# イオンサイクロトロン波動及び斜め伝搬ホイッスラーモード波動粒子相互作用のテスト粒子シミュレーション

Test Particle Simulation on Wave-Particle Interactions of EMIC waves and Obliquely Propagating Whistler-mode Waves

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担当：計算結果の理論的検討

**研究目的** (Research Objective):

Wave-particle interactions with whistler-mode waves and electromagnetic ion cyclotron (EMIC) waves significantly influence the behavior of energetic charged particles within the Earth's and other planets' magnetosphere, altering their energies and scattering their pitch angles. These wave-particle interactions play crucial roles in the dynamics, distribution, and energy states of these electrons. Research and simulations (e.g., Hikishima et al. (2010), Miyoshi et al. (2022)) have reported evidence of electron precipitation driven by whistler-mode waves, primarily under conditions where waves propagate parallel to the magnetic field lines. Despite these findings, the effects of larger wave normal angles on electron precipitation have been observed (Zhang et al., 2022) but not yet explored through simulation. This gap in research is significant because the resonance conditions for waves with normal angles near the resonance cone differ markedly from those for parallel or slightly oblique waves. On the other hand, ion acceleration induced by EMIC waves should follow a similar process to electrons accelerated by whistler-mode waves. However, so far there is no research discussing this topic.

The first aim of this study is to examine how electrons respond to interactions with whistler-mode chorus waves across various wave normal angles. The second aim is to check if the EMIC wave can really affect the ion's motions around the Earth or other planets.

**計算手法** (Computational Aspects)**:**

For the first aim:

We utilized test-particle simulations to track electron trajectories and create numerical Green's functions according to the results of the test-particle simulations. A Green's function represents the altered electron distribution following their interaction with the target waves. Our analysis included 12 wave models across three amplitude levels and four wave normal

angle variations, encompassing parallel, slightly oblique, and very oblique chorus waves. We conducted these simulations within the Earth's dipole magnetic field at L=4.5. The number of electrons that produced a Green's function is 3,600. There are 51,000 Green's functions for each wave model, which we call a Green's function set, with initial energies from 10keV to 6 MeV and initial equatorial pitch angles from the loss cone angle to 89 degrees.

For the second aim:

We first tried test particle simulation of an EMIC wave and protons in the Earth's magnetosphere, but the gyro radius of an ion is too large to perform wave-particle interactions. Then we found that Jupiter's magnetosphere is an ideal environment. It is a preliminary study so we tested a simple EMIC wave model with constant amplitude and constant frequency. We evaluated protons from around 240 MeV with various pitch angles and at various locations.

For both aims, hybrid parallel processing including MPI (Message Passing Interface) and OpenMP (Open Multi-Processing) is adopted for efficient computation.

**研究成果**（Accomplishments）：

For the first aim:

We comprehensively surveyed the electron precipitation induced by various kinds of whistler-mode waves, which contain various amplitudes and wave normal angles (as shown in Fig 1). From the results, we know that: (1) The most important factor that affects electron precipitation rate is wave amplitude. If the wave amplitude is large enough to perform nonlinear wave-particle interaction, the electron precipitation is critical. (2) The duration of the wave subpacket will also affect electron precipitation. It requires more investigation in the future works.

For the second aim:

Through test particle simulations, we reveal a nonlinear process called relativistic turning acceleration (RTA) by EMIC waves that can accelerate protons from a few hundred MeV to around GeV energies. We conducted various numerical simulations, adjusting initial equatorial pitch angles, wave amplitudes, wave frequencies, and radial distances to observe these effects. The RTA process is one of the reasons that form Jupiter's radiation belts.

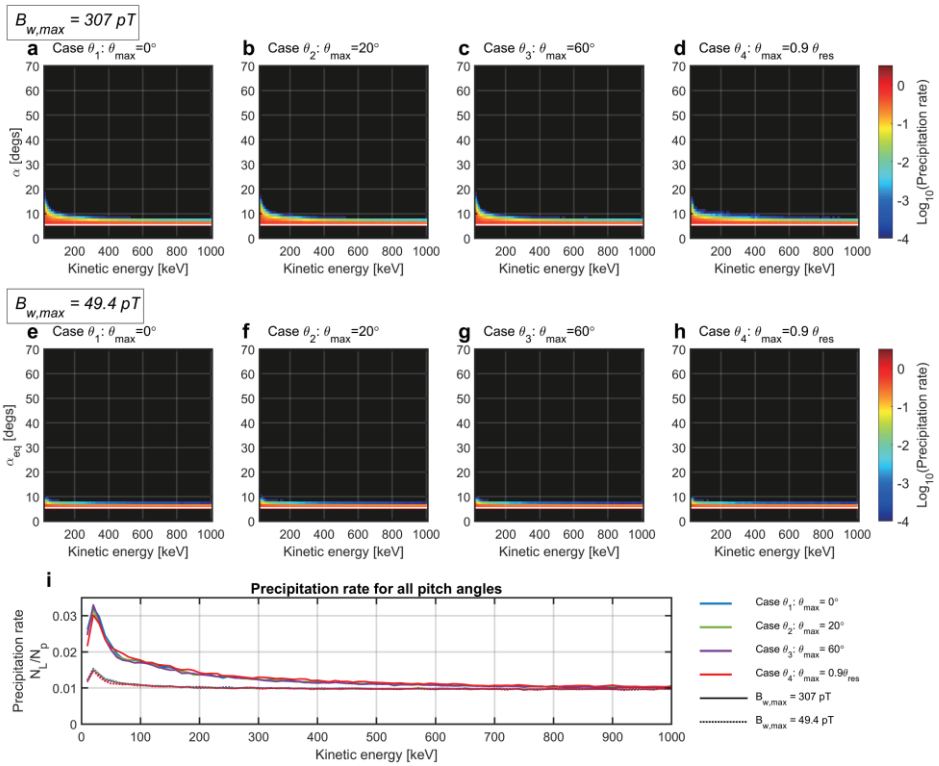


Fig.1 Precipitation rates for electrons interacting with a pair of chorus emissions at various wave amplitudes, wave normal angles, initial energies, and initial equatorial pitch angles.

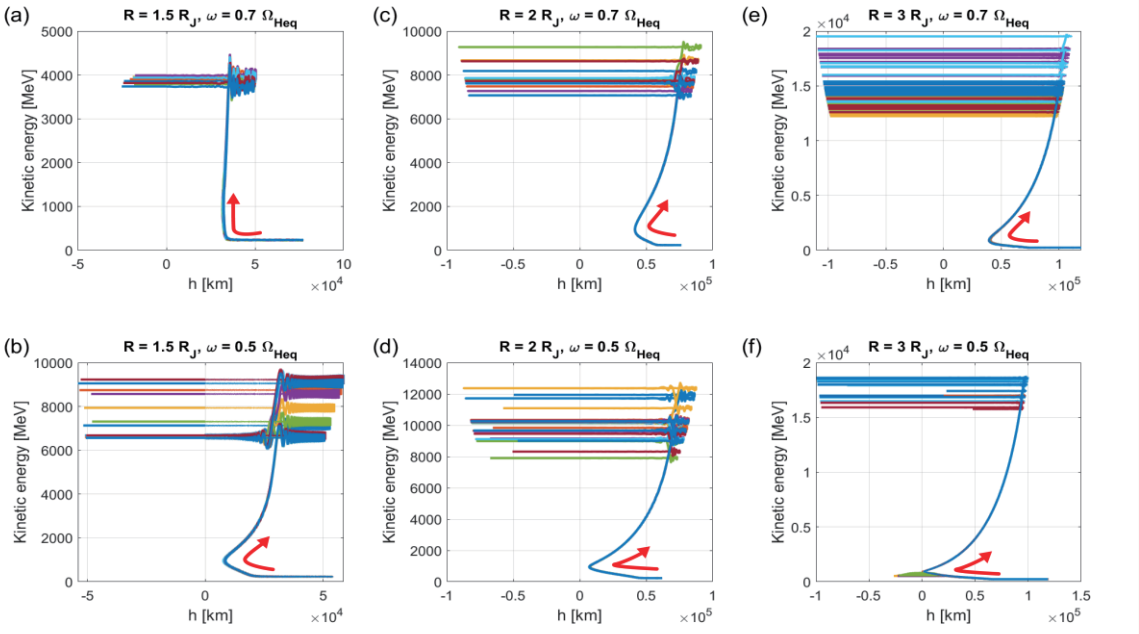


Fig.2 Protons undergo the relativistic turning acceleration process at various locations interacting with EMIC waves with frequencies 0.5 and 0.7 equatorial ion cyclotron frequency($\Omega_{Heq}$).

**公表状況**（Publications）：

**（論文）**

1. Hsieh, Y.-K., & Omura, Y. (2023). Precipitation rates of electrons interacting with lower-band chorus emissions in the inner magnetosphere. *Journal of Geophysical Research: Space Physics, 128*, e2023JA031307. https://doi.org/10.1029/2023JA031307
2. Sekine, T., Omura, Y., Summers, D., Hsieh, Y.-K., & Nakamura, S. (2024) Particle acceleration in Jupiter's ion radiation belts by nonlinear wave trapping. Submitted to *Journal of Geophysical Research: Space Physics*.

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1. Hsieh, Y.-K., & Omura, Y., Energetic electron precipitation due to nonlinear trapping and scattering in oblique chorus wave-particle interactions, American Geophysical Union (AGU) 2023 Meeting, San Francisco, USA & Online, Dec 2023. (招待講演)
2. Hsieh, Y.-K., & Omura, Y., Energetic Electron Precipitation induced by lower-band chorus emissions, The 7th Asia-Pacific Conference on Plasma Physics (AAPPS-DPP2023), Nagoya, Japan, Nov 2023. (招待講演)
3. Hsieh, Y.-K., & Omura, Y., Pitch angle scattering rates and energetic electron precipitation caused by chorus emissions in the inner magnetosphere, 第 154 回地球電磁気・地球惑星圏学会，仙台，2023 年 9 月.

**（ポスター）**

1. Hsieh, Y.-K., & Omura, Y., Electron Precipitation Processes due to Oblique Chorus Emissions, XXXVth General Assembly and Scientific Symposium of the International Union of Radio Science (URSI GASS 2023), Sapporo, Japan, Aug 2023.