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Nonlinear mixing of waves in a Yukawa one component plasma

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Abstract

The phenomenon of nonlinear wave mixing is investigated in a Yukawa one-component plasma using two-dimensional classical Langevin molecular dynamics simulations. The wave spectrum indicates that nonlinear interactions between the excited modes are primarily governed by a three-wave mixing mechanism, as confirmed by bispectral analysis. In particular, the mixing characteristics observed in the simulations closely resemble those reported in previous numerical studies of the forced Korteweg–de Vries (fKdV) model [Phys. Plasmas **29**, 032303 (2022)]. This similarity further validates the applicability of the fKdV fluid model in capturing the weakly nonlinear dynamics of dusty plasmas with reasonable accuracy.

1. Introduction

Nonlinear mixing (NLM) describes the generation of a cascade of waves (modes) resulting from the interaction of two or more primary waves (modes) in a nonlinear medium [1–4]. It occurs in a variety of physical systems and plays a key role in many practical applications, e.g., in optical media [5, 6], in plasmas [2, 7], in neutral fluids [8], and in material science [9, 10]. Some typical examples of NLM include the mixing of vortices in a Kerr-like nonlinear medium [11], generation of short wavelength light due to laser interactions [2], and nonlinear mixing in meta-materials [12, 13]. Recently, we demonstrated the success of a continuum fluid-based forced Korteweg-de Vries (fKdV) model equation [1] in capturing the characteristics of NLM in a dusty plasma medium. The dominant NLM process was found to be a three-wave mixing process as confirmed by a bispectral analysis [14].

The primary motivation of our present work is to investigate the phenomenon of nonlinear wave mixing at a kinetic level by carrying out detailed molecular dynamic simulations. In doing so we also establish a strong correlation with past results that were obtained using the fKdV model equation [14]. As is well known, the Korteweg-de Vries (KdV) model is derived from model fluid equations under restrictive assumptions and its applicability to various experimental conditions has therefore been somewhat debatable. Our present work provides a firmer physical basis for the applicability of the KdV model by demonstrating that the simulation results align remarkably well with the analytic predictions of the KdV model. This is a novel result and a significant advancement over past work that helps to extend the utility of the KdV model over a broad range of nonlinear phenomena by bridging the gap between theory, simulation, and real-world plasma dynamics.

In a typical electron-ion plasma, when the focus is on ion dynamics, the electrons primarily serve as a background medium that shields ion–ion interactions. In such cases, the ions can be effectively treated as a one-component plasma (OCP), interacting through a shielded potential without explicitly modeling the electrons. Similarly, in dusty plasmas, the combined presence of electrons and ions provides the background shielding for dust particles, which evolve on much slower timescales. This enables the dust component to be modeled as an OCP as well, where dust particles interact via a screened potential, again without explicitly resolving the electrons and ions. Hence, our simulations, although for dusty plasma, also represent generic one-component plasmas across different time and length scales. In both of these contexts, the screening effect leads to a pairwise interaction between like-charged particles that takes the form of a screened Coulomb or Yukawa potential. In