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Modification and Damping of Alfvén Waves in a Magnetized Dusty Plasma

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ABSTRACT

The dispersion characteristics of the circularly polarized electromagnetic waves along a homogeneous magnetic field in a dusty plasma have been investigated theoretically. The Vlasov equation has been employed to find the response of the magnetized plasma particles where the dust grains form a static background of highly charged and massive centers having certain correlation. It is found that in addition to the usual Landau damping which is negligible in the low temperature approximation, a novel mechanism of damping of the Alfvén waves due to the dust comes into play. The modification and damping of the Alfvén waves depend on the dust perturbation parameters. unequal densities of plasma particles, the average correlation length of the dust grains, temperature of the plasma and the magnetic field.

[Dusty plasmas, Alfvén waves, damping of waves, kinetic theory]

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§1. Introduction

There has been a growing interest in dusty plasmas because of their importance in astrophysical and space plasmas, fusion devices as well as in several technologies in recent years.[1–5] The highly charged ($Z_g \sim 10^3 - 10^4$) and massive dust grains of micron or submicron size are present in partially or fully ionized space plasmas, viz., the earth's ionosphere as pollution droplets, planetary rings, asteroid zones, cometary comae and tails, interstellar clouds, around protostars, supernova remnants, etc. and are also encountered in many laboratory devices and plasma processing technologies, such as, etching, welding and processing of novel materials, etc. Small dust grains in the micron and submicron size range have been detected in the magnetospheres of Jupiter and Saturn by Pioneer 10 and 11 and Voyager spacecrafts. They are almost ubiquitous in cosmic environments. The dust grains are generally electrically charged either negative or positive to a high potential since they are immersed in an ambient plasma and radiative environments. Charging processes may include plasma currents, photoionization, secondary electron impact emission, proton-induced secondaries, thermal emission, field emission, sputtering, ultraviolet ray irradiation or absorption of charged particles, etc. The influence of these highly charged and massive dust particles on the plasma properties and wave propagation and scattering processes is a subject of much current interest.

A number of studies[6–11] has been made on the wave propagation properties, damping, absorption, wave scattering, etc. in dusty plasmas without considering any magnetic field in them. However, in astrophysical situations dusty plasmas almost invariably occur in the presence of magnetic fields, where a number of additional modes may be present. In the present paper, our interest is to derive a general dispersion relation and take an example to examine the modifications in the magnetized dusty plasma described by the space-dependent distribution.

Recently, using fluid description, a number of authors[7,10,12,13] have studied collective effects and extended their studies to nonlinear structures, such as, solitons, shocks, double layers, vortices in dusty plasmas. They have considered the massive and charged grains as a third component of the plasma. However, the motion of the massive grains can be neglected with respect to the motion of plasma electrons and ions in connection with the wave-particle interactions. In many cases of wave propagation, the grain dynamics plays a less important role on the time scale of electron response. Thus, for the large grain to electron mass ratio, it is quite appropriate to consider grains as infinitely massive for consideration of propagation of waves in them.

A physically interesting situation is the random distribution of massive charged dust grains which introduces an inhomogeneous equilibrium electric field within the plasma. The random character of the electric field can be described by some suitable statistical function. Such a model of the static dust distribution was introduced first by de Angelis et al.[6] to study the dispersion, absorptions and scattering of waves in plasma and is quite useful for analytic investigations when the average dust electric field can be considered to be small compared to other equilibrium quantities. Further, although in real plasmas, dust particles may have wide range of distribution in size, shape, composition, charge and mass, one may treat the grains as point particles having constant mass and charge.

Study of the propagation of low frequency electromagnetic waves in space plasmas is essential for many physical processes in space and astrophysical situations. The role of dust grains in the dissipation of Alfvén waves in interstellar clouds have been numerically investigated by Pilipp et al.[15] . The random and static distribution of highly charged and massive grains can change the dispersive properties of the medium and hence, the electromagnetic waves particularly the low frequency waves, are supposed to suffer strong modification. Therefore, the propagation of Alfvén waves in the presence of massive dust grains with strong inhomogeneity and magnetic field demands a rigorous investigation. In this paper, we study the possible modification and damping of electromagnetic waves in a dusty plasma in the presence of a homogeneous and static magnetic field. The properties of dusty plasmas can be better understood if the dispersive properties and the modification and damping of these modes could be fully understood.

In § 2, the modification of the equilibrium distribution function due to strong inhomogeneous electric field of the random distribution of dust grains is obtained. The equilibrium velocity distribution thus becomes space-dependent. In §3, we study the propagation of any mode in a magnetized dusty plasma. We solve the Vlasov equation perturbatively for a small amplitude wave and obtain a general solution. Then, we derive the general dispersion relation for propagation of any mode either electrostatic and electromagnetic in §4. In §5, we solve the general dispersion relation for circularly polarized waves and obtain the modified dispersion relation of Alfvén waves in the dusty plasma. The dispersion function becomes complex giving rise to damping of the Alfvén waves at low temperature where the usual Landau damping is negligible. Finally, a brief discussion of the results is given in the last section.

§2. Modified Background Equilibrium Distribution

Following de Angelis et al.[6] we consider a homogeneous electron-ion plasma embedded with a random distribution of infinitely extended massive and highly charged dust grains in the presence of a static and homogeneous magnetic field ($B_o \parallel \hat{z}$). The equilibrium consists of charged dust particles, ions and electrons which satisfy the overall charge neutrality condition

$$\sum_{\alpha} q_\alpha n_{\alpha o} + QN_g = 0, \alpha = e, i \tag{1}$$

where $q_\alpha, n_{\alpha o}$ and Q, N_g are the charge and number density of electrons/ions and those of the dust particles, respectively. The stationary and randomly oriented dust particles give rise to an inhomogeneous background electrostatic field which is characterized by a potential function $\phi_o(\underline{r})$. The average of this potential is given by Whipple et al.[14]

$$\overline{\Phi}_o = \frac{1}{V}\int \phi_o(\underline{r}) d^3r = \frac{3Q}{\lambda_D}(\frac{\lambda_D}{r_o})^3.4\pi r_o^3 = 3N_g, \tag{2}$$

where r_o and λ_D are the average separation and Debye length of the dust particles, respectively.

The random distribution of the highly charged dust grains modifies the equilibrium distribution of the plasma electrons and ions by creating local inhomogeneities around the dust particles. We consider the regime where the plasma Debye length is much smaller than the average separation of the dust particles ($r_o \gg \lambda_D$) - a regime that has been referred to as "dust in the plasma".[6] We also make the assumption that the potential energy of a plasma particle (in this field) is much smaller than the thermal energy of electrons/ions ($\mu_\alpha = q_\alpha \overline{\Phi}_o / T_\alpha = QN_g/q_\alpha n_{\alpha o} \ll 1$). This assumption is crucial to the perturbative technique employed in ref.[6]

Let us first find the stationary equilibrium distribution function in the presence of the two "external" fields :

$$\underline{E}_o(\underline{r}) = -\underline{\nabla}\delta\phi_o(\underline{r}), \quad \underline{B}_o = \hat{z}B_o, \tag{3}$$

where $\underline{B}_o$ is the constant background magnetic field and $\delta\phi_o(\underline{r}) \equiv \phi_o(\underline{r}) - \overline{\Phi}_o$ is the fluctuating potential in the system due to the presence of a distribution $\rho^g(\underline{r})$ of massive, charged dust particles and is a solution of Poisson's equation :

$$\nabla^2 \delta\phi_o(\underline{r}) = -4\pi[\sum_{\alpha} q_\alpha \int \delta f_\alpha(\underline{r}, \underline{v}) d^3v + \delta\rho^g(\underline{r})], \tag{4}$$

where

$$\delta\rho^g(\underline{r}) = \rho^g(\underline{r}) - \overline{\rho}_g; \quad \overline{\rho}_g = \frac{1}{V}\int \rho^g(\underline{r}) d^3r, \tag{5}$$

and δf_α are the fluctuating distribution functions of the plasma particles due to the presence of the dust and satisfy the linearized and stationary Vlasov equation:

$$\underline{v} \cdot \underline{\nabla} \delta f_\alpha + \frac{q_\alpha}{m_\alpha c}(\underline{v} \times \underline{B}_o) \cdot \frac{\partial}{\partial \underline{v}} \delta f_\alpha = -\frac{q_\alpha}{m_\alpha} \underline{E}_o \cdot \frac{\partial F_{\alpha o}}{\partial \underline{v}}, \tag{6}$$

where$F_{\alpha o}(v_\perp^2, v_\parallel)$ is the equilibrium distribution function without any magnetic field. Hence, the stationary equilibrium distribution function of the dusty plasma is given by

$$f_{\alpha o}(\underline{r}, \underline{v}) = F_{\alpha o}(v_\perp^2, v_\parallel) + \delta f_\alpha(\underline{r}, \underline{v}). \tag{7}$$

Taking the Fourier transform of Eq.(6) we have

$$i\underline{k} \cdot \underline{v} \delta f_k^\alpha - \omega_{c\alpha} \frac{\partial}{\partial \phi} \delta f_k^\alpha = -\frac{q_\alpha}{m_\alpha} \underline{E}_{ok} \cdot \frac{\partial}{\partial \underline{v}} F_{\alpha o}, \tag{8}$$

where ϕ is the polar angle and

$$\frac{q_\alpha}{m_\alpha c}(\underline{v} \times \underline{B}_o) \cdot \frac{\partial}{\partial \underline{v}} = -\omega_{c\alpha} \frac{\partial}{\partial \phi}, \quad \omega_{c\alpha} = \frac{q_\alpha B_o}{m_\alpha c}. \tag{9}$$

Using

$$\begin{aligned} \underline{E}_{ok} \cdot \frac{\partial F_{\alpha o}}{\partial \underline{v}} &= -i\delta\phi_{ok} \underline{k} \cdot \frac{\partial F_{\alpha o}}{\partial \underline{v}} = -i\delta\phi_{ok} \left(k_\perp \cos\phi \frac{\partial}{\partial v_\perp} + k_\parallel \frac{\partial}{\partial v_\parallel} \right) F_{\alpha o}, \\ \underline{k} \cdot \underline{v} &= k_\perp v_\perp \cos\phi + k_\parallel v_\parallel, \end{aligned} \tag{10}$$

and the expansion in Bessel functions

$$\exp\left[-iz \sin\phi\right] = \sum_{n=-\infty}^{+\infty} J_n(z) \exp\left(-in\phi\right), \tag{11}$$

the solution of Eq.(8) for δf_k^α is given by :

$$\delta f_k^\alpha = \frac{q_\alpha}{m_\alpha} \delta\phi_{ok} \sum_l \sum_n \left(\frac{n\omega_{c\alpha}}{v_\perp} \frac{\partial F_{\alpha o}}{\partial v_\perp} + k_\parallel \frac{\partial F_{\alpha o}}{\partial v_\parallel} \right) \frac{J_n(\rho_\perp^\alpha) J_l(\rho_\perp^\alpha) \exp\left[-i(n-l)\phi\right]}{n\omega_{c\alpha} + k_\parallel v_\parallel}, \tag{12}$$

where $\rho_\perp^\alpha = k_\perp v_\perp / \omega_{c\alpha}$.

§3. Distribution Function in the Magnetized Dusty Plasma

The motion of electrons and ions in the presence of a mode $(\omega, \underline{k})$ in a magnetized dusty plasma is described by the linear Vlasov equation

$$\begin{aligned}\frac{\partial f_\alpha^T}{\partial t} + (\underline{v}\cdot\underline{\nabla})f_\alpha^T + \frac{q_\alpha}{m_\alpha}\frac{\underline{v}\times\underline{B}_o}{c}\cdot\underline{\nabla}_v f_\alpha^T &+ \frac{q_\alpha}{m_\alpha}\left[\underline{E}(\underline{r},t) + \frac{\underline{v}\times\underline{B}(\underline{r},t)}{c}\right]\cdot\underline{\nabla}_v f_{\alpha o}(\underline{r},\underline{v}) \\ &= \frac{q_\alpha}{m_\alpha}\underline{\nabla}\phi_o(\underline{r})\cdot\underline{\nabla}_v f_\alpha^T, \end{aligned} \tag{13}$$

where the superscript T stands for the total quantity involved, and $\underline{E}(\underline{r},t)$ and $\underline{B}(\underline{r},t)$ are the self-consistent electric and magnetic fields of the propagating mode, and m_α and c are the mass of the plasma particles α and the velocity of light in a vacuum, respectively.

The stationary equilibrium distribution function, Eq.(7) after Laplace-Fourier transformations is given by

$$\begin{aligned} f_{\alpha ok} &= F_{\alpha o}\delta(\underline{k}) + \delta f_k^\alpha, \\ F_{\alpha o}(\underline{v}) &= n_{\alpha o}(m_\alpha/2\pi T_\alpha)^{3/2}\exp\left(-m_\alpha v^2/2T_\alpha\right), \end{aligned} \tag{14}$$

T_α being the temperature in energy units for electrons and ions.

In the presence of a mode either electrostatic or electromagnetic in the magnetized dusty plasma, we decompose the total distribution function in Eq.(13) as

$$f_\alpha^T = f_{\alpha o}(\underline{r},\underline{v}) + f_\alpha(\underline{r},\underline{v},t) + \delta f_\alpha(\underline{r},\underline{v},t), \tag{15}$$

where the explicit contribution due to dust $\delta f_\alpha \ll f_\alpha$ and using the cylindrical coordinates $(v_\perp, \phi, v_\parallel)$ in the velocity space, we obtain

$$\frac{\partial f_\alpha}{\partial t} + \underline{v}\cdot\underline{\nabla}f_\alpha - \omega_{c\alpha}\frac{\partial f_\alpha}{\partial\phi} = -\frac{q_\alpha}{m_\alpha}\underline{E}\cdot\underline{\nabla}_v f_{\alpha o}(\underline{r},\underline{v}), \tag{16}$$

$$\frac{\partial\delta f_\alpha}{\partial t} + \underline{v}\cdot\underline{\nabla}\delta f_\alpha - \omega_{c\alpha}\frac{\partial\delta f_\alpha}{\partial\phi} = \frac{q_\alpha}{m_\alpha}\underline{\nabla}\phi_o(\underline{r})\cdot\underline{\nabla}_v f_\alpha(\underline{r},\underline{v}). \tag{17}$$

In Eq.(16), the dust term of Eq.(13) has been neglected and the effect of the dust particles has been taken through the modification of the space-dependent equilibrium distribution function, $f_{\alpha o}(\underline{r},\underline{v})$ given by Eqs.(7) and (12). The perturbed distribution function, $\delta f_\alpha(\underline{r},\underline{v},t)$ satisfies Eqs.(17) where the wave-effect is included through the solution of Eq.(16).

We obtain the solutions of Eqs.(16) and (17), which after Laplace-Fourier transformations (in the first order perturbation approximation) are given by

$$f_{\alpha\underline{k}\omega} = -\frac{iq_\alpha}{2T_\alpha}\sum_{n,l}\frac{J_n\exp\left(\overline{in-l\phi}\right)}{l\omega_{c\alpha}-\omega+k_\parallel v_\parallel}\int d\underline{k}' A_{l\underline{k}'\omega} f_{\alpha o\underline{k}-\underline{k}'}, \tag{18}$$

$$\begin{aligned}\delta f_{\alpha\underline{k}\omega} &= -\frac{iq_\alpha^2}{4m_\alpha T_\alpha}\sum_{m,n,p,l}\frac{J_p\exp\left[-i(m-\overline{n-l}-p)\phi\right]}{(m-\overline{n-l})\omega_{c\alpha}-\omega+k_\parallel v_\parallel} \\ &\times \int d\underline{k}''\phi_{o\underline{k}-\underline{k}''}\left[(J_{m+1}+J_{m-1})(\underline{k}-\underline{k}'')_\perp\frac{\partial}{\partial v_\perp}+2J_m(\underline{k}-\underline{k}'')_\parallel\frac{\partial}{\partial v_\parallel}\right. \\ &- \left.\frac{(n-l)(\underline{k}-\underline{k}'')_\perp}{v_\perp}(J_{m+1}-J_{m-1})\right]\frac{J_n(\rho_\perp'')}{l\omega_{c\alpha}-\omega+k_\parallel''v_\parallel}\int d\underline{k}' A_{l\underline{k}'\omega}f_{\alpha o\underline{k}''-\underline{k}'}.\end{aligned} \tag{19}$$

where $J_i = J_i(\rho_\perp), \rho_\perp = k_\perp v_\perp/\omega_{c\alpha}, \rho_\perp'' = k_\perp'' v_\perp/\omega_{c\alpha}$ and

$$\begin{aligned}A_{l\underline{k}\omega} &= a_x E_{\underline{k}\omega x} + a_y E_{\underline{k}\omega y} + a_z E_{\underline{k}\omega z}, \\ a_x &= v_\perp(J_{l+1}+J_{l-1}), \\ a_y &= -iv_\perp(J_{l+1}-J_{l-1}), \\ a_z &= 2v_\parallel J_l.\end{aligned} \tag{20}$$

§ 4. General Dispersion Relation

Substituting Eqs.(18), (19) in the definition of current density we obtain the components of the conductivity tensor from the following relations

$$\underline{J}^{(o)}_{\underline{k}\omega} = \sum_\alpha \overline{n}_\alpha q_\alpha \int \underline{v} f_{\alpha\underline{k}\omega} d^3v \equiv \underline{\underline{\sigma}}^{(o)}\cdot\underline{E}, \tag{21}$$

$$\underline{J}^{(D)}_{\underline{k}\omega} = \sum_\alpha \overline{n}_\alpha q_\alpha \int \underline{v}\delta f_{\alpha\underline{k}\omega} d^3v \equiv \underline{\underline{\sigma}}^{(D)}\cdot\underline{E}, \tag{22}$$

as

$$\sigma^{(o)}_{x\nu} = \sum_\alpha\sum_l\left(\frac{-\pi i\overline{n}_\alpha q_\alpha^2\omega_{c\alpha}}{T_\alpha k_\perp}\right)\int\int\frac{dv_\perp dv_\parallel v_\perp a_\nu}{l\omega_{c\alpha}+k_\parallel v_\parallel-\omega}lJ_l\left[F_{\alpha o}+\frac{u_\alpha}{m_\alpha v_\perp}\frac{\partial F_{\alpha o}}{\partial v_\perp}\right], \tag{23}$$

$$\sigma^{(o)}_{y\nu} = \sum_\alpha\sum_l\left(\frac{-\pi\overline{n}_\alpha q_\alpha^2}{T_\alpha}\right)\int\int\frac{dv_\perp dv_\parallel v_\perp^2 a_\nu}{l\omega_{c\alpha}+k_\parallel v_\parallel-\omega}J_l'\left[F_{\alpha o}+\frac{u_\alpha}{m_\alpha v_\perp}\frac{\partial F_{\alpha o}}{\partial v_\perp}\right], \tag{24}$$

$$\sigma^{o}_{z\nu} = \sum_\alpha\sum_l\left(\frac{-\pi i\overline{n}_\alpha q_\alpha^2}{T_\alpha}\right)\int\int\frac{dv_\perp dv_\parallel v_\perp v_\parallel a_\nu}{l\omega_{c\alpha}+k_\parallel v_\parallel-\omega}J_l\left[F_{\alpha o}+\frac{u_\alpha}{m_\alpha v_\perp}\frac{\partial F_{\alpha o}}{\partial v_\perp}\right], \tag{25}$$

$$
\begin{aligned}
\sigma_{x\nu}^{(D)} &= \sum_{\alpha}\sum_{mnl}\left(\frac{\pi i\omega_{c\alpha}\overline{n}_\alpha q_\alpha^2\mu_\alpha}{2m_\alpha k_\perp}\right)\int\int\frac{dv_\perp dv_\parallel v_\perp a_\nu}{(m-\overline{n-l})\omega_{c\alpha}+k_\parallel v_\parallel-\omega}\int d\underline{k}_2\left[(J_{m+1}+J_{m-1})k_{2\perp}\frac{\partial}{\partial v_\perp}\right.\\
&+ \left.2J_m k_{2\parallel}\frac{\partial}{\partial v_\parallel}-\frac{(n-l)k_{2\perp}}{v_\perp}(J_{m+1}-J_{m-1})\right]\frac{J_n\left(\frac{(\underline{k}-\underline{k}_2)_\perp v_\perp}{\omega_{c\alpha}}\right)}{l\omega_{c\alpha}+(\underline{k}-\underline{k}_2)_\parallel v_\parallel-\omega}\sum_{p,q}\frac{u_\alpha}{m_\alpha}S(\underline{k}_2)\\
&\times \left(\frac{p\omega_{c\alpha}}{v_\perp}\frac{\partial F_{\alpha o}}{\partial v_\perp}-k_{2\parallel}\frac{\partial F_{\alpha o}}{\partial v_\parallel}\right)(m-\overline{n-l+p-q})J_{m-\overline{n-l+p-q}}\frac{J_p\left(\frac{k_{2\perp}v_\perp}{\omega_{c\alpha}}\right)J_q\left(\frac{k_{2\perp}v_\perp}{\omega_{c\alpha}}\right)(-1)^{p+q}}{(p\omega_{c\alpha}-k_{2\parallel}v_\parallel)},
\end{aligned}
\tag{26}
$$

$$
\begin{aligned}
\sigma_{y\nu}^{(D)} &= \sum_{\alpha}\sum_{mnl}\left(\frac{\pi\overline{n}_\alpha q_\alpha^2\mu_\alpha}{2m_\alpha}\right)\int\int\frac{dv_\perp dv_\parallel v_\perp^2 a_\nu}{(m-\overline{n-l})\omega_{c\alpha}+k_\parallel v_\parallel-\omega}\int d\underline{k}_2\left[(J_{m+1}+J_{m-1})k_{2\perp}\frac{\partial}{\partial v_\perp}\right.\\
&+ \left.2J_m k_{2\parallel}\frac{\partial}{\partial v_\parallel}-\frac{(n-l)k_{2\perp}}{v_\perp}(J_{m+1}-J_{m-1})\right]\frac{J_n\left(\frac{(\underline{k}-\underline{k}_2)_\perp v_\perp}{\omega_{c\alpha}}\right)}{l\omega_{c\alpha}+(\underline{k}-\underline{k}_2)_\parallel v_\parallel-\omega}\sum_{p,q}\frac{u_\alpha}{m_\alpha}S(\underline{k}_2)\\
&\times \left(\frac{p\omega_{c\alpha}}{v_\perp}\frac{\partial F_{\alpha o}}{\partial v_\perp}-k_{2\parallel}\frac{\partial F_{\alpha o}}{\partial v_\parallel}\right)J'_{m-\overline{n-l+p-q}}\frac{J_p(k_{2\perp}v_\perp/\omega_{c\alpha})J_q(k_{2\perp}v_\perp/\omega_{c\alpha})(-1)^{p+q}}{(p\omega_{c\alpha}-k_{2\parallel}v_\parallel)}.
\end{aligned}
\tag{27}
$$

$$
\begin{aligned}
\sigma_{z\nu}^{(D)} &= \sum_{\alpha}\sum_{mnl}\left(\frac{\pi i\overline{n}_\alpha q_\alpha^2\mu_\alpha}{2m_\alpha}\right)\int\int\frac{dv_\perp dv_\parallel v_\perp v_\parallel a_\nu}{(m-\overline{n-l})\omega_{c\alpha}+k_\parallel v_\parallel\ \omega}\int d\underline{k}_2\left[(J_{m+1}+J_{m-1})k_{2\perp}\frac{\partial}{\partial v_\perp}\right.\\
&+ \left.2J_m k_{2\parallel}\frac{\partial}{\partial v_\parallel}-\frac{(n-l)k_{2\perp}}{v_\perp}(J_{m+1}-J_{m-1})\right]\frac{J_n\left(\frac{(\underline{k}-\underline{k}_2)_\perp v_\perp}{\omega_{c\alpha}}\right)}{l\omega_{c\alpha}+(\underline{k}-\underline{k}_2)_\parallel v_\parallel-\omega}\sum_{p,q}\frac{u_\alpha}{m_\alpha}S(\underline{k}_2)\\
&\times \left(\frac{p\omega_{c\alpha}}{v_\perp}\frac{\partial F_{\alpha o}}{\partial v_\perp}-k_{2\parallel}\frac{\partial F_{\alpha o}}{\partial v_\parallel}\right)J_{m-\overline{n-l+p-q}}\frac{J_p(k_{2\perp}v_\perp/\omega_{c\alpha})J_q(k_{2\perp}v_\perp/\omega_{c\alpha})(-1)^{p+q}}{p\omega_{c\alpha}-k_{2\parallel}v_\parallel},
\end{aligned}
\tag{28}
$$

with $\nu = x, y, z$, where the prime on the Bessel function denotes derivative with respect to its argument. In deriving Eqs.(23-28), we have taken the ensemble averages with the following relations for the Fourier component of the statistical function $\sigma(\underline{k})$

$$
\begin{aligned}
<\sigma(\underline{k})>=<\sigma^2(\underline{k})> &= \delta(\underline{k}).\\
<\sigma(\underline{k}_2)\sigma(\underline{k}-\underline{k}_1-\underline{k}_2)> &= S(\underline{k}_2)\delta(\underline{k}-\underline{k}_1),
\end{aligned}
\tag{29}
$$

where $S(\underline{k})$ is the correlation function. To further evaluate the integrals we may take a model Gaussian distribution for the correlation function, $S(\underline{q}) = (1/\pi\sqrt{\pi}q_o^3)\exp(-q^2/q_o^2)$, where q_o is the correlation length for the random static dust particles in the plasma.[6,17)]

Using Maxwell's equation

$$
-\underline{k}\times(\underline{k}\times\underline{E}_{\underline{k}\omega}) = \frac{\omega^2}{c^2}\underline{E}_{\underline{k}\omega}+\frac{4\pi i\omega}{c^2}\underline{J}_{\underline{k}\omega}
\tag{30}
$$

we finally obtain the components of the plasma dispersion tensor in the magnetized dusty plasma as

$$\begin{pmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{yx} & D_{yy} & D_{yz} \\ D_{zx} & D_{zy} & D_{zz} \end{pmatrix},$$

where

$$\begin{aligned}
D_{xx} &= 1 - \frac{k_{\|}^2 c^2}{\omega^2} + \frac{4\pi i}{\omega}\sigma_{xx}, \\
D_{xy} &= \frac{4\pi i}{\omega}\sigma_{xy}, \\
D_{xz} &= \frac{k_\perp k_{\|} c^2}{\omega^2} + \frac{4\pi i}{\omega}\sigma_{xz}, \\
D_{yx} &= \frac{4\pi i}{\omega}\sigma_{yx}, \\
D_{yy} &= 1 - \frac{k^2 c^2}{\omega^2} + \frac{4\pi i}{\omega}\sigma_{yy}, \\
D_{yz} &= \frac{4\pi i}{\omega}\sigma_{yz}, \\
D_{zx} &= \frac{k_\perp k_{\|} c^2}{\omega^2} + \frac{4\pi i}{\omega}\sigma_{zx}, \\
D_{zy} &= \frac{4\pi i}{\omega}\sigma_{zy}, \\
D_{zz} &= 1 - \frac{k_\perp^2 c^2}{\omega^2} + \frac{4\pi i}{\omega}\sigma_{zz};
\end{aligned} \tag{31}$$

$$\underline{\underline{\sigma}} = \underline{\underline{\sigma}}^{(o)} + \underline{\underline{\sigma}}^{(D)}.$$

The explicit contribution of dust is contained in $\underline{\underline{\sigma}}^{(D)}$.

§5. Dispersion Relation for Alfvén Waves

For the transverse electromagnetic wave propagating parallel to the magnetic field ($\underline{k} \parallel \underline{B}_o$), we can write (with $E_z = 0, k_\perp = 0, k = k_{\|}$)

$$\begin{pmatrix} D_{xx} & D_{xy} \\ D_{yx} & D_{yy} \end{pmatrix} \begin{pmatrix} E_x \\ E_y \end{pmatrix} = 0.$$

For the low density plasma we can have $k^2c^2 \gg \omega_{p\alpha}^2$, so that $E_x \ll E_y$. Then, the solution of the problem can be obtained from[16] $D_{yy} = 0$ and $D_{xy} = 0$.

On simplification with the approximation, $\omega, \omega_{c\alpha}, \omega \mp \omega_{c\alpha} > k_{\|} V_{th\alpha}$ and retaining only lower order Bessel functions ($m = n = p = q = 0$ and $l = 0, \pm 1$) in D_{yy} and D_{xy}, we obtain dispersion functions for the right-hand and left-hand circularly polarized electromagnetic waves

$$
\begin{aligned}
D_{R,L} &= 1-\frac{k_{\|}^2c^2}{\omega^2}+\frac{2\pi}{\omega}\sum_\alpha \frac{\omega_{p\alpha}^2}{V_{th\alpha}^2}\int\int dv_\perp dv_\| v_\perp^3 \frac{(1-\mu_\alpha)F_{\alpha o}}{k_\| v_\| -(\omega\mp\omega_{c\alpha})} \\
&+ \frac{2\pi}{\omega}\sum_\alpha \frac{\mu_\alpha^2\omega_{p\alpha}^2}{2}\int\int \frac{dv_\perp dv_\| v_\perp^3}{k_\| v_\| -(\omega\mp\omega_{c\alpha})}\int d\underline{q}q_\| \frac{\partial}{\partial v_\|}\frac{S(\underline{q})F_{\alpha o}}{(\underline{k}-\underline{q})_\| v_\| -(\omega\mp\omega_{c\alpha})},
\end{aligned}
\qquad (32)
$$

where the subscripts R and L on D indicate quantities for the right- and left-hand circularly polarized waves.

Further, we notice that the stationary and space-dependent equilibrium distribution of the plasma, $f_{\alpha o}(\underline{r},\underline{v})$ is close to the thermal equilibrium and the modifications due to the dust particles is incorporated in Eq.(7). The static magnetic field has the effect of changing the temperature of the equilibrium dusty plasma along and perpendicular to the magnetic field.[16) However, the dusty plasmas occur in most situations where the temperature of the plasma is usually very low. Therefore, to avoid mathematical complexities without loss of any generality, we neglect the small anisotropy in temperature introduced by the presence of the magnetic field. The wave propagation will be affected giving rise to additional or new modes by the magnetic field.

Thus, for a Maxwellian with isotropic distribution ($\partial F_{\alpha o}/\partial v_\perp^2 = \partial F_{\alpha o}/\partial v_\|^2$), we finally obtain the real and imaginary parts of the dispersion function as

$$
\begin{aligned}
D_{R,L}^r &= 1-\frac{k_\|^2c^2}{\omega^2}-\frac{1}{\omega}\sum_\alpha \frac{\omega_{p\alpha}^2}{\omega\mp\omega_{c\alpha}}\left[1-\mu_\alpha+\frac{\mu_\alpha^2 q_o^2 V_{th\alpha}^2}{4(\omega\mp\omega_{c\alpha})^2}\right], \\
D_{R,L}^i &= \frac{1}{\omega}\sum_\alpha \frac{\sqrt{\pi}\omega_{p\alpha}^2}{k_\| V_{th\alpha}}\left[(1-\mu_\alpha)\exp\left\{-\left(\frac{\omega\mp\omega_{c\alpha}}{k_\| V_{th\alpha}}\right)^2\right\}+\frac{\mu_\alpha^2(k_\|/q_o)I_\mp}{2\sqrt{\pi}}\right], \\
I_\mp &= \int_0^\infty \frac{dq_\| q_\| \exp\left[-\frac{q_\|^2}{q_o^2}-\left\{\frac{\omega\mp\omega_{c\alpha}}{(k_\|\mp q_\|)V_{th\alpha}}\right\}^2\right]}{(k_\|\mp q_\|)^2}.
\end{aligned}
\qquad (33)
$$

where $-$ sign is for the right-hand and $+$ sign is for the left-hand circularly polarized electromagnetic waves.

We now consider two cases depending upon the frequency of the waves with respect to the cyclotron frequencies of the plasma particles :

A. $\omega \gg \omega_{c\alpha}$ **: (high frequency waves)**

In this high frequency case of the cyclotron waves, the dispersion relation for both left-hand and right-hand circularly polarized waves is given by

$$\omega^2 = k_{\|}^2 c^2 + \sum_\alpha \omega_{p\alpha}^2 \left[1 - \mu_\alpha + \frac{\mu_\alpha^2 q_o^2 V_{th\alpha}^2}{4k_{\|}^2 c^2}\right]. \tag{34}$$

Neglecting dust we recover the usual electromagnetic wave in the unmagnetized plasma. The linear damping rate of this high frequency electromagnetic wave is given by

$$\gamma_L = -\sum_\alpha \frac{\sqrt{\pi}\omega_{p\alpha}^2 \omega^2}{2k_{\|}^3 c^2 V_{th\alpha}} \left[(1-\mu_\alpha)\exp\left[-\left(\frac{\omega}{k_{\|} V_{th\alpha}}\right)^2\right] + \frac{\mu_\alpha^2 (k_{\|}/q_o) I'_{\mp}}{2\sqrt{\pi}}\right]. \tag{35}$$

where

$$I'_{\mp} = \int_0^\infty \frac{dq_{\|} q_{\|}}{(k_{\|} \mp q_{\|})^2} \exp\left[-\frac{q_{\|}^2}{q_o^2} - \left(\frac{\omega}{(k_{\|} \mp q_{\|}) V_{th\alpha}}\right)^2\right]. \tag{36}$$

It is evident that the damping of the high frequency electromagnetic waves having $\omega \gg \omega_{c\alpha}$ is negligible.

B. $\omega \ll \omega_{c\alpha}$ **(Alfvén waves) :**

In this case we obtain the dispersion relation for both the left- and right-hand polarized Alfvén waves in the dusty plasma (from $D_{R,L}^r = 0$)

$$\omega = k_{\|} c/(1 + c^2/V_A^2)^{1/2}, \tag{37}$$

where the modified Alfvén velocity is given by

$$V_A = B_o/[4\pi(m_i \overline{n}_e \lambda_e + m_e \overline{n}_i \lambda_i)]^{1/2}, \tag{38}$$

$$\lambda_\alpha = 1 - \mu_\alpha + \mu_\alpha^2 q_o^2 V_{th\alpha}^2 / 4\omega_{c\alpha}^2. \tag{39}$$

The major modification enters through the nonneutrality of the average electron and ion densities $(\overline{n}_i \neq \overline{n}_e)$.

The linear damping rates of the Alfvén waves are given by

$$\begin{aligned}\gamma_L &= -D_{R,L}^i/(\partial D_{R,L}^r/\partial\omega) \\ &= -\sum_\alpha \frac{\sqrt{\pi}\omega_{p\alpha}^2 \omega^2}{2k_{\|}^3 c^2 V_{th\alpha}} \left[(1-\mu_\alpha)\exp\left[-\left(\frac{\omega_{c\alpha}}{k_{\|} V_{th\alpha}}\right)^2\right] + \frac{\mu_\alpha^2 (k_{\|}/q_o) I_{\mp}^A}{2\sqrt{\pi}}\right],\end{aligned} \tag{40}$$

where

$$I_{\mp}^{A} = \int_{o}^{\infty} \frac{dq_{\|}q_{\|}}{(k_{\|} \mp q_{\|})^2} \exp\left[-\frac{q_{\|}^2}{q_o^2} - \left(\frac{\omega_{c\alpha}}{(k_{\|} \mp q_{\|})V_{th\alpha}}\right)^2\right]. \tag{41}$$

In absence of the dust, Eq.(37) reduces to the usual Alfvén wave. However, the dust particles introduce a change in the Alfvén velocity, V_A mainly due to the inequality of the electron and ion densities of the dusty plasma. The damping of the Alfvén wave may be significantly affected by the presence of the charged grains. This damping depends on dust perturbation parameter, the correlation length, temperature of the plasma and the magnetic field. At low temperature, the usual Landau damping is negligible, but the dust introduces a new source of damping. This collisionless new damping mechanism is due to the resonant interaction with the particles whose velocities along the magnetic field $\underline{B}_o$ are given by $v_{\|} = (\omega_r \mp \omega_{c\alpha})/q_{\|}$ where ω_r is the real part of the angular frequency of the wave. The physical mechanism for this damping may be attributed to the fact that the random static distribution of grains can be regarded as a background zero-frequency wave which couples to the Alfvén wave and the particles resonate with the resultant beat structure to give rise to the wave damping.

§6. Discussion

We have investigated the propagation characteristics of transverse electromagnetic waves propagating along the static magnetic field in a magnetized dusty plasma. In the high frequency range we find modifications in the circularly polarized waves, which depend upon the dust perturbation parameter, correlation length, temperature of the plasma, and the strength of the magnetic field. In the cold plasma limit, we find important change in the Alfvén velocity which depends mainly on the nonneutrality of the electron and ion densities in the dusty plasma. However. the damping of the Alfvén waves is drastically modified on account of the presence of the dust grains in the plasma. In the low temperature regime where the usual Landau damping is negligible, an additional damping due to a new mechanism comes into play in the dusty plasma. This damping, depending upon the dust parameters. temperature and the magnetic field, may become significant.

The modification of other plasma modes and the nonlinear interaction due to the collective oscillations in the dusty plasmas with or without magnetic field are also of importance and the work on these are in progress.

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