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Modulational instability of dust ion acoustic waves in astrophysical dusty plasmas with non thermal electrons

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Abstract. Propagation of dust ion acoustic waves in plasmas composed of non-thermal distributed electrons and stationary dust particles is investigated. Nonlinear Schrdinger equation is derived to describe small amplitude waves, using the reduction perturbation technique. Modulation instability of dust ion acoustic waves is analysed for this system. Parametric investigation indicates that growth rate of the modulational instability is sensitive to the value of non-thermal parameter and relative density of plasma constituents.

Keywords: Modulational instability, dust ion acoustic waves, non-thermal electrons, Nonlinear Schrdinger equation

1 Introduction

Small amplitude localized perturbations associated with the dust ion acoustic waves (DIAW) [1, 2, 3], particularly the dust ion-acoustic envelope solitary waves [4, 5] have received great attention in plasma physics because of their importance in astrophysical environments as well as in laboratory experiments[6-11]. Comets are surrounded by multi-ion plasmas composed of electrons and protons (which come from solar wind), positively charged hydrogen H^+ and oxygen ions (originated from water molecules) and a sort of photo-electrons [12]. Other important species of hot ions like H_2^+, He^+, He^{2+}, CO^+ ,etc have been reported in the tail of comet Halley [13, 14]. Multiply ionized heavy particles also have been observed in comet McNaught-Hartley [15, 16]. Some measurements also indicated the presence of negative ions in some regions of earth's ionosphere and also in the Titans atmosphere [17, 18, 19]. Effects of such grains on the behaviour of astrophysical plasmas have been investigated extensively. Shukla and Silin [12] have theoretically shown that a dusty plasma (with negatively charged static dust) supports low-frequency dust ion-acoustic (DIA) waves (DIAWs) with phase velocity much smaller (larger) than the electron (ion) thermal speed, due to the conservation of equilibrium charge density. The DIAWs have also been observed in laboratory experiments [21, 22]. Mamun and Shukla [23, 24] have investigated DIASWs in unmagnetized dusty plasmas consisting of cold ion fluid, isothermal electrons, and negatively charged static dust particles. Mamun [25] discussed the propagation of nonlinear one-dimensional DIASWs in unmagnetized dusty plasmas containing adiabatic ions, electrons and negatively charged static dust grains. The standard multiple scale technique [26, 27] employed in the study of this mechanism, leads to a nonlinear Schroedinger-type equation (NLSE), describing the evolution of wave envelopes. Under certain conditions, the wave may undergo a BenjaminFeir-type (modulational) Instability (MI), i.e., its envelope may collapse under the

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influence of external perturbations. The NLSE is used in a variety of physical contexts to describe some behavioural aspects of systems [28, 29, 30]. This equation reveals the possibility of the existence of localized excitations like envelope solitary waves. The NLSE is able to successfully explain the characteristics depend on criteria, similar to the ones necessary for the MI in plasmas. These structures, sustained by the mutual compensation of dispersion and nonlinearity, may be the result of energy localization in the evolution stage following the wave amplitude collapse and propagate in the nonlinear medium for long times, surviving interactions with each other. The dynamics of modulated dust-acoustic wave packets in dusty plasmas with Boltzmann distributed electrons have been have been investigated in previous studies [31, 32, 33].

Numerous observations clearly indicate the presence of energetic electrons as ubiquitous in a variety of astrophysical plasma environments and measurements of their distribution functions revealed them to be highly non-thermal. non-thermal distributions are turning out to be a very common and characteristic feature of space plasmas where coherent nonlinear waves and structures are expected to play an important role. Such non-thermal populations may be distributed isotropically in velocities. They may possess a net streaming motion with respect to the background plasma. Their presence has been confirmed by many observations in space plasmas [26-29]. Observations made by the Viking spacecraft [38] and Freja satellite [39] have found electrostatic solitary structures in the magnetosphere with density depressions. Motivated by these events, Cairns et al. [40] showed that the presence of non-thermal distribution of electrons may change the nature of ion sound solitary structures and allow the existence of rarefactive ion-acoustic solitary structures like those observed by Freja and Viking. Some recent theoretical works focused on the effects of particle non-thermality on different types of linear and nonlinear collective processes [33-44]. From the best of our knowledge, the dynamics of modulated dust-acoustic wave in dusty plasmas with non-thermal electrons have never been addressed in the plasma literature. The aim of this paper is to study the MI of DIAWs in dusty plasmas consisting of negative dust particles as well as non-thermal electrons. The layout of this article goes as follows: In Section 2, we present the basic equations. Also we obtain a nonlinear Schrdinger equation, governing the slowly varying modulation, using the reductive perturbation technique. In section 3, we discuss the numerical results of MI analysis and present the influence of non-thermal parameters and dust (or electron/ion) concentration on the growth rate of the modulational instability. Section 4 is kept for discussion and conclusions.

2 Basic equations and derivation of NLSE

We consider an unmagnetized dusty plasma whose constituents are cold inertial ions, non-thermal distributed electrons, negatively charged immobile dust particles. The inertia of the system is provided by the ion mass, and the restoring force comes from the pressure of inertialess electrons, and the equilibrium charge neutrality condition is maintained by the stationary dust particles. In equilibrium, the charge neutrality condition is $n_{i0} = Z_d n_{d0} + n_{e0}$ where n_{i0}, n_{d0} and n_{e0} are unperturbed number densities of the ion, dust and electron, respectively. Hence, the usual ion fluid equations, which include the continuity equation, momentum balance equation, and Poisson's equation, governing the DIAW are as follows:

$$\frac{\partial n}{\partial t} + \frac{\partial nu}{\partial x} = 0 \tag{1}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = -\frac{\partial \phi}{\partial x} \tag{2}$$

$$\frac{\partial^2\phi}{\partial x^2} = \mu n_e - n + 1 - \mu \tag{3}$$

where n is the ion number density normalized by its equilibrium value (n_{i0}). u is the ion fluid speed, normalized by $c_i = \sqrt{T_e/m_i}$ and ϕ is the electrostatic wave potential normalized by (T_e/e), where T_e is the electron temperature. The time t and the distance x are normalized by the ion plasma frequency $\omega_{pi}^{-1} = \sqrt{\frac{m_i}{4\pi n_{i0}e^2}}$ and the Debye radius $\lambda_{Di} = \sqrt{\frac{T_e}{4\pi n_{i0}e^2}}$, respectively. We have denoted $\mu = \frac{n_{e0}}{n_{i0}}$. The non-thermal electron number density is given by [53]:

$$n_e = (1 - \beta\phi + \beta\phi^2)e^{\phi} \tag{4}$$

where $\beta = \frac{4\alpha}{1+3\alpha}$ and α is a parameter that determines the fraction of energetic non-thermal electrons and characterizes the degree of electron non-thermality. Now using n_e in the Poissons equation we get

$$\frac{\partial^2\phi}{\partial x^2} = 1 + c_1\phi + c_2\phi^2 + c_3\phi^3 - n \tag{5}$$

where

$$\begin{aligned} c_1 &= \mu(1-\beta) \\ c_2 &= \frac{\mu}{2} \\ c_3 &= \frac{\mu}{2}(\frac{1}{3} + \beta) \end{aligned} \tag{6}$$

We employ the standard reductive perturbation technique [54] to investigate the amplitude modulation of DAWs in dusty plasmas with non-thermal electrons and ions. The independent variables are stretched as $\xi = \epsilon(x - V_0 t)$ and $\tau = \epsilon^2 t$, where ϵ is a small constant and V_0 is a free parameter to be determined later as the group velocity of moving waves by the compatibility condition. The dependent variables are expanded as follows:

$$\begin{aligned} n &= 1 + \sum_{r=1}^{\infty}\epsilon^r \sum_{l=-\infty}^{+\infty} n_l^r(\xi,\tau)e^{il(kx-\omega t)} \\ u &= \sum_{r=1}^{\infty}\epsilon^r \sum_{l=-\infty}^{+\infty} u_l^r(\xi,\tau)e^{il(kx-\omega t)} \\ \phi &= \sum_{r=1}^{\infty}\epsilon^r \sum_{l=-\infty}^{+\infty} \phi_l^r(\xi,\tau)e^{il(kx-\omega t)} \end{aligned} \tag{7}$$

where n_l^r, u_l^r and ϕ_l^r are real functions in a way that, for example, $n_l^r = n_l^{r*}$ and the asterisk denotes complex conjugation. Substituting these expressions along with stretching coordinates into equations (1)-(6) and collecting the terms in the different powers of ϵ, we can find all orders of reduced equations. We obtain the first-order ($r = 1$) equation quantities with $l = 1$ as follows:

$$\begin{aligned} &-i\omega n_1^1 + iku_1^1 = 0 \\ &-i\omega u_1^1 - ik\phi_1^1 = 0 \\ &n_1^1 + (k^2 + c_1)\phi_1^1 = 0 \end{aligned} \tag{8}$$

The solution for the first harmonics is:

$$n_1^1 = -(k^2 + c_1)\phi_1^1 \qquad (9)$$
$$u_1^1 = -\frac{\omega}{k}(k^2 + c_1)\phi_1^1$$

that give rise to the following dispersion relation for the DIAWs:

$$\frac{\omega^2}{k^2} = \frac{1}{k^2 + c_1} \qquad (10)$$

At second order in ϵ and using the zeroth and second harmonics, we expect to extract expressions for the group velocity V_0. For $r = 2$ and $l = 1$, we need to impose a compatibility condition in the following form:

$$\frac{\partial \phi_1^1}{\partial t} + V_0 \frac{\partial \phi_1^1}{\partial x} = 0 \qquad (11)$$

where we have defined the group velocity $V_0(k) = \frac{\partial \omega}{\partial k}$ given by:

$$V_0 = \frac{\omega}{k}\left(1 - \omega^2\right) = c_1 \frac{\omega^3}{k^3} \qquad (12)$$

The expressions for the amplitudes corresponding to the first harmonics in order ϵ^2 are given by:

$$-i\omega n_1^2 + iku_1^2 = V_0 \frac{\partial n_1^1}{\partial \xi} - \frac{\partial u_1^1}{\partial \xi} \qquad (13)$$
$$-i\omega u_1^2 + ik\phi_1^2 = V_0 \frac{\partial n_1^1}{\partial \xi} + \frac{\partial \phi_1^1}{\partial \xi}$$
$$-n_1^2 - (k^2 + c_1)\phi_1^2 = 2ik \frac{\partial \phi_1^1}{\partial \xi}$$

The second-harmonic modes $r = 2$, $l = 2$ arising from the nonlinear self-interaction of the carrier waves are obtained in terms of $(\phi_1^1)^2$ as

$$\begin{aligned} n_2^2 &= A_n(\phi_1^1)^2 \\ u_2^2 &= A_u(\phi_1^1)^2 \\ \phi_2^2 &= A_\phi(\phi_1^1)^2 \end{aligned} \qquad (14)$$

where

$$\begin{aligned} A_n &= -c_2 - \left(\frac{k^2 + 3k^2\omega^2}{\omega^2}\right) A_\phi \\ A_u &= \frac{\omega}{k}\left(A_n - \frac{k^4}{\omega^4}\right) \\ A_\phi &= -\frac{c_2}{3k^2} - \frac{k^2}{2\omega^4} \end{aligned} \qquad (15)$$

The zeroth-harmonic mode (in terms of $|\phi_1^1|^2 = (\phi_1^1)^*(\phi_1^1)$) also appears due to the self interaction of the modulated carrier wave. Its expression cannot be determined completely within the second order and we will have to consider the third-order equations. Thus, the

$l = 0$ components of the third-order part of the reduced equations determine the following second-order quantities in the zeroth-harmonic:

$$\begin{aligned} n_0^2 &= B_n|\phi_1^1|^2 \\ u_0^2 &= B_u|\phi_1^1|^2 \\ \phi_0^2 &= B_\phi|\phi_1^1|^2 \end{aligned} \tag{16}$$

where

$$\begin{aligned} B_n &= -c_1 B_\phi - 2c_2 \\ B_u &= -\frac{2k^3}{\omega^3} + V_0 B_n \\ B_\phi &= -\frac{2c_2 V_0^2 + 3c_1 + k^2}{1 - c_1 V_0^2} \end{aligned} \tag{17}$$

Finally, substituting all the previous derived expressions into the relations for $n = 3$, $l = 1$ lead to the following NLS equation:

$$i\frac{\partial \Phi}{\partial \tau} + P\frac{\partial^2 \Phi}{\partial \xi^2} + Q|\Phi|^2\Phi = 0 \tag{18}$$

For the slowly varying first-order amplitude of the plasma perturbation potential, $\Phi = \phi_1^1$. In the above equation, the coefficients P and Q are given as:

$$\begin{aligned} P &= -\frac{3}{2}c_1\frac{\omega^5}{k^4} \\ Q &= \frac{\omega^2}{2k^2}\left[3c_3 + 2c_2\left(A_\phi + B_\phi\right) - 2\frac{k}{\omega}\left(k^2 + c_1\right)\left(A_u + B_u\right) - \left(k^2 + c_1\right)\left(A_n + B_n\right)\right] \end{aligned} \tag{19}$$

3 Modulation instability (MI)

We have studied the MI of DAWs through considering a small perturbation $\delta\phi$ from the potential Φ. Therefore, we set $\Phi = (\Phi_0 + \delta\phi)e^{i\Delta\tau}$, where Φ_0 is the amplitude of the pump carrier which is much larger than the perturbation, i.e. $\Phi_0 \gg |\delta\phi|$ where $\Phi = \phi_1^1$; also here, Δ is a nonlinear frequency shift produced by the nonlinear interaction. After substituting $\Phi = (\Phi_0 + \delta\phi)e^{i\Delta\tau}$ into equation 18 and collecting terms of the same order, we obtain [55]

$$\Delta = -Q|\Phi_0|^2 \tag{20}$$

and

$$i\frac{\partial \delta\phi}{\partial \tau} + P\frac{\partial^2 \delta\phi}{\partial \xi^2} + Q|\Phi_0|^2(\delta\phi + \delta\phi^*) = 0 \tag{21}$$

where $\delta\phi^*$ is the conjugate of $\delta\phi$. Upon assuming the amplitude perturbation varying as $e^{i(k\xi - \Omega\tau)}$, we obtain the following nonlinear dispersion relation

$$\Omega^2 = -P^2k^2(k^2 - 2Q|\Phi_0|^2/P) \tag{22}$$

Clearly, if $PQ < 0$, for all values of k, the DAW is stable at the presence of small perturbations, since Ω is always a real number. On the other hand, when $PQ > 0$, the modulation instability (MI) would arise as Ω becomes imaginary. This happens when the modulation

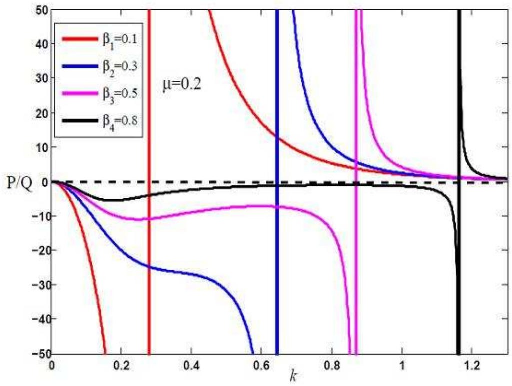

Figure 1: Variation of the NLSE coefficients ratioP/Q with respect to the carrier wave number k for different values of β with $\mu = 0.2$.

wave number k of external perturbation is less than the critical value $k_{cr} = \sqrt{2Q|\Phi_0|^2/P}$. In the region $PQ > 0$ and $k < k_{cr}$, the MI growth rate is

$$\Gamma = Im(\Omega) = \sqrt{P^2 k^2 (k_{cr}^2 - k^2)} \tag{23}$$

Obviously, the growth rate reaches its maximum value, $\Gamma_{max} = Q|\Phi_0|^2$, for $k = \frac{|k_{cr}|}{2}$. Our primary aim is to demonstrate the effects of the non-thermal electrons and ions on the instability of DAWs. As mentioned before, we expect MI arise for $PQ > 0$. Our analysis shows that the coefficient P is always negative, but Q can be negative or positive. Apparently, the coefficients of dispersion term P and nonlinear term Q are related to β and μ. Therefore, we expect that these parameters affect the instability characteristics which may develop in our plasma system. To investigate these effects with more details, we plot the ratio of P/Q versus the carrier wave number k for different parameters. In all cases which we have presented here, $Q = 0$ corresponds to zero dispersion point leading to $P/Q \to \pm\infty$. The corresponding value of k ($= k_c$) is called critical or threshold wave number for the onset of MI.

Figure 1 presents P/Q ratio as functions of k for different values of non-thermal parameter β. This figure shows that threshold wave number k_c shifts toward larger values as non-thermal parameter β increases. This means that fast particles prevent the MI.

Figure 2 demonstrates P/Q ratio respect to wave number k for different values of $\mu = \frac{n_{e0}}{n_{i0}}$. As figure 2 presents, the threshold wave number goes toward lower values as μ increases. Thus, onset of MI shifts toward greater wave number in plasmas with higher population of ion particles. This means that existence of ion particles helps the stability of plasmas.

4 Conclusion and Remarks

Modulational instability in unmagnetized dusty plasma containing cold inertial ions, non-thermal distributed electrons and negatively charged immobile dust particles has been investigated. We have shown that small perturbations in the potential evolves according to the nonlinear Schrdinger equation. Growth rate of such perturbations is very sensitive to the excess fast electrons and population of ions. Onset of modulational instability shifts toward larger wave number in plasmas with more numbers of excess fast electrons. On the other hand, increase in the population of ions improves the system stability. Any way for

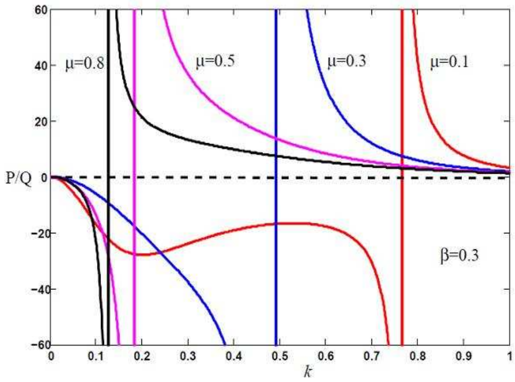

Figure 2: Variation of the NLSE coefficients ratioP/Q respect to the carrier wave number k for different values of μ with $\beta = 0.3$.

some values of population ratio of plasma constituents, perturbations grow in a way that the plasma becomes unstable.

It is interesting to investigate other multi components plasmas containing non-thermal electrons. Comparing the results gives more clear view from the role of fast electrons in plasmas. Also, other distribution functions for plasma species should be studied and the results would be compared to find better perspective about the nature of plasma systems. Such investigations can be done in further works.

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