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Dust ion-acoustic rogue waves in a three-species ultracold quantum dusty plasmas

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HIGHLIGHTS

- The nonlinear Schrödinger equation is derived for the low frequency limit.
- Modulational instability growth rate is discussed.
- The first- and second-order dust ion-acoustic rogue waves are examined numerically.

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ABSTRACT

Dust ion-acoustic (DIA) rogue waves are reported for a three-component ultracold quantum dusty plasma comprised of inertialess electrons, inertial ions, and negatively charged immobile dust particles. The nonlinear Schrödinger (NLS) equation appears for the low frequency limit. Modulation instability (MI) of the DIA waves is analyzed. Influence of the modulation wave number, ion-to-electron Fermi temperature ratio ρ and dust-to-ion background density ratio N_d on the MI growth rate is discussed. The first- and second-order DIA rogue-wave solutions of the NLS equation are examined numerically. It is found that the enhancement of N_d and carrier wave number can increase the envelope rogue-wave amplitudes. However, the increase of ρ reduces the envelope rogue-wave amplitudes.

1. Introduction

In the astrophysical and laboratory dusty plasmas [1–5], each charged dust grain introduces a number of the wave modes such as the dust–ion acoustic (DIA) mode [6] and dust acoustic (DA) mode [7].

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Experiments have been conducted to investigate the DIA waves [8–10]. Efforts have been made to understand the properties of linear and nonlinear DIA waves in the dusty plasmas [11].

Quantum effects have been found to be significant in the ultrasmall electronic devices [12], quantum dots and quantum wires [13], quantum wells and quantum diodes [14], ultracold plasmas [15], dense astrophysical environments [16] as well as laser-produced plasmas [17]. Wave propagation in the quantum plasmas has been investigated in some aspects: For example, propagation of the DA soliton in a quantum dusty plasma has been studied via the one-dimensional Korteweg–de Vries (KdV) equation [18]. Properties of the DIA waves in a magnetized quantum dusty plasma have been investigated via the Zakharov–Kuznetsov equation [19]. Quantum DA waves in a nonuniform ultracold quantum dusty plasma have been investigated based on the modified KdV equation [20].

Rogue waves are the rare events appearing in the ocean [21]. Amplitudes of such waves are larger than those of the surrounding waves [22–24]. Notion of the rogue waves has been transferred into the realm of plasmas [25], Bose–Einstein condensations [26,27], superfluids [28], capillary waves [29] and optical fibers [30]. Numerical investigations have been reported for the generation of acoustic rogue waves in a dusty plasma composed of negatively-charged dust grains, electrons and ions [31]. Existence of the rogue waves in a multicomponent plasma with a certain concentration of negative ions has been experimentally confirmed [32,33]. Nonlinear Langmuir rogue waves in the collisionless electron–positron plasmas have been investigated [34]. Mathematical description of a rogue wave has been provided via the so-called Peregrine soliton [35].

The aim of this paper will be to investigate the DIA rogue waves and modulational instability (MI) of the DIA waves in an ultracold quantum dusty plasma. In Section 2, with the stationary negatively-charged dust particles, inertialess electrons and ion taken into account, the nonlinear Schrödinger (NLS) equation will appear for the low frequency limit. In Section 3, the MI of the DIA waves will be studied and the effects of the plasma parameters on the first- and second-order rogue waves will be discussed. Section 4 will be our conclusions.

2. The NLS equation

Refs. [36–38,7] have claimed that the electrons, ions and dust particles in a one-dimensional zero-temperature Fermi gas obey the pressure law

$$p_j = \frac{m_j V_{Fj}^2}{3n_{j0}^2} n_j^3, \tag{1}$$

where j equals e for electrons, i for ions and d for dust particles, p_j is the pressure function of the jth species, n_j is the number density, m_j is the mass, $V_{Fj} = \sqrt{2K_B T_{Fj}/m_j}$ is the Fermi speed, K_B is the Boltzmann constant, T_{Fj} is the Fermi temperature and n_{j0} is the equilibrium number density of the jth species. At the equilibrium, the charge neutrality condition is $n_{i0} = n_{e0} + Z_d n_{d0}$, with Z_d as the number of electrons residing on the dust surface [38,7].

The DIA waves in a three-species ultracold quantum dusty plasma comprised of the inertialess electrons, inertial ions, and negatively-charged immobile dust particles can be described by the following normalized equations [38,7]:

$$\frac{\partial \varphi}{\partial x} - n_e \frac{\partial n_e}{\partial x} + \frac{H^2}{2} \frac{\partial}{\partial x} \left[\frac{\frac{\partial^2}{\partial x^2}\sqrt{n_e}}{\sqrt{n_e}} \right] = 0, \tag{2a}$$

$$\frac{\partial \upsilon_i}{\partial t} + \upsilon_i \frac{\partial \upsilon_j}{\partial x} + \frac{\partial \varphi}{\partial x} + \rho n_i \frac{\partial n_i}{\partial x} = 0, \tag{2b}$$

$$\frac{\partial n_i}{\partial t} + \frac{\partial}{\partial t}(n_i \upsilon_i) = 0, \tag{2c}$$

$$\frac{\partial^2 \varphi}{\partial x^2} + n_i - \epsilon_i n_e - N_d = 0, \tag{2d}$$

where the electrostatic wave potential φ is normalized by $2K_B T_{Fe}/e$, e is the charge, the ion-fluid velocity υ_i is normalized by the quantum ion-acoustic speed $(2K_B T_{Fe}/m_i)^{\frac{1}{2}}$, n_j is normalized by n_{j0},