Modulational Instability and Rogue Wave Formation in a Two–Electron–Fluid Plasma

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Multi-component plasmas are relevant to various space environments, e.g. in planetary magnetospheres, where the coexistence of electron populations with distinct characteristics (velocity distribution) affects plasma wave dispersion properties and may enhance nonlinear dynamical mechanisms, e.g. wave-wave interaction and energy localization [1, 2]. The presence of multiple electron populations with differing thermal properties introduces additional degrees of freedom into the dispersion relation, significantly enriching the nonlinear wave dynamics. In this work, we have focused on nonlinear self-modulation – an ubiquitous mechanism in Space plasmas [3] – associated with electron plasma (Langmuir) wavepackets in plasmas containing two different electron populations with distinct thermal characteristics.

We consider an unmagnetized plasma composed of stationary positive ions and two inertial electron populations (cool and hot), both modelled as "warm fluids" characterised by distinct equilibrium temperatures and number densities. Employing a fluid–Poisson description and a multiple-scale perturbation technique (reductive perturbation method), we have derived a nonlinear Schrödinger equation (NLSE) governing the slow modulation of the Langmuir wave envelope. The NLSE coefficients encode the combined effects of linear dispersion and nonlinear self-interaction, and their explicit dependence on plasma parameters is derived and analysed in detail.

The interplay between dispersion and nonlinearity, governed by the hot-to-cool electron density ratio and the temperature ratio , determines the modulational stability profile and predicts the first stage of evolution towards the formation of localized structures. A detailed parametric study maps the modulational instability (MI) domains in the (,) parameter space, identifying the conditions under which the Langmuir wavepacket is modulationally unstable and subject to exponential growth of perturbations. In the focusing (modulationally unstable) domain, the model supports bright envelope solitons and Peregrine-type rogue wave structures, providing prototype candidates for extreme electrostatic events in space and laboratory plasmas. The Peregrine soliton, in particular, serves as a deterministic model for the emergence of freak waves from a uniform wave background, and its properties are examined as a function of plasma composition.

These localized structures are of direct relevance to satellite observations of anomalous electrostatic wave activity in planetary magnetospheres and the solar wind. A systematic parametric study predicts the onset of modulational instability and elucidates how plasma composition controls the occurrence of energy localization as a precursor to freak wave formation [4-6].

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