{\Lambda\chi^2[\Omega_e-(\gamma/n)\omega]}{2(\Omega_e-\omega)}\right)\right]\frac{\partial\Omega_e}{\partial z}\right\}$$

➡ Why oblique chorus emissions cause higher precipitation rate than parallel chorus emissions?

Appendix: How fast do electrons precipitate from high equatorial pitch angles

Initial equatorial pitch angle: 70-89°

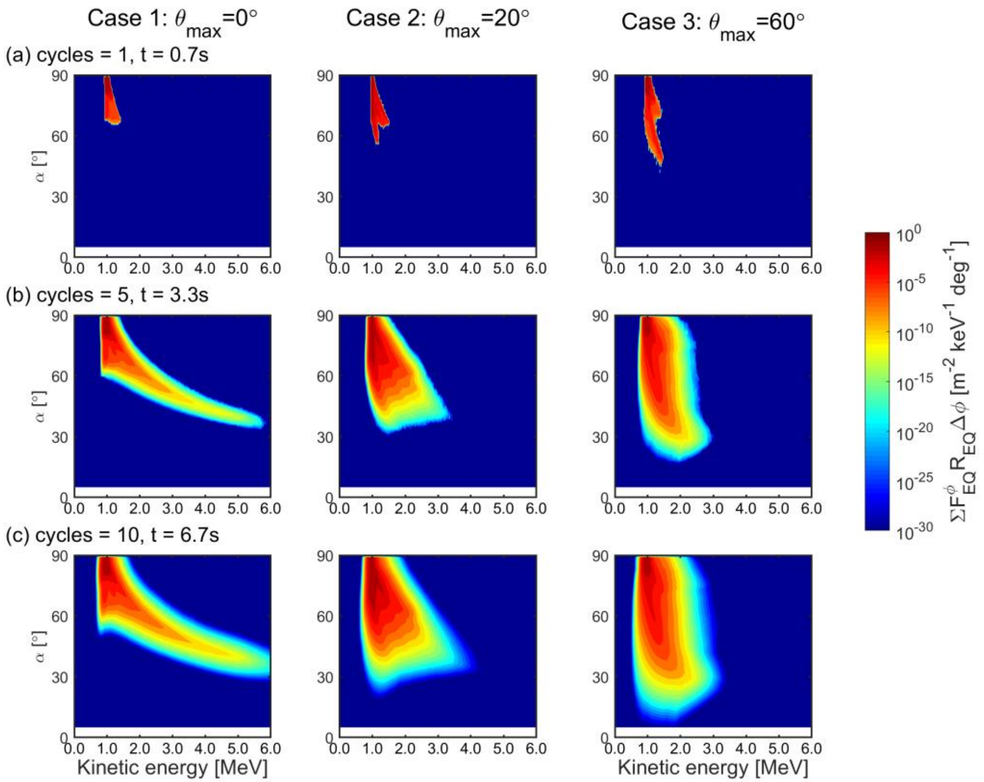
Low energy electrons (10s keV)



- The electrons precipitate within 3 emissions rapidly!
- Electron energy becomes much higher in the oblique cases than that in the parallel case.

Time

High energy electrons (MeV)



- Higher energy electrons needs more interaction cycle to reach low α.
- Oblique emissions scatter electrons more effectively than parallel ones.