Physica A 509 (2018) 162–168

Contents lists available at ScienceDirect

Physica A

journal homepage: www.elsevier.com/locate/physa

Nonplanar ion acoustic waves in collisional quantum plasma

Biswajit Sahu

Department of Mathematics, West Bengal State University, Barasat, Kolkata 700 126, India

HIGHLIGHTS

- Ion acoustic waves in collisional quantum plasma are addressed.
- Nonplanar Kakutani and Kawahara equation is derived.
- Electron–ion collision induced dissipation leads to the formation of low-frequency shock structures.

ARTICLE INFO

Article history:
Received 8 May 2018
Received in revised form 8 June 2018
Available online xxxx

Keywords:
Ion acoustic waves
Collisional quantum plasma
Nonplanar Kakutani and Kawahara equation
Solitons
Shocks

ABSTRACT

The dynamics of nonlinear ion acoustic waves (IAWs) is studied in homogeneous, unmagnetized, collisional quantum plasma consisting of electrons and ions in bounded nonplanar (cylindrical/spherical) geometries. By using the reductive perturbation method, the nonplanar Kakutani and Kawahara equation is derived to investigate the nonlinear quantum IAW profiles. The dissipation is introduced by taking into account the collision among the plasma constituents in presence of quantum diffraction effect. Numerically, the effects of various plasma parameters, such as, the collisional parameter (η), the quantum diffraction parameter H, have been examined on the propagation of nonplanar IAW structures in quantum plasma. It is shown that in nonplanar geometry, plasma parameters play a vital role on the basic features of nonlinear structures (viz. amplitude, width, speed, and so on). It is also found that the properties of IAW structures in nonplanar geometry significantly differ from those in planar geometry.

1. Introduction

The ion acoustic wave (IAW) is caused by the density perturbation and is among the most well studied electrostatic modes in both linear and non linear regimes [1,2] in electron–ion (EI) plasmas. Nonlinear theory of IAWs has been studied by using a mechanical analogy approach by Sagdeev [3], and then Ikezi et al. [4] observed IA solitons in the experimental observations. The non linear waves related to the IAWs have been studied extensively by numerous researchers [5–10] using nonlinear techniques under different plasma environments. Investigation of nonlinear structures is carried out usually by adopting some form of perturbation method. In small amplitude approximation, one ends up deriving some form of nonlinear partial differential equation like Korteweg–de Vries (KdV) or modified Korteweg–de Vries (m-KdV) or Kadomtsev–Petviashvili (KP) equation or nonlinear Schrödinger equation, etc.

The elucidation of the dynamics of quantum plasmas is recognized as a challenging area of research among researchers during the last decade. The study of quantum degeneracy in plasmas becomes important when the thermal de Broglie wavelengths of plasma species become equal or larger than the interparticle distance. The quantum effects in dense plasmas appear due to Heisenberg's uncertainty principle, i.e., localizing the particles in a small region, say ∇x, gives a momentum of $\nabla p \sim \hbar/\nabla x$ to the particle, and for high density ∇x becomes small. Therefore, electrons have higher Fermi energy as

E-mail address: biswajit_sahu@yahoo.co.in.

https://doi.org/10.1016/j.physa.2018.06.028
0378-4371/

compared to their thermal energy. The effects of the electron degeneracy arise due to Heisenberg's uncertainty principle and Pauli's exclusion principle for overlapping electron wave functions that result in tunneling of electrons and the electron degeneracy pressure [11]. The ions are nondegenerate due to their relatively large mass in comparison with the electron mass in dense EI plasmas. There has been recent increasing interest in quantum plasmas because of their application in many aspects of plasma like quantum plasma echo [12], high-energy-density compressed plasmas created by powerful laser beams [13], as well as semiconductors [14,15] and metallic nanostructures [16] for highly technological applications, quantum diodes [17], compact astrophysical objects [18–20], and other important plasma researches.

The wave propagation in a degenerate plasma can be studied using at least two main approaches, i.e., kinetic and hydrodynamic models. In kinetic theory, the unperturbed electron distribution is frequently given by a Fermi–Dirac function, while in hydrodynamics, the momentum equation for electrons is made consistent with the equation of state of a degenerate electron Fermi gas [21,22]. A quantum hydrodynamic model for a quantum system was worked out by Gardner and Ringhofer [23], by deriving the effective stress tensor and the energy density in the Born approximation to the Bloch equation. The nonlinear fluid description for a quantum plasma, in a strictly one-dimensional (1D) geometry, was presented by Manfredi and Haas [24], accounting for the moments of the Wigner equation and by prescribing the form of the electron distribution function. Haas et al. [25] studied the effects of Bohm potential on the linear and nonlinear properties of the IAW in an unmagnetized electron–ion plasma using the quantum hydrodynamic (QHD) model. It was found that the quantum effects modify the linear wave frequency, and the variation of these quantum effects is responsible to produce the shock waves, the bright and the dark solitons of the IAWs. Ali et al. [26] studied the linear and nonlinear ion acoustic waves in an unmagnetized quantum plasma. Several authors have investigated different aspects of ion acoustic solitary and shock waves in quantum plasmas [27–32]. It was observed that the inclusion of the quantum statistical and Bohm potential terms appreciably modified the scale lengths of these structures.

In most of the aforementioned works, the collision effects have not been taken into account. The collisions between plasma particles can influence not only on the system instability but also on its mode structure. If dissipation in the plasma system is high enough, the system instability leads to a well-known dissipative instability. By considering the ion hydrodynamical time scale much smaller than that of the electron–ion or ion–dust collisions, it is found that the damping of the nonlinear ion-acoustic wave is caused by collision between plasma particles [33,34]. Kakutani and Kawahara [35] studied weak nonlinear IAWs in collisional plasma consisting of cold ions warm electrons using a nonlinear perturbation method. Fedila and Djebli [36] investigated the effect of collision on small amplitude nonlinear electrostatic waves in a collisional complex plasma with positively charged dust. Misra et al. [37] have investigated the propagation characteristics of dust IA waves in a collisional negative-ion plasma with immobile charged dusts. Recently, Ghosh and Chakrabarti [38] investigated the propagation characteristics of weak nonlinear low-frequency modes in dissipative quantum plasma. All of these works are limited to one dimensional planar geometry, which may not be a realistic situation for laboratory devices and space plasmas where the geometry distortion effects on waves always exist. The observations in the auroral region cannot be explained by a purely planar geometry model, particularly at the higher polar altitude [39]. In this regard, the capsule implosion (spherical geometry), shock tube (cylindrical geometry), supernova explosions, white dwarfs, neutron stars, and black holes are some important plasma environments where nonplanar geometry plays an important role. IAWs in the nonplanar plasmas have been extensively studied in the last few decades [40–44]. Thus, it is important to investigate the propagation of nonlinear waves in a collisional quantum plasma by taking into account bounded nonplanar geometries. The paper is organized as follows. In Section 2, we present the basic equations of our theoretical model. In Section 3, nonplanar Kakutani–Kawahara equations are derived in quantum plasma by using reductive perturbation method. Section 4 deals with the numerical results and discussion of the nonlinear evolution equation, while Section 5 is kept for conclusion.

2. Basic equations

Consider the IAWs propagating in a fully ionized collisional quantum plasma whose constituents are nondegenerate ions and degenerate electrons. The ions undergo elastic collisions among electrons. According to Krooks collisional model [38,45], if $R_i = -m_i n_i \nu_{ie}(v_e - v_i)$ and $R_e = m_e n_e \nu_{ei}(v_e - v_i)$ are the momentum losses of ion and electron fluids per unit volume due to electron–ion elastic collisions, where $n_{i(e)}$ is the ion (electron) unperturbed number density, $v_{i(e)}$ is the ion (electron) fluid velocity, and $\nu_{ie(ei)}$ is the ion–electron (electron–ion) collision frequency, then

$$R_i + R_e = 0 \Rightarrow \nu_{ie} = \left(\frac{m_e}{m_i}\right)\left(\frac{n_e}{n_i}\right)\nu_{ei} \tag{1}$$

The ion dynamics in nonplanar geometry are given by the following ion momentum equation:

$$m_i n_i \left(\frac{\partial v_i}{\partial t} + v_i \frac{\partial v_i}{\partial r}\right) = e n_i E - m_i n_i \nu_{ie}(v_i - v_e) \tag{2}$$

where E is the electric field and the classical pressure effects of ions are neglected because of their large masses (compared to electrons). Also, the quantum effects of ions are negligibly small.