# Nonlinear Wave-Particle Interactions in the Magnetosphere

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Recent spacecraft observations with high time resolution and large-scale computer simulations with realistic models have revealed the nonlinear nature of waves in space plasmas. Two different kinds of wave phenomena have been identified as nonlinear coherent waves. These waves cannot be described by conventional linear and quasi-linear theories in which the spectra of constant frequency waves with random phases are assumed. One type is electrostatic solitary waves (ESW), and the other is whistler-mode chorus emissions. These waves are quite different in appearance, but both are closely associated with the nonlinear dynamics of resonant electrons. ESW are generated by electron beam instabilities driven by beam electrons accelerated by shocks or an induced electric field along a static magnetic field. ESW are primarily longitudinal electrostatic waves moving along a static magnetic field line, and they are observed in various regions of the magnetosphere including the plasma sheet boundary layer and auroral regions. ESW have a coherent phase variation localized in space and time, and cannot be described properly by frequency spectra. Whistler-mode chorus emissions, on the other hand, are transverse electromagnetic waves with a coherent phase variation that appears typically as rising tones in the frequency spectra. Chorus waves are generated by a whistler-mode instability driven by the temperature anisotropy of energetic electrons trapped near the magnetic equator. Recent simulation studies show that a coherent chorus element starts to grow from a threshold amplitude with a progressively rising frequency near the magnetic equator, and propagates away from the equator along the static magnetic field with a growing wave amplitude.

In both wave phenomena, nonlinear wave trapping of energetic electrons plays an essential role in generating the waves. ESW are associated with the formation of electrostatic electron holes, which are a kind of BGK mode formed along a static magnetic field. The number of resonant electrons trapped in a wave potential is smaller than that of untrapped electrons surrounding the wave potential, thereby resulting in an electron hole. Likewise, whistler-mode chorus emissions are generated by formation of the electromagnetic electron hole in the three-dimensional velocity phase space via the cyclotron resonance. Nonlinear motions of the resonant electrons forming these electron holes are described by a pendulum equation. In the case of chorus emissions, the inhomogeneity due to both the frequency variation and the spatial gradient of the magnetic field contribute to an additional nonhomogeneous term in the pendulum equation. This plays a vital role in the formation of a resonant current that gives rise to the growth of the wave.

As a result of the frequency variation accompanying the nonlinear wave growth, a chorus element can interact with electrons over a wide range of energy from several keV to a few MeV at the equator. During the generation process we find that a fraction of resonant electrons are energized very efficiently by special forms of nonlinear wave trapping called relativistic turning acceleration (RTA) and ultra-relativistic acceleration (URA). Particle energization by nonlinear wave trapping is a universal acceleration mechanism that can be effective in space and cosmic plasmas that contain a magnetic mirror geometry.