Experimental, simulation, and theoretical studies of nonplanar pinned solitons in a dusty plasma

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ABSTRACT

We report on the first experimental observations of cylindrical and spherical *pinned solitons* in a flowing dusty plasma medium. The experiments are performed in the inverted Π-shaped DPEx device in which a dusty plasma is made to flow over a charged object (of cylindrical or spherical shape). It is found that over a range of supersonic velocities, 2-D half-cylindrical or 3-D half-spherical soliton structures get excited and remain attached to the front of the charged object. An important finding is the multi-humped nature of the spatial structure of these solitons and a decrease in the number of humps with increasing flow velocity. To provide theoretical support to these experimental findings, we perform molecular dynamics simulations and also construct and numerically solve a model forced Kadomtsev–Petviashvili equation appropriate for the experimental conditions. The theoretical results show good qualitative agreement with the observations and provide valuable insights into the origin and dynamics of these nonlinear structures.

I. INTRODUCTION

Solitons are a special class of nonlinear localized waves that can propagate for a long time without changing their identity and can retain their shape and size after interacting with each other. These kinds of nonlinear waves arise in a medium through an exact balance between nonlinear steepening and dispersive broadening of the wave. Historically, solitons were first observed in water waves by John Scott Russell in a canal when a moving boat was suddenly stopped, leading to a large amplitude perturbation on the surface of the water caused by the mass accumulation in front of the prow vessel. This generated a long-lived nonlinear structure that moved forward ahead of the boat.[1,2] Solitons are ubiquitous and have been widely observed and studied in many different disciplines such as in fluid dynamics,[3] nonlinear optics,[4,5] plasma physics,[6] astrophysics,[7] and molecular biology.[8] Mathematically, they are exact solutions of a host of model nonlinear partial differential equations such as the Korteweg–de Vries (KdV) equation,[9,10] the Kadomtsev–Petviashvili (KP) equation,[11] the Klein–Gordon equation,[12] and the Schrödinger equation,[13] which are all completely integrable. The excitation and propagation characteristics of solitons have been extensively investigated in laboratory experiments in plasmas[14,15] and also in dusty plasmas.[16–19]

In contrast to the original scenario described by Scott Russell in which a single soliton structure was created due to a sudden arrest of the boat's movement, solitons were also found to be generated by a continuously moving object in the fluid.[20] The condition for generation of such solitons was that the object velocity had to exceed a critical speed, namely, the phase speed of a typical normal mode of the system. These solitons created in front of the object then move away from the object at a speed faster than the speed of the object and are known as precursor solitons. At higher speeds of the object, it is also possible to excite another kind of soliton—one that travels at the same speed as the object and remains attached to it. These are known as pinned solitons. Originally studied in the context of water waves and applications to marine engineering, such solitons have recently become the object of much interest in plasma physics after it was suggested that precursors in the form of ion-acoustic solitons can be excited by fast moving charged objects in a plasma[21] and may have important applications in the detection of orbital debris objects in the Earth's ionosphere. These precursor solitons were shown to be solutions of a forced Korteweg–de Vries (f-KdV) equation and were subsequently also obtained from the full set of fluid equations[22] and in molecular dynamic simulations.[23] In a series of papers, Truit *et al.* carried out a detailed feasibility study of