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Kinetic Alfvén waves in a homogeneous dusty magnetoplasma with dust charge fluctuation effects

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Kinetic Alfvén waves with finite Larmor radius effects have been examined rigorously in a uniform dusty plasma in the presence of an external/ambient magnetic field. Two-potential theory has been applied for these electromagnetic waves and the dispersion relation is derived which shows a cutoff frequency at the dust-lower-hybrid frequency due to the hybrid motion of magnetized ions and cold and unmagnetized dust dynamics. The dust charge fluctuation effect was analyzed for finding the damping of the electromagnetic kinetic Alfvén waves, which arises on account of the electrostatic parallel component of the waves. The dust charge fluctuation damping is seen to be contributed dominantly by the perpendicular motion of electrons and ions in the dusty magnetoplasma. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2710457]

I. INTRODUCTION

Dusty plasmas are quite common in astrophysical environments and laboratory situations.[1–4] In recent years, waves and instabilities are seen to occupy the major thrust of basic research in low-frequency electrostatic waves with or without the presence of external/ambient static magnetic field.[5,6] The role of dynamics of the relatively highly charged and massive dust grains on these waves and their instabilities has been clarified. In fact, by including the dust dynamics in unmagnetized dusty plasmas, two new wave modes known as dust-acoustic and dust-ion-acoustic waves have been discovered about one and a half decades ago.[7,8] Tremendous advances in the physics of dusty plasmas have taken place after these natural dusty plasma modes are seen to exist.

However, ambient static magnetic field is invariably present in space and astrophysical situations, and external magnetic field is applied purposefully to laboratory experiments with a view to confining and controlling the plasma properties. In the presence of an external static magnetic field, the most significant electrostatic wave is the dust-lower-hybrid wave in the low-frequency regime where the hybrid motion of magnetized ions and the cold and unmagnetized dust dynamics gives rise to this mode.[9] However, the limited investigations have been done on the electromagnetic (EM) regime in magnetized dusty plasmas.

Alfvén waves are ubiquitous in space environments for transport of electromagnetic energy in magnetized plasmas. They occur in interstellar clouds, comet tails, planetary atmospheres and rings, solar corona and winds, Earth's ionosphere and magnetosphere, etc.[10] They are also important in fusion devices for resonant heating of tokamak plasmas, current drives etc.,[11] Alfvén waves not only transport electromagnetic energy, but communicate information relating changes in plasma currents and magnetic field structures. There are basically two kinds of Alfvén waves below the ion-cyclotron frequency. The compressional Alfvén wave propagates along the external magnetic field and the shear Alfvén wave propagates making some angle with the external magnetic field direction. Shear Alfvén waves with finite Larmor radius effects are known as the kinetic Alfvén waves (KAW). The kinetic Alfvén wave develops a longitudinal parallel electrostatic field due to the finite-Larmor radius (FLR) effects. Thus, the kinetic Alfvén wave can transfer the wave energy to electrons via Landau damping resulting in the heating of plasmas or accelerate electrons along the magnetic field direction.

In dusty plasmas, there is a characteristic damping mechanism for electrostatic waves.[12–14] This arises due to the dust charge fluctuations effect involving the dust dynamics. But, no charge density perturbations is associated with a pure transverse electromagnetic wave. However, because of the longitudinal electrostatic component, the kinetic Alfvén wave can be damped by the dust charge fluctuation effects in a dusty plasma. Earlier, Kotsarenko *et al.*[15] have studied KAW using fluid description of the dusty plasma. Das *et al.*[16] have shown charge fluctuation effect on KAW by taking FLR effects of the dust component neglecting ion FLR effects in the plasma. Massive dust grains were taken magnetized and hot, and considered the frequency regime of the KAW below the dust cyclotron frequency in the space and laboratory conditions. In the present paper, we have investigated rigorously the low-frequency electromagnetic kinetic Alfvén waves and their damping due to the dust charge fluctuation effects by considering cold and unmagnetized dust component. We retain the FLR effect through the magnetized ion dynamics. Our result reduces to the usual KAW in absence of the dust component of the plasma.

The organization of the paper is as follows: In Sec. II, we have employed the relevant two-potential approximation for writing the related Maxwell's equations for the kinetic Alfvén wave in a collisionless and homogeneous dusty plasma in the presence of an external magnetic field. Number densities and current densities due to the presence of KAW have been derived using appropriate distribution functions in Sec. III. The dust charge fluctuation effects have been considered in Sec. IV. Then, the dispersion relation and the damping of the KAW due to the dust-charge fluctuation effects have been investigated in Sec V. Finally, a brief discussion of the results is given in Sec. VI.

II. TWO-POTENTIAL THEORY FOR KINETIC ALFVÉN WAVES

We consider the propagation of an electromagnetic kinetic Alfvén wave in a homogeneous and collisionless dusty plasma in the presence of an external static magnetic field ($\mathbf{B}_0 \| \hat{z}$). Let the electric field and propagation vector of the KAW lie in the same plane (XZ plane) but not in the same direction. For a low β dusty plasma also, we can neglect the magnetic compression of the EM wave along the direction of the external magnetic field ($B_{1z}=0$). In this consideration, we can assume the two different electrostatic potentials to represent the transverse and parallel components of the electric field of the KAW (Refs. 10, 11, and 17),

$$\mathbf{E}_\perp = -\nabla_\perp \phi, \tag{1}$$

$$E_\| = -\frac{\partial \psi}{\partial z}, \tag{2}$$

where $\phi \neq \psi$ and the symbol $\|(\perp)$ represents a quantity parallel (perpendicular) to the direction of the external magnetic field.

We consider a magnetized dusty plasma where the electrons are thermal and strongly magnetized, ions are magnetized and hot, and the relatively highly charged and massive dust grains are cold and unmagnetized

$$\omega \ll \omega_{cj}, \quad j=e,i,$$

$$k_\| v_{te} \gg \omega,$$

$$k_\| v_{ti} \ll \omega, \tag{3}$$

where $(\omega,\mathbf{k})$ are the angular frequency and the wave number vector of the KAW, $v_{tj}=(2T_j/m_j)^{1/2}$ is the thermal velocity and $\omega_{cj}=q_jB_0/m_jc$ is the cyclotron frequency of the jth species. Here, q_j, m_j, T_j, and c are the charge, mass, temperature in energy units of the jth species, and the velocity of light in a vacuum, respectively. We assume electric charge quasineutrality condition

$$n_{e0} = n_{i0} + Q_{d0}n_{d0}/e, \tag{4}$$

where $n_{\alpha 0}$ with $\alpha=e,i,d$ are the equilibrium number densities, $Q_{d0}=-Z_d e$ (with Z_d as the number of electronic charge on a grain) is the equilibrium charge on an average dust grain, and e is the electronic charge. Here, we consider the negatively charged dust grains which are charged by electron/ion currents. This situation is commensurate with most of the space and laboratory dusty plasmas.

Denoting the perturbed quantities by a subscript 1, the linearized Poisson's equation is

$$\nabla_\perp^2 \phi + \frac{\partial^2 \psi}{\partial z^2} = 4\pi e\left[n_{e1} - n_{i1} - \frac{Q_{d0}}{e}n_{d1} - \frac{n_{d0}}{e}Q_{d1}\right]. \tag{5}$$

Combining the Ampere's and Faraday's laws, one may easily write

$$\frac{\partial}{\partial z}\nabla_\perp^2(\phi-\psi) = \frac{4\pi}{c^2}\frac{\partial}{\partial t}(J_{e1z}+J_{i1z}+J_{d1z}), \tag{6}$$

where $\mathbf{J}_\alpha$'s are the current densities.

III. NUMBER DENSITY AND CURRENT DENSITY PERTURBATIONS

Defining

$$n_{\alpha 1} = \int f_{\alpha 1} d\mathbf{v},$$

$$\mathbf{J}_{\alpha 1} = q_\alpha \int \mathbf{v} f_{\alpha 1} d\mathbf{v}, \tag{7}$$

where $\alpha=e,i,d$ and $f_{\alpha 1}$ is the perturbed distribution function of the species α and considering the variation of any perturbed quantity in the presence of the KAW as $\exp[-i(\omega t - \mathbf{k}\cdot\mathbf{x})]$, the coupled equations (5) and (6) reduce to

$$-(k_\perp^2\phi + k_\|^2\psi) = 4\pi e\left[n_{e1} - n_{i1} - \frac{Q_{d0}}{e}n_{d1} - \frac{n_{d0}}{e}Q_{d1}\right], \tag{8}$$

$$k_\| k_\perp^2(\phi-\psi) = \frac{4\pi\omega}{c^2}(J_{e1\|}+J_{i1\|}+J_{d1\|}). \tag{9}$$

For calculating the number densities and the current densities in Eqs. (8) and (9), we have to find the appropriate distribution functions for various species. Since electrons are assumed strongly magnetized, we can neglect the finite Larmor radius (FLR) effects of electrons for long perpendicular wavelength as $k_\perp v_{te} \ll \omega_{ce}$ is satisfied and consider only the parallel dynamics of the hot electrons. Thus, the perturbed distribution function for the hot and strongly magnetized electrons is given by

$$f_{e1} = \frac{ek_\|\psi}{m_e(\omega - k_\| v_\|)}\frac{\partial f_{e0}}{\partial v_\|}, \tag{10}$$

where f_{e0} can be taken as Maxwellian.

Since the ions are hot and magnetized and Larmor radius is larger ($\rho_i \gg \rho_e$), where ρ_j is the Larmor radius of the jth species, the ion FLR effect must be taken into account. We solve the Vlasov equation for the hot and magnetized ions in terms of the guiding center coordinates[18,19] and obtain the perturbed distribution function for any electromagnetic wave as

$$f_{i1} = e^{-i(\omega t - \mathbf{k}\cdot\mathbf{x})}\left(\frac{n_{i0}e}{T_i}\right)\sum_l \sum_n \frac{k_\parallel v_\parallel \psi + n\omega_{ci}\phi}{\omega - n\omega_{ci} - k_\parallel v_\parallel} e^{i(n-l)\theta} J_n \times \left(\frac{k_\perp v_\perp}{\omega_{ci}}\right) J_l\left(\frac{k_\perp v_\perp}{\omega_{ci}}\right) f_{i0}, \tag{11}$$

where J_n is the Bessel function of first kind of order n and f_{i0} is the Maxwellian distribution function for the ions.

Since the dust component of the plasma is considered cold and unmagnetized, we can employ the hydrodynamical fluid equations for finding the dust number density and current density perturbations.

Using Eq. (10) in Eqs. (7), we obtain

$$n_{e1} = \frac{en_{e0}\psi}{T_e}[1 + \xi_{e0}Z(\xi_{e0})], \tag{12}$$

$$J_{e1\parallel} = \frac{e^2 n_{e0}\psi}{m_e v_{te}}\xi_{e0}Z'(\xi_{e0}), \tag{13}$$

$$J_{e1x} = J_{e1y} = 0, \tag{14}$$

where $\xi_{e0} = \omega / k_\parallel v_{te}$, Z' is the derivative of Z with respect to its argument, and Z is known as the plasma dispersion function.[20]

Using Eq. (11) in Eqs. (7), we obtain

$$n_{i1} = -\frac{n_{i0}e}{T_i}\frac{1}{k_\parallel v_{ti}}\sum_n [k_\parallel v_{ti}(1 + \xi_{in}Z(\xi_{in}))\psi + n\omega_{ci}Z(\xi_{in})\phi] I_n e^{-b_i}, \tag{15}$$

where $\xi_{in} = (\omega - n\omega_{ci})/k_\parallel v_{ti}$, $b_i = k_\perp^2 v_{ti}^2 / 2\omega_{ci}^2$, and I_n is the modified Bessel function of first kind of order n and argument b_i. The oscillatory factor is implied in n_{i1}, ψ, and ϕ. The components of the current density for ions turn out to be

$$J_{i1x} = -\frac{n_{i0}e^2}{T_i k_\parallel v_{ti} k_\perp}\sum_n n\omega_{ci}[k_\parallel v_{ti}(1 + \xi_{in}Z(\xi_{in}))\psi + n\omega_{ci}Z(\xi_{in})\phi] I_n e^{-bi}, \tag{16}$$

$$J_{i1y} = -\frac{in_{i0}e^2}{T_i k_\parallel}\left(\frac{k_\perp v_{ti}}{2\omega_{ci}}\right)\sum_n [k_\parallel v_{ti}(1 + \xi_{in}Z(\xi_{in}))\psi + n\omega_{ci}Z(\xi_{in})\phi](I_n - I_n')e^{-b_i}, \tag{17}$$

$$J_{i1\parallel} = -\frac{n_{i0}e^2}{T_i k_\parallel}\sum_n [(1 + \xi_{in}Z(\xi_{in}))(k_\parallel v_{ti}\xi_{in}\psi + n\omega_{ci}\phi)] I_n e^{-b_i}. \tag{18}$$

Using the momentum balance equation and the continuity equation for the cold and unmagnetized dust component, we obtain

$$n_{d1} = \frac{n_{d0}Q_{d0}}{m_d\omega^2}(k_\perp^2\phi + k_\parallel^2\psi),$$

$$J_{d1x} = \frac{n_{d0}Q_{d0}^2 k_\perp \phi}{m_d\omega},$$

$$J_{d1y} = 0,$$

$$J_{d1\parallel} = \frac{n_{d0}Q_{d0}^2 k_\parallel \psi}{m_d\omega}. \tag{19}$$

IV. DUST CHARGE FLUCTUATION EFFECTS

The EM kinetic Alfvén wave is a mixed mode consisting of a pure EM wave and an electrostatic component which propagates along the magnetic field direction and arises due to the FLR effects of ions. The density perturbation arises because of this electrostatic part, which is described by the Poisson's equation. In this section, we calculate the dust density perturbation due to the dust charge fluctuation effects.

The charging equation for dust grains in a dusty plasma is given by

$$\frac{d}{dt}Q_{d1}(\omega,\mathbf{k}) = I_{e1} + I_{i1}, \tag{20}$$

where $Q_d = Q_{d0} + Q_{d1}$ and I_{e1} and I_{i1} are the perturbed charging currents for electrons and ions.

To calculate the perturbed currents of the magnetized electrons and ions, we assume $\rho_{e,i} \leqslant a_0$ where $\rho_{e,i}$ are the Larmor radii of electrons/ions and a_0 is the radius of the grains. Also, we assume $\lambda_D \sim a_0$, so that we can use the orbit-limited motion avoiding sheath limited effect.

In the presence of the wave perturbation, the charging currents are given by[21]

$$I_{j1}(\mathbf{x},t) = \int\int \mathbf{J}\cdot d\mathbf{S} = 2\pi a_0^2 q_j \int (v_\perp \cos\theta + v_\perp \sin\theta + v_\parallel) f_{j1} d\mathbf{v}, \tag{21}$$

where $j = e, i$ and f_{e1} and f_{i1} are given by Eqs. (10) and (11). Here, θ is the angle made by $\mathbf{v}_\perp$ with the x axis.

Thus,

$$Q_{d1} = -\frac{i}{\omega}\beta, \tag{22}$$

where

$$\beta = \beta_1\psi + \beta_2\phi, \tag{23}$$

with

$$\beta_1 = -2\pi a_o^2\left[e^{e\Phi_G/T_e}\frac{n_{e0}e^2}{m_e v_{te}}\xi_{e0}Z'(\xi_{e0}) - e^{(-e\Phi_G/T_i)}\frac{n_{i0}e^2}{T_i k_\parallel}\sum_n\left\{\left(\frac{n\omega_{ci}}{k_\perp v_{ti}}I_n e^{-b_i} - \frac{k_\perp v_{ti}}{i2\omega_{ci}}(I_n - I_n')e^{-b_i}\right)\cdot k_\parallel v_{ti}(1+\xi_{in}Z(\xi_{in})) - \frac{k_\parallel v_{ti}}{2}\xi_{in}Z'(\xi_{in})I_n e^{-b_i}\right\}\right], \tag{24}$$

$$\beta_2 = 2\pi a_0^2 e^{-e\Phi_G/T_i}\frac{n_{i0}e^2}{T_i k_\parallel}\sum_n\left[n\omega_{ci}Z(\xi_{in})\left(\frac{n\omega_{ci}}{k_\perp v_{ti}}I_n e^{-b_i} - \frac{k_\perp v_{ti}}{i2\omega_{ci}}(I_n - I_n')e^{-b_i}\right) + n\omega_{ci}(1+\xi_{in}Z(\xi_{in}))I_n e^{-b_i}\right]. \tag{25}$$

In deriving Eq. (22), we have assumed that the dust grain surface potential is constant, $\phi_G = Q_{d0}/a_0$ where Q_{d0} is the equilibrium charge on a spherical grain of radius a_0.

V. DISPERSION RELATION FOR THE KINETIC ALFVÉN WAVE

Using Eqs. (12)–(19) in Eqs. (8) and (9) and on simplification, we obtain the coupled equations as

$$A\phi + B\psi = 0, \tag{26}$$

$$C\phi + D\psi = 0, \tag{27}$$

where

$$A = k_\perp^2 + \frac{1}{\lambda_{Di}^2}\frac{1}{k_\parallel v_{ti}}\sum_n n\omega_{ci}Z(\xi_{in})I_n e^{-b_i} + i\frac{2\pi a_0^2 e^{-e\Phi_G/T_i}}{\omega}\frac{n_{d0}}{k_\parallel\lambda_{Di}^2}\sum_n\left\{n\omega_{ci}Z(\xi_{in})\left(\frac{n\omega_{ci}I_n}{k_\perp v_{ti}} + i\frac{k_\perp v_{ti}}{2\omega_{ci}}(I_n - I_n')\right)e^{-b_i} + n\omega_{ci}I_n e^{-b_i}(1+\xi_{in}Z(\xi_{in}))\right\} - \frac{k_\perp^2\omega_{pd}^2}{\omega(\omega+i\nu_d)}, \tag{28}$$

$$B = k_\parallel^2 + \frac{1}{\lambda_{De}^2}(1+\xi_{e0}Z(\xi_{e0})) + \frac{1}{\lambda_{Di}^2}\sum_n(1+\xi_{in}Z(\xi_{in}))I_n e^{-b_i} - \frac{i2\pi a_0^2 n_{d0}}{\omega}\left[\frac{e^{e\Phi_G/T_e}\omega_{pe}^2}{v_{te}}\xi_{e0}Z'(\xi_{e0}) - \frac{e^{-e\Phi_G/T_i}}{k_\parallel\lambda_{Di}^2}\sum_n\left\{k_\parallel v_{ti}(1+\xi_{in}Z(\xi_{in}))\left(\frac{n\omega_{ci}I_n}{k_\perp v_{ti}} + i\frac{k_\perp v_{ti}}{2\omega_{ci}}(I_n - I_n')\right)e^{-b_i} - \frac{k_\parallel v_{ti}}{2}I_n e^{-b_i}\xi_{in}Z'(\xi_{in})\right\}\right] - \frac{k_\parallel^2\omega_{pd}^2}{\omega(\omega+i\nu_d)}, \tag{29}$$

$$C = k_\perp^2 c^2 k_\parallel + \frac{\omega}{k_\parallel\lambda_{Di}^2}\sum_n n\omega_{ci}(1+\xi_{in}Z(\xi_{in}))I_n e^{-b_i}, \tag{30}$$

$$D = -k_\perp^2 c^2 k_\parallel - \omega\left[\frac{\omega_{pe}^2}{v_{te}}\xi_{eo}Z'(\xi_{e0}) + \frac{1}{\lambda_{Di}^2}\sum_n\frac{v_{ti}}{2}\xi_{in}Z'(\xi_{in})I_n e^{-b_i} + \frac{\omega_{pd}^2 k_\parallel}{\omega+i\nu_d}\right], \tag{31}$$

with $\lambda_{Dj}^2 = v_{tj}^2/2\omega_{pj}^2$, $j=e,i$ and ν_d is the average dust-neutral collision frequency which is usually small in most dusty plasmas.

Thus, the dispersion relation for the kinetic Alfvén waves is obtained from

$$AD - BC = 0. \tag{32}$$

Now, applying the realistic approximations for the dusty magnetoplasmas of astrophysical and laboratory conditions in Eq. (3) and neglecting the complex parts, we obtain

$$A_r = \frac{k_\perp^2 f_i}{\omega^2}\left(1 - \frac{3}{4}b_i\right)(\omega^2 - \omega_{dlh}^2), \tag{33}$$

$$B_r = \frac{1}{\omega^2\lambda_{De}^2}(\omega^2 - k_\parallel^2\lambda_{De}^2\omega_{pd}^2), \tag{34}$$

$$C_r = c^2 k_\perp^2 k_\parallel, \tag{35}$$

$$D_r = \frac{2\omega^2\omega_{pe}^2}{k_\parallel v_{te}^2} - k_\parallel(\omega_{pd}^2 + k_\perp^2 c^2), \tag{36}$$

where $f_i = \omega_{pi}^2/\omega_{ci}^2$, $\omega_{dlh}^2 = \omega_{pd}^2\omega_{ci}^2/\omega_{pi}^2$, and the subscript r denotes a real quantity. In deriving Eqs. (33)–(36), we assume $k_\parallel\lambda_{De} < 1$.

Thus, from the dispersion relation Eq. (32), we obtain a biquadratic equation for ω in terms of the plasma parameters,

$$P\omega^4 + Q\omega^2 + R = 0, \tag{37}$$

where

$$P = \frac{2\omega_{pe}^2}{k_\parallel v_{te}^2}, \tag{38}$$

$$Q = -\frac{2\omega_{pd}^2}{k_\parallel v_{te}^2}\omega_{dlh}^2 - k_\parallel(\omega_{pd}^2 + k_\perp^2 c^2) - \frac{k_\parallel v_A^2}{\lambda_{De}^2}\left(1 + \frac{3}{4}b_i\right), \tag{39}$$

$$R = \omega_{dlh}^2 k_\parallel(\omega_{pd}^2 + k_\perp^2 c^2) + k_\parallel^3 v_A^2\omega_{pd}^2\left(1 + \frac{3}{4}b_i\right). \tag{40}$$

From Eqs. (38)–(40), one can easily show that $Q^2 > 4PR$. Thus, the dominant root of Eq. (37) reduces to

$$\omega^2 = \omega_{dlh}^2 + k_\parallel^2 v_A^2\left[1 + \left\{\frac{3}{4} + \frac{T_e}{T_i}\delta\left(1 + \frac{\omega_{pd}^2}{k_\perp^2 c^2}\right)\right\}b_i\right], \tag{41}$$

where $v_A = c\omega_{ci}/\omega_{pi}$ is the Alfvén speed and the non-neutrality parameter, $\delta = n_{i0}/n_{e0}$.

This is the dispersion relation of the EM kinetic Alfvén waves in the presence of unmagnetized and cold but mobile dust grains. In the absence of the dust component of the plasma, this dispersion relation reduces to that for the usual kinetic Alfvén wave in an electron-ion plasma where the FLR effects arise through the ion dynamics. Thus, the dust dynamics introduces a new cutoff frequency to the KAW in the dusty plasma and a modification of the FLR effect through the magnetized and hot ions.

Now, including the dust charge fluctuations, Q_{d1} given by Eq. (22) in the Poisson Eq. (8) and following the same procedure, we obtain $A_i \simeq C_i = 0$ and $B_i \gg A_r D_i / C_r$ where the subscript i denotes the complex part of a quantity. Thus, we obtain the damping rate of the KAW in the presence of dust charge fluctuation effects from $B_i \approx 0$ where

$$B_i = \frac{\sqrt{\pi}\xi_{e0}e^{-\xi_{e0}^2}}{\lambda_{De}^2} + \frac{\sqrt{\pi}\xi_{i0}e^{-\xi_{i0}^2}}{\lambda_{Di}^2} + \frac{\sqrt{\pi}}{\lambda_{Di}^2}(\xi_{i+}e^{-\xi_{i+}^2} + \xi_{i-}e^{-\xi_{i-}^2})I_1(b_i)e^{-b_i} + \frac{4\pi a_0^2 n_{d0}\omega_{pe}^2}{\omega_r v_{te}}\left[e^{e\Phi_G/T_e}\xi_{e0} - e^{-e\Phi_G/T_i}\frac{\delta}{2}\sqrt{\frac{T_e m_e}{T_i m_i}}\left(\frac{1}{\xi_{i0}} + \left(\frac{1}{\xi_{i+}} + \frac{1}{\xi_{i-}}\right)I_1 e^{-b_i}\right)\right] + \frac{2k_\parallel^2\omega_{pd}^2}{\omega_r^2}\frac{\gamma}{\omega_r}. \tag{42}$$

Here, we assume $\omega = \omega_r + i\gamma$ with $\gamma \ll \omega_r$ and $\xi_{i\pm} = (\omega \pm \omega_{ci})/k_\parallel v_{ti}$.

Thus, we obtain the normalized damping rate of the KAW including collisionless Landau damping and the charge fluctuation effects, as

$$\frac{\gamma}{\omega_r} = -\sqrt{\frac{\pi}{4}}\frac{\omega_r^2}{\omega_{pd}^2}\frac{1}{k_\parallel^2\lambda_{De}^2}\left[\xi_{e0}e^{-\xi_{e0}^2} + \delta\frac{T_e}{T_i}(\xi_{i0}e^{-\xi_{i0}^2} + (\xi_{i+}e^{-\xi_{i+}^2} + \xi_{i-}e^{-\xi_{i-}^2})I_1 e^{-b_i}) + \frac{2\sqrt{\pi}a_0^2 n_{d0} v_{te}}{\omega_r}\left\{e^{e\Phi_G/T_e}\xi_{e0} - \frac{\delta}{2}\left(\sqrt{\frac{T_e m_e}{T_i m_i}}\right)e^{-e\Phi_G/T_i}\left(\frac{1}{\xi_{i0}} + \left(\frac{1}{\xi_{i+}} + \frac{1}{\xi_{i-}}\right)I_1 e^{-b_i}\right)\right\}\right], \tag{43}$$

where ξ's are defined earlier. It is noticed from Eq. (43) that both the collisionless Landau damping and the charge fluctuation damping are contributed mainly by the motion of electrons. For nearly perpendicular propagation (small $k_\parallel$), the collisionless Landau damping will be negligible and the charge fluctuation damping is the main mechanism of damping of the electromagnetic kinetic Alfvén waves involving the dust parameters. Juli *et al.*[22] also showed by numerical calculations that the Landau damping of the transverse ordinary Alfvén waves propagating parallel to the magnetic field is negligible.

VI. DISCUSSION

In the present paper, we have made a rigorous analytical study on the electromagnetic kinetic Alfvén waves using the standard two-potential theory in a collisionless and homogeneous dusty plasma in the presence of an external/ambient uniform magnetic field. Electrons are the lighter component of the plasma and are considered to be strongly magnetized with smaller Larmor radius compared to that of ions. For sufficiently longer wavelength of the electromagnetic waves, the finite Larmor radius effect due to electrons is neglected. However, ions having larger Larmor radius for a given magnetic field, the finite Larmor radius effect arises through the dynamics of the magnetized and hot ions. Generally, dusty plasmas are collisionless and since the micron/submicron sized dust grains are much heavier than ions (e.g., $m_d/m_i \sim 10^{12}$), they can be logically considered cold and unmagnetized in space and laboratory conditions. Thus, we obtain the dispersion relation of the kinetic Alfvén waves in the dusty magnetoplasma. The dispersion relation, Eq. (41) shows a new cut-off frequency for the kinetic Alfvén wave due to the hybrid dynamics of the unmagnetized and cold dust particles and the gyrating motion of the ions. The dust charge fluctuation in the presence of the EM kinetic Alfvén wave gives rise to a dust density perturbation which is taken into account in the Poisson's equation. Thus, we obtain the damping of the kinetic Alfvén wave due to this dust charge fluctuation effect. It is noticed that the damping of this electromagnetic wave [cf. Eq. (43)] is due to mainly the motion of the strongly magnetized electrons along the external magnetic field direction. It may be added here that the collisionless Landau damping for the Alfvén waves is negligible for the usual parameters of a dusty plasma. This was shown numerically by Juli *et al.*[22]

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