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# Charged Particle Dynamics in the Poloidal- and Toroidal-mode ULF waves

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Ultralow frequency (ULF) electromagnetic waves in the mHz range are a major energy source accelerating charged particles to relativistic energies in the inner magnetosphere, which can usually be categorized into poloidal and toroidal modes in terms of their directions of field perturbations. Transverse perturbations of field lines in the radial direction yields azimuthal electric field oscillations which are referred to as poloidal waves. Field line oscillations in the azimuthal direction yields electric fields in the radial direction and are referred to as toroidal waves. Here we summarize the historical background and recent advances in understanding the interaction between different ULF wave modes and charged particles.

It has been widely accepted that poloidal ULF waves play a key role in magnetospheric particle dynamics since the wave-carried azimuthal electric field aligned with the particle's drift velocity enables an efficient interaction known as drift resonance. The characteristic signatures of drift resonance from conventional theory (180$^{\circ}$ phase difference between particle fluxes across the resonant energy) have been identified in observations. However, some observed signatures cannot be explained by conventional theories, in which linear approximation has been used. We generalize the conventional theory of drift resonance by considering the wave temporal and spatial distributions, which predicts increasingly tilted stripes in particle energy spectrum[1,2], and extend the resonant theory into the nonlinear regime in which particle motion can be described by a pendulum equation[3]. The newly-developed nonlinear theory predicts rolled-up structures in energy spectrum. These predicted signatures are found to be consistent with the observations.

On the other hand, toroidal waves have long been considered incapable of accelerating particles since their radial electric field is perpendicular to the azimuthal drift velocity of inner magnetospheric particles unless their drift paths are significantly distorted by dayside compression of the magnetosphere. Here we show that even in a pure dipole field, the toroidal waves can still resonate with energetic particles because of the nonzero curl of the wave electric field in association with the compressional magnetic field oscillations[4]. The resonant condition, originally believed to apply only for poloidal waves, also applies for compressional toroidal waves. The predictions of compressional toroidal wave-particle drift resonance show good agreement with spacecraft observations. Further analysis shows that the particle nonlinear behavior in the toroidal wave field can be described by a modified pendulum equation. Therefore, it is important to consider not only the poloidal but also the toroidal modes in the study of ULF wave-particle interactions.

References

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