# ABSTRACTS (PH D THESIS)

## Study on nonlinear acceleration of electrons by oblique whistler mode waves

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Whistler mode wave-particle interactions are significant phenomena causing electron accelerations and precipitations in the Earth's inner magnetosphere. The waves also play important roles in radiation belt dynamics. Whistler mode chorus emissions propagating at an oblique angle are frequently observed by satellites. The structure and propagation of oblique whistler mode waves are much more complicated than that of parallel waves. Hence, the dynamics of oblique wave-particle interactions are very different from parallel ones. To reveal the nonlinear dynamics of oblique wave-particle interactions is the purpose of the present thesis.

First, we analyze propagation conditions of an obliquely propagating coherent wave by solving the cold plasma dispersion relation and develop a wave model with the whistler mode dispersion relation. We find that in conditions that wave frequency less than half the cyclotron frequency or wave normal angle smaller than 15°, the wave group velocity propagates nearly parallel to the background magnetic field. Under this nearly parallel propagating feature, a one-dimensional simulation is able to calculate wave-particle interactions of oblique whistler mode wave. We also compare the dispersion relation between the exact form and the quasi-longitudinal approximation, which is usually applied in oblique wave-particle interactions. The comparison shows that the approximation is not available for wave with high frequencies or with wave normal angles near the resonance cone angle.

Second, we confirm that the gyroaveraging method, which averages the cyclotron motion to the gyrocenter and reduces the simulation from two-dimensional to one-dimensional, is valid for oblique wave-particle interaction. Multiple resonances appear for oblique propagation but not for parallel propagation. We calculate the possible range of resonances with the first-order resonance condition as a function of electron kinetic energy and equatorial pitch angle. To reveal the physical processes and the efficiency of electron acceleration by multiple resonances, we assume a simple uniform wave model with constant amplitude and frequency in space and time. We perform test particle simulations with electrons starting at specific equatorial pitch angles and kinetic energies. The simulation results show that multiple resonances contribute to acceleration and pitch angle scattering of energetic electrons.

Third, we focus on interactions between relativistic electrons and a whistler mode chorus packet propagating at oblique angles. We trace evolution of a delta function of relativistic electrons in a phase space of kinetic energy and equatorial pitch angle and obtain numerical Green's functions of the chorus wave-particle interactions. Examining the Green's functions in a wide range of kinetic energies, we find that Landau resonance can accelerate MeV electrons efficiently and that higher $n$th resonances such as $n = -1$ and $n = 2$ also contribute to acceleration of electrons at high equatorial pitch angles (about 70°) and high energies (about 2 MeV). We investigate the rate of energy gain of the cyclotron resonance acceleration and the Landau resonance acceleration and find that the perpendicular component of wave electric field dominates both accelerations for MeV electrons. Furthermore, the proximity between the parallel phase velocity and parallel group velocity of oblique whistler mode waves and the nonlinear trapping condition make the interaction time of Landau resonance much longer than that of $n = 1$ cyclotron resonance, resulting in efficient acceleration of MeV electrons.

Fourth, we demonstrate the effective acceleration by test particle simulations with parameters for the Earth's inner magnetosphere at $L = 5$ and a small wave normal angle 10°. Analyzing the wave electric fields and the resonant currents for Landau resonance, we find that effective wave damping takes place at around half the electron gyrofrequency. Furthermore, we confirm that this damping is dominated by parallel components of resonant currents for electrons with a few keV, and perpendicular components of resonant currents for electrons with tens of keV. The simulation results reveal that nonlinear damping through Landau resonance is one of the mechanisms dividing chorus emissions into the upper band and the lower band.

In the present study we address the nonlinear processes of oblique wave-particle interactions. By carefully analyzing the results of test particle simulations, we confirm the importance of the effective electron acceleration and wave damping through Landau resonance under the condition of the Earth's inner magnetosphere.

**References**

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