Modulated Wavepackets in Saturn's Magnetosphere

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Non-Maxwellian particle distributions, effectively modeled by kappa distributions, are widely observed in space and astrophysical plasma environments, where they play a crucial role in particle acceleration and energy transport. In Saturn's magnetosphere, in situ measurements from the Cassini spacecraft reveal that the electron population is well described by kappa-type distributions. Typical values of the kappa index lie in the range $\kappa \sim 2$–4, consistent with observational and theoretical studies [1, 2]. In particular, the cool electron population typically exhibits values $\kappa_c \approx 1.8$–3, increasing to 8–10 in the inner magnetosphere, while the hot electron population is characterized by $\kappa_h \sim 3$–7 [3]. These superthermal populations dominate in the outer magnetospheric region ($R \sim 13$–$18\,R_S$) and may significantly influence the properties of electrostatic waves propagating in the magnetospheric plasma.

In this work, we investigate the existence domains and nonlinear characteristics of dust-ion acoustic (DIA) wavepackets in a plasma model incorporating two-temperature kappa-distributed electrons, relevant to Saturn's dusty magnetospheric environment. The combined occurrence of charged dust and superthermal electrons is expected to modify the dispersive and nonlinear properties of the medium, impacting the characteristics of localized electrostatic structures (solitons) [2, 3].

Adopting a (Nayfeh/Newell type) multiple scales perturbation technique, we have undertaken the derivation of a nonlinear Schrödinger equation (NLSE), to investigate the amplitude modulation dynamics of a DIA wavepacket [4]. Based on the derivation of analytical expressions for the dispersion and nonlinearity coefficients involved in the NLSE, we investigate the conditions for modulational instability. It is found that the background electron kappa index in addition to the plasma configuration (essentially, dust concentration and electron relative density and temperature) strongly influence the stability thresholds and thus impact the formation of nonlinear structures.

In particular, specific parameter regimes favor the formation of envelope solitons and extreme excitations in the form of rogue waves (freak waves), indicative of strong energy localization and transient extreme events. These localized structures are of particular interest as they provide a possible theoretical framework for interpreting intermittent electrostatic bursts and nonlinear wave signatures observed in spacecraft data within Saturn's magnetosphere [5, 6].

Our results highlight the importance of non-Maxwellian statistics in governing nonlinear plasma dynamics and contribute to a deeper understanding of wave–particle interactions and complexity in dusty space plasmas. This study further contributes to the understanding of complexity in plasma systems, where nonlinear self-modulation and interactions among different dynamical scales result in energy localization, leading to the emergence of coherent structures and extreme events.

References:

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