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):

The population, motion, and distribution of energetic electrons in the Earth's inner magnetosphere are strongly affected by wave-particle interactions with whistler mode waves, resulting in energy increasing/decreasing and pitch angle scattering of these electrons. Several observations and simulations show evidence of whistler-mode wave-driven electron precipitation (e.g., Hikishima et al., 2010; Nishimura et al., 2010; Kurita et al., 2016; Miyoshi et al., 2022) under the parallel propagating assumption. However, electron precipitation regarding large wave normal angles has been reported (Zhang et al., 2022) but has not yet been studied by simulation. When the wave normal angle is very close to the resonance cone angle, the resonance condition should be very different from parallel waves or slightly oblique waves. This study aims to investigate electron precipitation for broad initial kinetic energies and equatorial pitch angles interacting with whistler-mode chorus with various wave normal angles. We checked the differences between precipitation rates and wave normal angles, and then examined the precipitation mechanism of different nth order resonances.

計算手法 (Computational Aspects):

We applied test-particle simulations to calculate the electron trajectories interacting with a pair of chorus emissions. With the results of the test particle simulations, we generated the numerical Green's function as the modified electron distribution after wave-particle interactions. We have 12 wave models with 3 amplitude settings and 4 wave normal angle settings covering parallel chorus waves, slightly oblique chorus waves, and very oblique chorus waves. The wave models are shown in Fig.1. We simulated wave-particle interactions in the Earth's dipole magnetic field at around L=4.5. We input 3600 electrons in a test particle simulation with electrons with the same initial kinetic energy and the same equatorial pitch angle. For a Green's function set, we calculate initial energy K_0 from 10 keV to 6 MeV and initial equatorial pitch angle α_0 from 5° to 89°. We submitted 183,600,000 electrons for one

Green's function set. Both MPI and OpenMP methods are employed for parallel computing. After generating the Green's functions, we integrated electrons inside the loss cone to calculate the precipitation rates of each initial pitch angle and kinetic energy. Finally, we compared the precipitation rates of the different wave models.

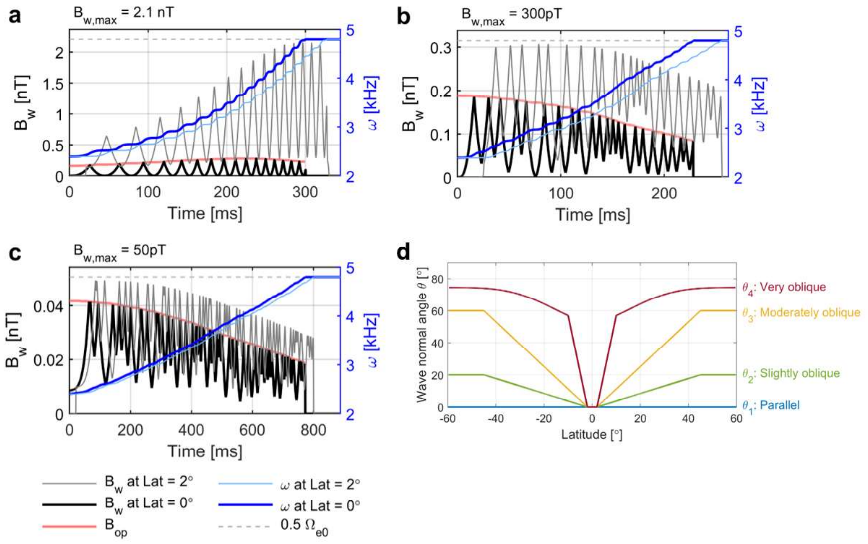

Fig.1 Wave models: (a-c) 3 various wave amplitudes. (d) 4 various wave normal angles.

研究成果（Accomplishments）：

We theoretically derived the equatorial pitch angle scattering rates of resonant electrons and analyzed them in different wave amplitudes, wave frequencies, wave normal angles, and nth resonances. We also compared the pitch angle scatter rates to the simulated precipitation rates. The physical findings are itemized as follows:

1. Amplitude is the most critical factor affecting electron precipitation.
2. In general, low-energy electrons have a higher precipitation rate than high-energy electrons because the pitch angle scattering rate of n=1 cyclotron resonance is higher for low-energy electrons than high-energy electrons. (See red parts of Fig. 2 a-d)
3. For large amplitude waves, the precipitation rate of the very oblique chorus waves is about 1.5 times greater than that of the parallel waves and about 1.2 times greater than that of the slightly oblique waves due to the active nonlinear trapping via the n = 0 Landau resonance and the n = -1 cyclotron resonance and nonlinear scattering of the n = 2 cyclotron resonance. (See Fig. 2e)
4. In the large amplitude and very oblique case, electrons can precipitate from initial equatorial pitch angles > 40 deg around 100 keV because of strong nonlinear trapping via the n = -1 cyclotron resonance. (See Fig. 2d and magenta circles in Fig. 3.)
5. The anomalous trapping effect is much weaker in the oblique cases than in the parallel case.

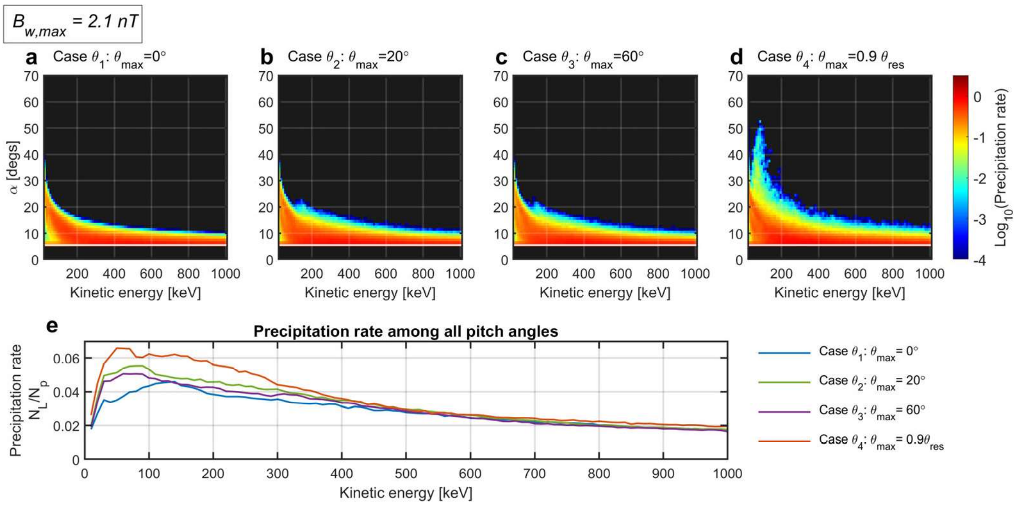

Fig.2 Precipitation rates for electrons interacting with a pair of chorus emissions shown in Fig. 1a.

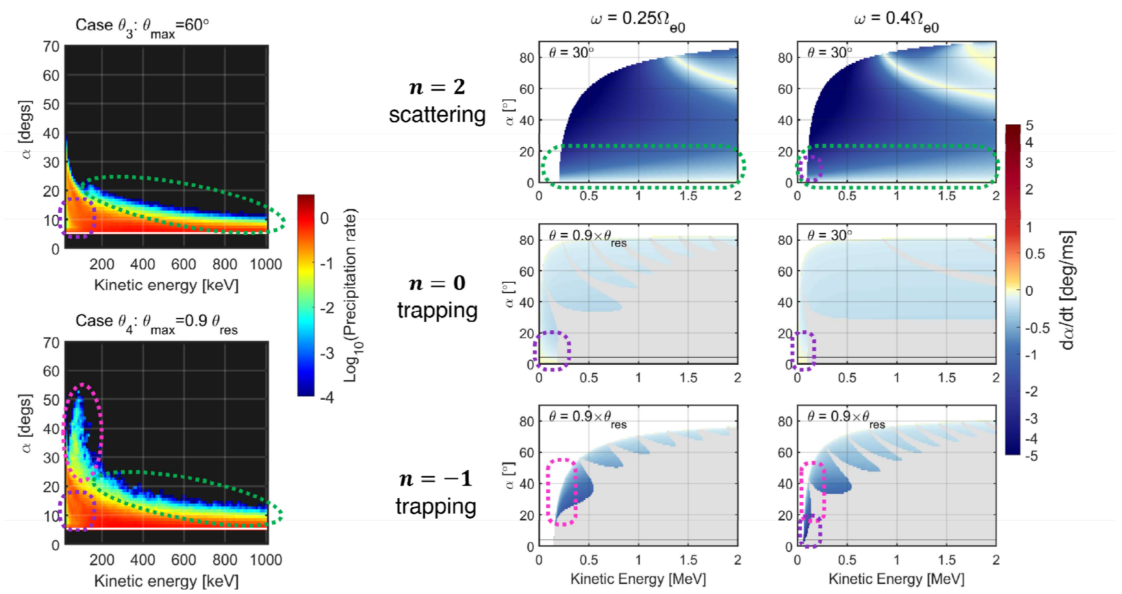

Fig. 3 Connection of simulated precipitation rates (left panel) and theoretical pitch angle scattering rates (right panel).

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. Submitted to *Journal of Geophysical Research: Space Physics*.

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1. Hsieh, Y.-K., Y. Omura, Electron precipitation rates due to nonlinear effects of parallel and oblique whistler mode waves in the Earth’s inner magnetic field, American Geophysical Union (AGU) 2022 Fall Meeting, Chicago, USA & Online, Dec 2022.
2. Hsieh, Y.-K., Y. Omura, Energetic electron precipitation associated with nonlinear wave-particle interactions between electrons and very oblique chorus waves, The 10th VLF/ELF Remote Sensing of Ionospheres and Magnetospheres Workshop (VERSIM 2022), Sodankylä, Finland & Online, Nov 2022.
3. Hsieh, Y.-K., Y. Omura,Energetic electron precipitation induced by very oblique chorus waves in the Earth’s inner magnetosphere, 第 152 回地球電磁気・地球惑星圏学会, 相模原, 2022 年 11 月.
4. Hsieh, Y.-K., Y. Omura, Comparison of Energetic Electron Precipitation Induced by Parallel and Oblique Whistler Mode Chorus Waves, Asia Oceania Geosciences Society (AOGS) 19th Annual Meeting, Online, Aug 2022.
5. Hsieh, Y.-K., Y. Omura, Precipitation of resonant electrons interacting with parallel and oblique whistler mode chorus waves, AT-AP-RASC 2022, Gran Canaria & Online, May-June 2022.
6. Hsieh, Y.-K., Y. Omura, Precipitation rates of energetic electrons interacting with parallel and oblique whistler mode chorus emissions in the magnetosphere, Japan Geoscience Union (JpGU) Meeting 2022, Chiba, Japan & Online, May 2022.
7. Hsieh, Y.-K., Y. Omura, Energetic electron loss process associating with oblique chorus emissions in the outer radiation belt, EGU General Assembly 2022, Vienna & Online, May 2022.

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1. Hsieh, Y.-K., & Omura, Y., Energetic electron precipitation driven by oblique whistler mode chorus emissions: Test particle simulation and Green’s function method, The 14th International School for Space Simulations (ISSS-14), Online,Sep 2022.
2. Hsieh, Y.-K., & Omura, Y., Pitch angle scattering rates and precipitation rates of energetic electrons interacting with lower-band chorus emissions during nonlinear interactions with multiple resonances, Asia Oceania Geosciences Society (AOGS) 19th Annual Meeting, Online, Aug 2022.

（受賞）

1. Hsieh, Y.-K., Outstanding Presentation Awards for Early Career Scientists of the 10th VLF/ELF Remote Sensing of the Ionosphere and Magnetosphere (VERSIM) workshop. 2022 Nov. 11th.