Fluid Simulations of Electrostatic Solitary Waves in Non-Maxwellian Plasmas

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Electrostatic (ES) solitary waves are an ubiquitous occurrence in laboratory [1] and space plasmas [2], frequently observed as bipolar electric field structures by missions in planetary magnetospheres [3]. While the classical Sagdeev pseudopotential method [4] and the Korteweg–de Vries (KdV) framework [5] have long provided a basis for modeling these structures, they often rely on the assumption of thermal equilibrium. However, space plasma populations typically deviate from Maxwellian statistics, exhibiting high-energy "tails" effectively modeled by a kappa-type distribution [6, 7]. In this study, we move beyond standard fluid models to investigate the dynamics of electrostatic pulses in the presence of superthermal particles [8]. Using first-principles fluid simulations, we analyze how the kappa index influences the stability, propagation, and mutual interaction of these solitary waves. Our results indicate that the presence of superthermal populations significantly modifies the acoustic speed and the amplitude-velocity relationship of the pulses. While solutions near the modified acoustic speed maintain "KdV-like" characteristics, the transition to strongly superacoustic regimes reveals unique stability properties indicating a soliton-like dynamical behavior. These findings provide a realistic benchmark for the interpretation of high-resolution satellite data in environments where non-equilibrium effects dominate.

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