Onset of whistler chorus in the magnetosphere

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Whistler chorus waves are discrete very low frequency (VLF) waves that propagate in the Earths magnetosphere, which are usually excited during magnetic substorm periods by plasma-sheet energetic electrons injected to the inner magnetosphere near the magnetic equator. The fine coherent structures are observed that chorus frequency chirps as a rising or falling tone during the injection of the anisotropic plasma sheet electrons. The chirping events occur more frequently near the magnetic equator in a very short time scale, typically 10ms, which cannot be explained from a linear theory that takes into account the spatial variation of equilibrium parameters.

Y.Omura et al.(Y.Omura, et al. J.Geo.Research,113,2008) obtained a nonlinear wave-particle interaction theory to study the generation process of the rising tone whistler-mode chorus emissions, which is sustained and amplified by a nonlinear resonant current due to the mirror force from the inhomogeneity of the dipole magnetic field. Work in the fusion community by H.L.Berk et al.(H.L.Berk, et al. Phys.Lett.A, 234, p213,1997) provided another candidate theory for frequency chirping, where the linear mode in tokamak is a marginally unstable standing mode structure, and with background dissipation frequency chirping is triggered due to the formation of hole/clump phase space structure. Both of theories depend on nonlinear wave-particle resonant interaction but with different chirping driving sources.

We extended Berk-Breizman theory from standing single mode structures observed in tokamak (e.g. Alfven avalanche) to dispersive waves propagating in free space (e.g. whistler chorus), which allows multiple modes but with a narrow spreading bandwidth $\Delta k/k \ll 1$. Without any perturbation, three adiabatic invariants in dipole magnetic field are constants of motion. With a perturbation, these adiabatic invariants will evolve in response to the chorus. However, a single particle Hamiltonian in our approximation uncovers a slow and fast scale separation along the dipole magnetic field, where only one canonical action depends on the fast scale and needs to be updated during the nonlinear evolution.

Scale separation provides a simplication to enable a self-consistent full Earth-scale simulation of chorus waves in the magnetosphere are studied the nonlinear interaction between the energetic electrons and chorus wave. In our simulation, a hole in phase space arises because the magnetic mirror force drags the cyclotron-resonant electrons to move in the phase space. The phase space hole propagates along the magnetic field. Once it approaches the magnetic equator, a strong rising tone is triggered by the hole with an amplifying amplitude. The excited rising tone chorus propagates away from the equator. Eventually the hole is found to fade away in phase space when it crosses over the equator. Our calculation also confirms the adiabaticity of trapped electrons during the frequency chirping.