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Backward Test Particle Simulation of Nonlinear Cyclotron Wave-Particle Interactions in the Radiation Belts

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The Earth's magnetosphere can support various electromagnetic wave modes that play a vital role in near-Earth space dynamics. The propagation of these waves is governed by the 'cold' (~1-10 eV) and dense (~10-5000 el/cc) background particle population that is typically treated as a magnetized plasma fluid. Plasma waves of which the whistler mode is of particular importance, concurrently interact with higher energy (~1-100 keV) radiation belt particles which are trapped in a magnetic mirror configuration of the geomagnetic field. Two primary aspects of whistler mode wave-particle interactions are the amplification of the waves by an unstable hot particle distribution, and the precipitation and/or acceleration of these particles by the waves.

In general, modeling wave amplification along with particle scattering and acceleration is a difficult problem that requires a self-consistent solution to the Vlasov-Maxwell system of equations. Several researchers have approached the self-consistent problem using particle-in-cell or hybrid simulations [1]; however, such simulations are computationally intensive in scenarios where modifications to the wave are small and particle scattering is of greater interest. A common approach is to specify the wave-fields and neglect feedback which results in a simpler but only approximate system of equations. For small amplitude and incoherent signals such as plasmaspheric hiss, quasi-linear diffusion theory is a common method to track the time-evolution of a particle distribution. For arbitrary wave-fields, however, the dynamics of the particle distribution is more accurately investigated using test particle simulations with a large number of particles. Although test particle simulations have been successful in previous work, simulations with large-amplitude and coherent waves can still require many millions of particles to accurately describe the nonlinear phase-space dynamics of the particle distribution function.

In order to alleviate the computational cost of traditional test-particle methods, a more efficient backward test particle solution to the Vlasov equation is employed here to evaluate the nonlinear effects of large-amplitude coherent waves on the energetic particle distribution function. The backward test particle approach exploits the conservation of phase space as articulated in Louisville's theorem and permits determination of the prior state of a particle distribution if the forcing function are known. Practically, this technique allows regions of interest in phase-space to be defined a-priori which thus greatly reduces the number of particles that need to be tracked in the simulations and avoids complications from potential under sampling. The method has been previously utilized to efficiently model particle precipitation by coherent whistler mode waves since the loss-cone is well defined [2]. In addition, the technique is well-suited for analyzing acceleration to high energies and second-scale variations to the particle distribution function. In this work, the detailed temporal dynamics of the nonlinear wave-induced trap in phase-space is shown at a higher resolution than has been shown in previous works. This high resolution allows for the accurate determination of resonant currents and scattered fields to investigate salient features of amplified and triggered magnetospheric waves.

References

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