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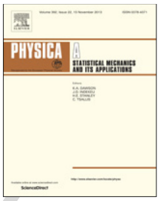

Q1 Ion-acoustic rogue waves in magnetized solar wind plasma with nonextensive electrons

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HIGHLIGHTS

- Rogue waves are investigated in a nonextensive two-component magnetized solar wind plasma.
- Typical solar wind plasmas parameters are used.
- The wave number domain for the onset of ion-acoustic modulational instability enlarges as the electrons depart from their thermal equilibrium.
- As the solar wind plasma expands far out from the sun, the wave amplitude increases and the rogue wave concentrates significant amount of energy.

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ABSTRACT

Ion-acoustic rogue waves are investigated in a two-component magnetized solar wind plasma, composed of positively charged fluid ions, as well as nonextensive electrons. Typical solar wind plasmas parameters are used. It is shown that the wave number domain for the onset of ion-acoustic modulational instability enlarges as the electrons evolve towards their thermal equilibrium. Interestingly, we show that as the solar wind plasma expands far out from the sun, the wave amplitude increases and the IA rogue wave concentrates therefore a significant amount of energy. Our investigation may be of wide relevance to astronomers and space scientists working on the solar wind and interstellar plasmas.

1. Introduction

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Plasmas are known to support a wide variety of low and high frequency wave modes [1]. One of the most well studied of such modes is the so-called ion-acoustic wave (IAW) which arises due to the restoring force provided by the electron thermal pressure while the inertia is due to the ion mass. Nonlinear ion-acoustic waves (IAWs) in plasma have been studied for a very long period of time. It was shown that the celebrated Korteweg–de Vries (K–dV) equation can be used to describe waves with moderate amplitude [2]. The nonlinear ion-acoustic waves (IAWs) have been investigated theoretically [3] as well as experimentally [4].

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During these last years, rogue waves have been among the most studied phenomena in nature [5]. They are short-lived violent phenomena occurring spontaneously and have been observed in mid-ocean and coastal waters [6]. Rogue waves are powerful enough to be fatal for ocean liners and extremely dangerous for various hydrotechnic constructions such as petroleum platforms, nuclear power plants which sit on the edge of ocean, etc. They have been widely reported over all the world and their existence has been scientifically proven. The rogue wave is a single wave with height/amplitude exceeding a certain threshold related to the sea state. Recently similar phenomena were observed in different fields of physics. In particular, it has been found experimentally that rogue waves may develop in optical systems [7,8]. Within the theoretical framework of nonlinear theory, the modulational instability (MI) has been suggested as one possible mechanism of rogue waves generation. This process can be investigated in the framework of weakly nonlinear models like the nonlinear Schrödinger (NLS) equation. Recently, many authors have investigated the properties of rogue waves in different plasma models [9–14]. Ruderman [9] discussed the generation of large amplitude short-lived rogue waves in laboratory and space plasmas. Moslem [10] analyzed Langmuir rogue waves that may accompany collisionless electron–positron plasmas. Sabry et al. [12] examined the properties of IA rogue waves for typical parameters of white dwarfs and magnestar corona. El-**Q4** Tantawy et al. [13] investigated IA super rogue waves in ultracold neural plasmas with nonthermal electrons. Bacha et al. [14] examined the generation of ion-acoustic rogue waves in a plasma with a q-nonextensive electron velocity distribution. Since then, they seem to spring up in many other fields including semiconductors [15]. Unique features of rogue waves, contrary to other solitary waves, are both their extreme magnitude but also their sudden appearance and disappearance.

We recall that over the last few years, there has been a renewed interest in nonextensive plasmas, covering different plasma modes, instabilities, collisions of solitary waves, and other collective phenomena effects (see Refs. [16–20] and references therein for an actual view of the theory and its breadth of use). This interest has been mainly motivated by the fact that during the last two decades, it has been proven that systems endowed with long-range interactions, long-time memory, fractality of the corresponding space–time/phase-space, or intrinsic inhomogeneity are untractable within the conventional Boltzmann–Gibbs (BG) statistics. To overcome this shortcoming, Tsallis [21], in a celebrated and influential paper, proposed a nonextensive generalization of the BG entropy. This generalization was first recognized by Rényi [22] and subsequently proposed by Tsallis, suitably extending the standard additivity of the entropies to the nonlinear, nonextensive case where one particular parameter, the entropic index q, characterizes the degree of nonextensivity of the system under hand (for $q \to 1$, the standard BG statistics is recovered). The maximization of this Tsallis entropy under the constraint of internal energy had derived the probability distribution of energy within the framework of canonical ensemble.

Owing to an increasing amount of experimental and theoretical evidence showing that the BG formalism fails to describe systems with long-range interactions and memory effects, Tsallis proposed the following q-entropy [21]

$$S_q = k_B \frac{1 - \sum_i p_i^q}{q-1} \tag{1}$$

where k_B is the Boltzmann constant, p_i is the probability of the ith microstate, and q a parameter quantifying the degree of nonextensivity. For $q = 1, S_q$ reduces to the habitual standard BG entropy. A very important property of the nonextensive formalism is that the distribution function which maximizes S_q is non-Maxwellian and reads as [23] $f(E) \sim \left[1-(q-1)\frac{E}{T}\right]^{1/(q-1)}$, where E denotes the total energy of the particle and T its kinetic temperature. The Tsallis q-entropy and the ensuing generalized statistics have been employed with success in plasma physics [23–33]. Silva et al. [23] generalized the Maxwell's first derivation of the equilibrium distribution function for a dilute gas in the spirit of the nonextensive q-statistics proposed by Tsallis. Lima et al. [24] discussed the dispersion relations for electrostatic plane-wave propagation in a collisionless thermal plasma in the context of the nonextensive statistics proposed by Tsallis. Du [25] studied the nonextensivity in a nonisothermal plasma system with the Coulombian long-range interaction in the framework of Tsallis statistics, and presented for the first time a mathematical expression of the nonextensive parameter q based on the mathematical theory about the generalized Boltzmann equation and the $q - H$ theorem and the Maxwellian q-velocity distribution. Liyan and Du [26] investigated the dispersion relation and Landau damping of ion-acoustic waves in a collisionless magnetic-field-free plasma described by the nonextensive q-distributions of Tsallis statistics. Liu et al. [27] examined the instability of current-driven ion-acoustic waves in a collisionless magnetic-field-free space plasma by using a nonextensive approach. Tribeche et al. [28] addressed arbitrary amplitude ion-acoustic solitary waves in a two-component plasma with a q-nonextensive electron velocity distribution. Ait Gougam and Tribeche [29] investigated weak ion-acoustic double-layers in a two-component plasma in the context of the nonextensive statistics proposed by Tsallis. Tribeche et al. [30] generalized the model of Cairns et al. and outlined a new physically meaningful nonextensive nonthermal velocity distribution which can be termed as the Tribeche–Tsallis–Cairns (TTC) distribution. Bacha et al. [31] revisited the dust-modified ion-acoustic waves within the theoretical framework of the Tsallis statistical mechanics in a dusty plasma with self-consistent dust charge fluctuation. Bacha and Tribeche [32] investigated nonlinear nonextensive dust-acoustic waves in a dusty plasma with self-consistent nonadiabatic grain charge fluctuation. Saberian and Esfandyari-Kalejahi [33] studied the Langmuir oscillations, Landau damping, and growing unstable modes in an electron–positron (EP) plasma by using the Vlasov and Poisson's equations in the context of the Tsallis's nonextensive statistics.

The solar wind is a continuous stream of high-speed charged plasma particles released from the upper atmosphere of the Sun [34]. The solar wind is a tenuous plasma with a frozen-in magnetic field, and is mainly composed of electrons, ions, and occasionally other heavy ions [35]. Observations of spike-like dips called magnetic holes have been made by Voyager 1 in the

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