Investigation of Dust-Ion Acoustic Waves in a Magnetized Collisional Dusty Plasma with Kappa Distribution Function for Electrons

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ABSTRACT—The propagation of arbitrary amplitude dust ion acoustic waves (DIAWs) in a magnetized collisional dusty plasma including hot electrons, with kappa velocity distribution for electrons, warm ions and dust particles has been studied. In the presence of immobile massive dust particulates, DIAWs have been investigated through the Sagdeev pseudo-potential method. It is demonstrated that the amplitude and width of the pseudo-potential are increased with the ion density and also with Directional cosines. It is shown that the behaviors of the amplitude and the width of the wave in terms of all of plasma parameters is similar to the our recently work, and the spectral index has a little effect on the wave.

KEYWORDS: magnetized dusty plasma, Dust ion acoustic waves, Sagdeev pseudo-potential method.

I. INTRODUCTION
Nowadays, the study of dusty plasmas properties has received a great deal of attention both theoretically and experimentally. In the presence of massive and highly charged dust particulates in an usual electron ion plasma new types of waves, such as dust acoustic (DA) waves and dust-ion-acoustic (DIA) waves are excited. These dusts can be regarded as static or mobile particles [1]. The nonlinear waves particularly, the DIA solitary waves (DIASW) have been theoretically investigated by several authors [2-6].

In the most of the above mentioned investigations, Maxwellian or Maxwellian Boltzmann distribution functions have been used. However, a lot of theoretical observations of space plasmas are often characterized by a non- Maxwellian particle distribution function. In these plasmas, superthermal particles which are produced due to the effect of wave particle interaction or external forces. Superthermal plasmas are relativistic pulsar wind, solar wind, magnetosphere, interstellar medium, auroral zone plasmas, plasmas produced during an ultra-intense laser pulse interaction with matter. [7, 8]. These kinds of a plasma, can be characterized by generalized Lorentzian or kappa distribution function [9, 10]. This Lorentzian (kappa) velocity distribution is used to model the electrons in magnetosphere and electromagnetic ion cyclotron waves in equatorial ring protons [11, 12]. Using a kappa distribution for plasma particles, many authors have studied the propagation of ion acoustic waves in a magnetized plasma using Sagdeev potential method. The one dimensional kappa velocity distribution is

\[ F_\kappa(v) = \frac{1}{(\pi \theta^2)^{3/2}} \frac{\Gamma(\kappa + 1)}{\Gamma(\kappa - 1/2)} \left( 1 + \frac{v^2}{\kappa \theta^2} \right)^{-(\kappa+1)} \]  

(1)

where \( \theta \) is the most probable speed (effective thermal speed), related to the usual thermal
velocity \( V_e = \left( K_0 T / m \right)^{1/2} \) by \\
\( \theta = \left[ (2x - 3) / \kappa \right] v_e \). \( T \) is the characteristic kinetic \\
temperature, \( \kappa \) is spectral index and \( K_0 \) is the Boltzmann \\
constant. The most probable speed, and hence the \( \kappa \)-distribution, is defined for \\
\( \kappa > 3/2 \) [7, 8, 11]. Nonlinear propagation of ion \\
aoustic waves in a magnetized plasma, electron acoustic waves in a two \\
temperature electron plasma, linear and nonlinear \\
propagation of these sound waves again with the presence of hot electron component and so \\
on have been already studied [13].

Recently, we have investigated the propagation of dust ion acoustic wave in a \\
dusty plasma in the presence of nonthermal \\
electrons [14]. In this paper, the previous work \\
has been extended with the warm ions and hot \\
electrons. In the second section, the governing \\
basic equations are presented similar to our \\
previous paper [14]. The resultant dispersion \\
relation and as well as the Sagdeev potential \\
are derived in the third section. Finally, the \\
umerical investigations are presented in the \\
last section.

\section{II. Basic Equations}

The continuity and momentum equations for \\
ions and also Poisson equation are:

\[
\partial_t n_i + \nabla \cdot (n_i \mathbf{v}_i) = 0, \tag{2}
\]

\[
\partial_t \mathbf{v}_i + (\mathbf{v}_i \cdot \nabla) \mathbf{v}_i = \frac{e}{m_i} \left( \mathbf{E} + \frac{B_0}{c} \mathbf{v}_i \times \mathbf{e}_z \right), \tag{3}
\]

\[
\nabla^2 \varphi = -4\pi \left[ -en_e + en_i - e z_d n_d \right], \tag{4}
\]

where \( n_e \), \( n_i \), and \( n_d \) are electron, ion, and \\
dust densities respectively. \( \mathbf{v}_i \), \( v \), and \( m_i \) \\
indicating the ion velocity, collision frequency \\
and its mass. \( q_d = -e z_d \) where \( \varphi \) is the plasma \\
potential, \( z_d \) is the dust charge number, so that \\
the charge of the dust is given by \( q_d = -e z_d \), \\
with \( e \) being the elementary charge. Here, \\
electrons are assumed to be kappa distributed \\
and the expression for the electron density is \\
as follows:

\[
n_e = \frac{1}{\delta_1} \left( 1 - \frac{\varphi}{\kappa - 3/2} \right)^{-(\kappa-1/2)}, \tag{5}
\]

where, \( \delta_1 = \frac{n_{i0}}{n_{e0}} \).

We assume that the wave is propagating in the \\
x-z plane. After normalization, the above 

system of equations is reduced to:

\[
\partial_t n + \partial_z (nv_z) + \partial_z (nv_e) = 0 \tag{6}
\]

\[
\partial_t v_z + (v_z \partial_z + v_e \partial_e) v_z = -\partial_z \varphi + v_z, \tag{7}
\]

\[
\partial_t v_z + (v_z \partial_z + v_e \partial_e) v_z = -v_z - \gamma \partial_z n + n v_z \tag{8}
\]

\[
\partial_t v_z + (v_z \partial_z + v_e \partial_e) v_z = -\partial_z \varphi - \gamma \partial_z n + n v_z \tag{9}
\]

\[
(\partial_{xx} + \partial_{zz}) \varphi = \beta \left[ \frac{1}{\delta_1} \left( 1 - \frac{\varphi}{\kappa - 3/2} \right)^{-(\kappa-1/2)} \right], \tag{10}
\]

where, \( \beta = r_g^2 / \lambda_e^2 \), \( \delta_1 = n_{i0} / n_{e0} \), \( \delta_2 = n_d z_d / n_{e0} \), \\
and \( \lambda_e = (T_e / 4\pi n_{e0} e^2)^{1/2} \) is the electron Debye length. 

\( C_s = (T_e / m_i)^{1/2} \) is the ion acoustic velocity, and \\
\( \Omega_e = eB_0 / m_i c \) is the ion gyro frequency. \( n_{e0} \) and \( n_{i0} \) \\
are unperturbed electron and ion densities, respectively. 

The normalizations are:

\[
\Omega t \rightarrow t, \ (C_s / \Omega) \nabla \rightarrow \nabla, \ v_z / C_s \rightarrow v_z, \ n_i / n_{i0} \rightarrow n, \text{ and } e\varphi / T_e \rightarrow \varphi, \\
\]

To derive the dispersion relation for low 

frequency waves, we write the dependent 

variables as sum of equilibrium and perturbed 

parts. Assuming \( n = 1 + \tilde{n} \), \( v_z = \tilde{v}_z \), \( v_e = \tilde{v}_e \), 

\( v_x = \tilde{v}_x \), Eqs. (5) - (9) can be rewritten as:

\[
\partial_t \tilde{n} + \partial_t \tilde{v}_z + \partial_z \tilde{v}_z = 0 \tag{11}
\]
\[
\partial_t \ddot{v}_x = -\partial_x \ddot{\phi} + \ddot{v}_y - \gamma \frac{\partial_x \dddot{v}_x + \nu \dot{v}_x}{1+n} 
\] (12)

\[
\partial_t \ddot{v}_y = -\nu \dot{v}_x + \dot{v}_y 
\] (13)

\[
\partial_t \ddot{v}_z = -\partial_z \ddot{\phi} - \gamma \frac{\partial_z \dddot{v}_z + \nu \dot{v}_z}{1+n} 
\] (14)

\[
(\partial_{xx} + \partial_{zz}) \phi = \beta \left[ \frac{\kappa-1/2}{\kappa-3/2} \dddot{\phi} - \delta \dddot{n} \right] 
\] (15)

We assume that the perturbation is of the form \( \exp(i k_s x + k_z z - \omega t) \), where \( k_s \) and \( k_z \) are the wave numbers in \( x \) and \( z \) directions, respectively. Hence, the dispersion relation for ion acoustic wave can be obtained as

\[
\beta_i (i\omega (v + i\omega)^3 + k_s^2 (v + i\omega)^2 + i\omega (v + i\omega) + \gamma) + \delta k_z^2 = 0 
\] (16)

\[
\left( \gamma \nu^2 k^2 - (\gamma \nu^2 - \gamma) k_z^2 - 3\nu^2 \omega^2 + \omega^2 - \omega^2 \right) - \delta \left( \frac{\nu^2 + \omega^2}{k_z^2} \right) = 0 
\] (17)

where \( \beta_i = k^2 / \beta + \frac{\kappa-1/2}{\kappa-3/2} \). By assuming \( \omega = \omega_t + i\omega_i \), the above equation reads as

\[
X + iY = 0 \), where

\[
X = \beta_i \left( (1 + 3\nu^2) \lambda + \gamma k_z^2 + \gamma \nu^2 (\nu^2 + \lambda) - \omega \nu \left( \nu^2 + 1 - 6\omega^2_r + 3\lambda + 2\gamma k_z^2 \right) \right) + \delta k_z^2 (\nu^2 - 2\omega \omega_i \lambda) - \delta k_z 
\] (18)

and

\[
Y = -2\omega \omega_i k^2 \left( 1 + 3\nu^2 \right) (\gamma + \delta_i) + \beta_i \nu^2 (\nu^2 + 3\nu^2 - 9\nu \omega_i \omega^2_i + 9\nu \omega_i \omega_i + 9\nu \omega_i \omega^2_i + 9\nu \omega_i \omega_i + 9\nu \omega_i \omega_i - 2\delta \omega \omega_i k^2 
\] (19)

Here \( \lambda = \omega^2_t - \omega^2_i \) introducing a new variable \( \eta = \omega_x l + \omega_z z - Mt \), where \( \omega_x \) and \( \omega_z \) are directional cosines and \( M \) is the Mach number. Equations (5)–(9) can be written as ordinary differential equations in terms of \( \eta \):

\[
M(1-n) + n(1, \nu_x + L_z z) = 0 
\] (20)

\[
-\frac{M d\nu}{d\eta} + \left( \nu_x \frac{d}{d\eta} + \nu_z \frac{d}{d\eta} \right) v_x = \left( -l_x \frac{d}{d\eta} \right) v_y + \gamma l_z \frac{d}{d\eta} v_y 
\] (21)

\[
-\frac{M d\nu}{d\eta} + \left( \nu_x \frac{d}{d\eta} + \nu_z \frac{d}{d\eta} \right) v_y = \left( -l_z \frac{d}{d\eta} \right) v_z + \gamma l_z \frac{d}{d\eta} v_z 
\] (22)

Substituting Eq. (19) in Eq. (20), we have:

\[
M \frac{d\nu}{d\eta} = l_x \frac{d}{d\eta} - \gamma \frac{d}{d\eta} + \nu_x 
\] (25)

Using Eq. (19), Eqs. (21) and (20) are rewritten as:

\[
M \frac{d\nu_x}{d\eta} = v_x + \nu_y 
\] (26)

\[
M \frac{d\nu_z}{d\eta} = l_z \frac{d}{d\eta} + \gamma l_z \frac{d}{d\eta} + \nu_z 
\] (27)

\[
G(\phi) = \int_0^\phi \frac{d}{d\eta} 
\] (28)
\[ v_z = b_1 \phi + b_2 \phi^2 + b_3 \phi^3 + \ldots \]  

(29)

Considering Eq. (23), we get:

\[ \frac{1}{2} \left( l_z^2 + l_z^2 \right) \left( \frac{d \varphi}{d \eta} \right)^2 = \beta \left[ 1 + \varphi + \frac{\kappa - 1/2}{2(\kappa - 3/2)} \varphi^2 - \delta_1 G(\varphi) + \delta_2 \varphi \right] \]  

(10)

Comparing the coefficients of equal powers of \( \varphi \) in Eqs. (26) and (28), up to the second order, one can obtain:

\[
\begin{aligned}
&\left( \frac{1}{3} (-2\gamma a_1 l_z + Mb_1 - l_z^2) A_z - 2\alpha a_1 l_2^2 + 2Mb_2 \\
&-2\alpha a_1 l_z \right) \sqrt{A_z} - 2\alpha a_1 \nu b_1 - \nu b_2 \right) \varphi^2 + \left( (-2\gamma a_1 l_z \\
&+ Mb_1 - l_z) + \sqrt{A_z} - \nu b_1 \right) \varphi = 0
\end{aligned}
\]  

(21)

### III. Pseudo-Potential Approach

The Eq. (29) can be written as

\[
\frac{1}{2} \left( \frac{d \varphi}{d \eta} \right)^2 + V(\varphi) = 0
\]

(32)

The above equation is an “energy integral” of an oscillatory particle with unit mass, pseudo-velocity \( \frac{d \varphi}{d \eta} \) at the pseudo-position \( \varphi \) in a pseudo-potential well \( V(\varphi) \). To obtain an equation for \( G(\varphi) \), one can expand \( G(\varphi) \) and \( v_z \) in terms of \( \varphi \):

\[ G(\varphi) = \varphi + a_1 \varphi^2 + a_2 \varphi^3 + \ldots \]  

(33)

\[ v_z = A \varphi + B \varphi^2 + C \varphi^3 + \ldots \]  

(34)

To find the coefficients, one can substitute the Eqs. (31) and (32) in Eq. (29) to get,

\[
\left( \frac{d \varphi}{d \eta} \right)^2 = \frac{2\beta}{l_z^2 + l_z^2} \left[ 1 + \delta_1 - \delta_2 \right] \varphi
\]

\[
+ \frac{2(\kappa - 1/2)}{\kappa - 3/2} \left( 4\delta_3 a_1 \right) \varphi^2
\]

\[
+ \frac{\kappa - 1/4}{(\kappa - 3/2)^2} - 6\delta_3 a_2 \right) \varphi^3 + \ldots
\]

(45)

And up to the second order we have

\[ \frac{d^2 \varphi}{d \eta^2} = A_1 \varphi + A_2 \varphi^2 = -\frac{dV}{d\varphi} \]  

(56)

\[ \frac{d^2 \varphi}{d \eta^2} = A_1 \varphi + A_2 \varphi^2 = -\frac{dV}{d\varphi} \]  

(67)

where,

\[ A_1 = \frac{\beta}{l_z^2 + l_z^2} \left[ \frac{2(\kappa - 1/2)}{\kappa - 3/2} - 4\delta_3 a_1 \right] \]  

(38)

and

\[ A_2 = \frac{\beta}{(\kappa - 3/2)^2} - 6\delta_3 a_2 \]  

(79)

Eqs. (24) and (25) can be solved as

\[ M \frac{dv_z}{d\varphi} \frac{d\varphi}{d\eta} = v_z G(\varphi) + \nu v_z G'(\varphi) \]  

(40)

\[ v_z = l_z \frac{d\varphi}{d\eta} + l_z \frac{\nu}{G'(\varphi)} \frac{dG(\varphi)}{d\eta} + \nu v_z - \frac{M}{G(\varphi)} \frac{dv_z}{d\eta} \]  

(41)

Equating the coefficients in the Eqs. (36) and (37), and expansion of \( \left( \frac{d \varphi}{d \eta} \right)^2 \) and substituting in Eq. (39) one can obtains up to second order.
\[
\left( \frac{10l_ab_1}{l_x} - 16Mv^2a_1^2 + 3Mv^2a_2 - \frac{\nu^2b_1l_z}{l_x} \right) + 8Ma_1l_x + \frac{8M^3a_1^2}{l_x} - 12M^3a_2 - \\
2M^2A_3a_1 - \frac{2l_b^2}{l_x} - 10va_1l_x - 12M\gamma a_1l_A - \\
\left( \frac{l_b}{l_x} - \frac{16M_0^2}{l_x} + \frac{4M^2a_bA_1}{l_x} + 2\gamma v_aL_A + \right) \phi^2 + \\
\left( \frac{-2Ma_1}{l_x} - 2Mv^2a_1 + 2\gamma v_aL_A - 2M^3a_1A_1 + \\
\frac{4M^2v_aL_A}{l_x} + M_1A_1 - 2M\gamma a_1l_A + \\
\nu^2b_1l_z - \frac{b_1l_z}{l_x} + \frac{l_z^2}{l_x} - v\lambda A_1 \right) \phi = 0
\] (42)

The coefficients \(a_1, a_2, b_1\) and \(b_2\) can be determined by solving the Eqs. (30) and (39). From equation (34), as like as [14], we get:

\[
\phi = -\frac{3A_1}{2A_2} \sec h^2 \left( \sqrt{A_1} \eta/2 \right) 
\] (43)

**IV. NUMERICAL INVESTIGATIONS**

The above results i.e. Eqs. (35)–(41), show that all coefficients are dependent to the spectral index and all plasma parameters. So for investigating the plasma parameters effects on the wave propagation, we use parameters written in Table 1:

**TABLE 1: Plasma parameters used in numerical investigation.**

<table>
<thead>
<tr>
<th>Plasma parameters</th>
<th>(\beta)</th>
<th>(\delta_1)</th>
<th>Mach number (M)</th>
<th>Directional cosines (l_z)</th>
<th>Spectral index ((\kappa))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range of Values</td>
<td>0.46, 0.49, 0.55</td>
<td>1.54, 2.54, 3.54</td>
<td>2, 2.25, 2.1, 0.1, 0.4, 0.58</td>
<td>5/2</td>
<td></td>
</tr>
</tbody>
</table>

The variation of the pseudo-potential versus ion to electron density ratio is shown in Fig. 1. It is seen that the amplitude of \(V(\varphi)\) increases with increasing the density ratio. It is concluded that increasing the ion density can lead to higher amplitude waves and also it can be said that for all positive values of \(\varphi\), \(V(\varphi)\) is positive and vice versa.

From Fig. 2, it is concluded that the behavior of the pseudo-potential is the same for all \(\beta\) values and only their amplitudes increases slightly. In other words, it can be said that the behavior of the potential is linearly dependent to the electron temperature.

In Fig. 3, the pseudo-potential is plotted as a function of \(\varphi\). It is clear that for fixed value of the \(\varphi\), the amplitude of the Sagdeev potential is increasing with \(l_z\).
In Fig. 5 the pseudo-potential, $\phi$ is plotted versus the $\eta$, for $l_z = 0.1$, $M = 2.25$, and $\beta = 0.46$ for different values of $\delta_1$. It is concluded that increasing the $\delta_1$ may increase the plasma amplitude. Also this is negative for negative values of $\phi$, and vice versa. Figure 6 shows that for all values of $\delta_1$, i.e. the ratio of ion density to the equilibrium electron density, the plasma potential is negative. It is also seen that the amplitude and the width of the potential increases as $\delta_1$ increases. Comparing the results for high magnitudes of $\delta_1$, it can be said that the slope of the amplitude is decreased with increasing the ion density.
The variation of plasma potential is plotted as a function of $\eta$ for $l_z = 0.1$, $M = 2.25$, and $\delta_1 = 2.54$ for different values of $\beta$ in Fig. 6. It is seen that decreasing the magnitude of $\beta$ may increase the width and amplitude of the potential.

In Fig. 7, we have illustrated the variation of plasma potential as a function of $\eta$ for $M = 2.25$, $\delta_1 = 2.54$, and $\beta = 0.46$ for different values of $l_z$ and for values of $\delta_1$. It is seen that the amplitude is negative and that the negative amplitude and the width of the potential are increased by increasing $l_z$.

In Fig. 8, we have illustrated the variation of plasma potential as a function of $\eta$ for $l_z = 0.1$, $\delta_1 = 2.54$, and $\beta = 0.46$ for different values of $M$.

In Fig. 8, we have illustrated the variation of plasma potential as a function of $\eta$ for $l_z = 0.1$, $\delta_1 = 2.54$, and $\beta = 0.46$ for different values of Mach number.

V. CONCLUSION

Using Sagdeev potential, the dispersion relation of dust ion acoustic wave in a collisional magnetized dusty plasma is obtained in the presence of warm ions and hot electrons. It is shown that the amplitude and the width of the wave is dependent on the plasma parameters such as plasma particles density and temperatures, plasma potential, Mach number and etc. The behavior of the amplitude and the width of the wave in terms of all of these parameters is similar to that in our previous work [14]. However, the values of these two variables are different. It is shown that the Sagdeev potential has negative value for positive plasma potential and vice versa. We have also shown that increasing $\delta_1$ and decreasing $\beta$ can lead to the increasing of wave amplitude and also they can cause an increase in the width and the amplitude of the potential. Finally, it is found that the spectral index, i.e. the quantity when goes to infinite, the kappa distribution changes to Maxwellian one, has little effect on the propagation properties of the wave.

REFERENCES


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