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Excitation of dipole oscillons in a dusty plasma containing elongated dust rods

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Abstract. The dispersion properties and excitation mechanisms of 'dipole oscillons' in a dusty plasma containing charged elongated rod-like dust grains are investigated in the presence of streaming plasma particles for cases without and with an external static magnetic field. In a magnetized dusty plasma, a new 'oscillon-ion lower-hybrid' mode is found, which can be excited by the equilibrium energy of cross-field drifting ions.

Contents

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1. Introduction

Waves and instabilities occupy a significant part of modern plasma physics research because most properties of plasmas are related to the fundamental wave modes in laboratory and space plasma systems. In recent years, numerous studies have been confined to dusty plasmas having electrons, ions, and charged dust grains of spherical shapes [1]–[5]. However, in cosmic environments, dust particles of different sizes and shapes are quite common [2, 6]. The observed infrared and submillimetre radiation are attributed to the thermal emission from dust clouds heated by shock waves, the universal ultraviolet radiation, or stellar radiation, etc. Elongated dust grains are assumed to be formed by coagulation of smaller particulates in partially or fully ionized plasmas by some attractive forces [7, 8], the details of which are not yet fully understood. However, it is thought that inelastic, adhesive and collective interactions between micron-sized charged dust particles give rise to kilometre-sized bodies, which are known as planetesimals. Results from a microgravity aggregation experiment [9] flown onboard the space shuttle revealed the structure and growth of dust agglomeration. Specifically, Blum *et al* [9] reported that a thermally aggregating swarm of dust particles evolves very rapidly and forms unexpected open-structure agglomerates.

Obviously, the dust grains formed in laboratory and astrophysical environments by nucleosynthesis and coagulation may have any shape and size. Recently, many authors [10]–[12] have investigated the electrodynamics and dispersion properties of dusty plasmas whose constituents are electrons, ions and elongated, rotating charged dust grains in the absence and/or in the presence of external magnetic fields. There is a distribution of charges on rod-like dust particles, and an inhomogeneous charge distribution on the dust grain surface produces a finite dust dipole moment, which introduces new physics in dusty plasmas. In particular, it has been shown that oscillating dipoles of elongated charged dust rods give rise to a new wave mode, which is referred to as the 'dipole oscillon' [13]. The frequency of the latter is $k_\perp \lambda_D \Omega_{el}$, where $k_\perp$ is the wave-vector component of the dipole oscillon perpendicular to the direction of the dust rod alignment [14, 15], λ_D is the effective plasma Debye radius, $\Omega_{el} = \left(4\pi d^2 n_{d0}/I\right)^{1/2}$, d is the magnitude of the dipole moment, n_{d0} is the equilibrium number density of elongated dust rods, and I is the moment of inertia of the dipole. We note that the dipole oscillon is a compressional mode, since it propagates in a direction nearly perpendicular to the dust rod alignment. Physically, 'dipole oscillons' arise due to the combined action of the restoring force, which comes from the pressure of inertialess electrons and ions, and the moment of inertia of dust dipoles that oscillate around their equilibrium position.

In this paper, we present a rigorous study on possible electrostatic waves and their associated instabilities in a streaming dusty plasma containing electrons, ions, elongated charged dust rods, and neutrals in the presence/absence of an external magnetic field. The paper is organized as follows. In section 2, we consider the unmagnetized case in collisionless and collisional limits. In section 3, the effect of an external uniform magnetic field on the waves and instabilities of dusty plasmas having nonspherical elongated charged dust grains is presented. Finally, a brief discussion of our results is contained in section 4.

2. Unmagnetized dusty plasmas

Here, we study the dust dipole oscillations in an unmagnetized dusty plasma and their associated instabilities in the presence of streaming plasma particles, in both collisionless and collisional limits. The dispersion properties of electrostatic waves $(\omega, \boldsymbol{k})$ in a dusty plasma are governed by

$$\epsilon(\omega, \boldsymbol{k}) \equiv 1 + \chi_e + \chi_i + \chi_d = 0, \tag{1}$$

where ω and $\boldsymbol{k}$ are the frequency and the wavevector, respectively. The plasma susceptibilities for electrons and ions $(j = e, i)$ are [1]

$$\chi_j(\omega, \boldsymbol{k}) = \frac{1}{k^2\lambda_{Dj}^2}\left[1 + \xi_j Z(\xi_j)\right]\left[1 + \frac{\mathrm{i}\nu_{jn}}{\sqrt{2}kv_{tj}}Z(\xi_j)\right]^{-1}, \tag{2}$$

where $\lambda_{Dj} = (T_j/4\pi n_{j0}Q_j^2)^{1/2}$ is the Debye radius, Q_j is the charge, T_j is the temperature, Z is the plasma dispersion function of Fried and Conte [16], $\xi_j = (\omega - \boldsymbol{k}\cdot\boldsymbol{u}_{j0} + \mathrm{i}\nu_{jn})/\sqrt{2}kv_{tj}$, $v_{tj} = (T_j/m_j)^{1/2}$ is the thermal speed of the species j, m_j is the mass, ν_{jn} is the collision frequency between the species j and neutrals, and $\boldsymbol{u}_{j0}$ is the uniform streaming velocity of the jth species. In equation (1), χ_d is the dielectric susceptibility of the elongated dust rods [11]–[15] given by $-k_\perp^2\Omega_{el}^2/k^2\omega^2$. The latter holds if the wave frequency is much larger than the dust plasma frequency, since the motion of elongated dust rods has been ignored. Accordingly, dust oscillons are decoupled from the dust acoustic waves.

2.1. Collisionless streaming plasmas

Here, we consider electrons having a Boltzmann distribution while the ions are streaming with a uniform velocity $\boldsymbol{u}_{i0} \parallel \hat{\boldsymbol{z}}$ parallel to the direction of the dust rod alignment. The streaming ion motion is caused by the presence of a dc electric field, as in the sheath region of a laboratory rf discharge. We focus on waves with $kv_{td} \ll |\omega| \ll \nu_{en} \ll kv_{te}$ and $|\omega - k_\parallel u_{i0} + \mathrm{i}\nu_{in}| \ll kv_{ti}$, where ν_{en} and ν_{in} are collision frequencies of electrons and ions with neutral atoms/molecules. Accordingly, from equations (1) and (2) we obtain

$$1 + \frac{1}{k^2\lambda_{De}^2} + \frac{1}{k^2\lambda_{Di}^2}\left[1 + \mathrm{i}\sqrt{\frac{\pi}{2}}\frac{\omega - k_\parallel u_{i0}}{kv_{ti}}\right] - \frac{k_\perp^2}{k^2}\frac{\Omega_{el}^2}{\omega^2} = 0, \tag{3}$$

where $k_\parallel$ is the z-component of the wavevector $\boldsymbol{k}$, and the z axis is parallel to the direction of the alignment of dust dipole rods.

Letting $\omega = \omega_r + \mathrm{i}\omega_i$ in equation (3), where ω_r and ω_i are the the real and imaginary parts of the frequency, we obtain

$$\omega_r = \frac{k_\perp C_{rd}}{\sqrt{1 + k^2\lambda_D^2}}, \tag{4}$$

where $C_{rd} = \Omega_{el}\lambda_D$, $\lambda_D^{-2} = \lambda_{De}^{-2} + \lambda_{Di}^{-2}$, and

$$\omega_i = \sqrt{\frac{\pi}{8}}\frac{\omega_r^3}{\Omega_{el}^2}\frac{k_\parallel u_{i0} - \omega_r}{k_\perp^2\lambda_{Di}^2 kv_{ti}}, \tag{5}$$

which exhibits an instability of the 'dipole oscillon' if $u_{i0} > (k_\perp/k_\parallel)C_{rd}/\sqrt{1 + k^2\lambda_D^2}$.

2.2. Collisional dusty plasmas

We now consider waves with $|\omega|$, $\nu_{en} \ll kv_{te}$ and $|\omega - k_\parallel u_{i0}| \ll \nu_{in} \ll kv_{ti}$. Here, hot electrons follow a Boltzmann distribution and we have $\chi_e \approx 1/k^2\lambda_{De}^2$. On the other hand, the ions are collisional. In such a situation, equations (1) and (2) give

$$1 - \frac{\Omega_{DIA}^2}{(\omega - k_\parallel u_{i0} + i\nu_{in})(\omega - k_\parallel u_{i0}) - 3k^2 v_{ti}^2} - \frac{\Omega_r^2}{\omega^2} = 0, \tag{6}$$

where

$$\Omega_r = \frac{k_\perp C_{re}}{\sqrt{1 + k^2\lambda_{De}^2}}, \tag{7}$$

$$\Omega_{DIA} = \frac{k_\perp C_s}{\sqrt{1 + k^2\lambda_{De}^2}}, \tag{8}$$

$C_{re} = \Omega_{el}\lambda_{De}$ and $C_s = \omega_{pi}\lambda_{De}$. Letting $\omega = \omega_r + i\omega_i$ in equation (6), where $\omega_i \ll \omega_r$, we obtain

$$\omega_r \simeq \frac{\Omega_r}{[1 + \Omega_{DIA}^2/3k^2 v_{ti}^2]^{1/2}}, \tag{9}$$

and

$$\omega_i = \frac{\nu_{in}\omega_r\Omega_{DIA}^2}{18k^4 v_{ti}^4}(k_\parallel u_{i0} - \omega_r). \tag{10}$$

Equation (10) exhibits instability if $u_{i0} > \omega_r/k_\parallel$.

2.3. Effect of collisions on the ion-dust two-stream instability

For streaming ions, hot electrons, and cold dust rods, the conditions $\nu_{en} \ll |\omega| \ll kv_{te}, k_\parallel u_{i0}$ and $\nu_{in} \ll k_\parallel u_{i0}$, are usually satisfied in a collisional plasma. Here, we consider the case of a strong ion flow compared to the conditions described in the previous subsection. Using, equations (1) and (2), and the conditions mentioned above, we obtain the following dispersion relation

$$1 + \frac{1}{k^2\lambda_{De}^2} - \frac{\omega_{pi}^2}{(\omega - k_\parallel u_{i0} + i\nu_i)^2}\left[1 + i\frac{\nu_{in}}{\omega - k_\parallel u_{i0} + i\nu_{in}}\right] - \frac{k_\perp^2}{k^2}\frac{\Omega_{el}^2}{\omega^2} = 0. \tag{11}$$

Neglecting collisions, namely $\nu_{in} \simeq 0$, and assuming $k_\parallel u_{i0} \gg |\omega|$, equation (11) gives a Buneman-type instability with $\omega_r \sim \omega_i$, where

$$\omega_r = \frac{1}{2^{4/3}}\left(\frac{k_\perp}{k}\right)^{2/3}\left(\frac{\omega_{pi}}{\Omega_{el}}\right)^{1/3}\frac{\Omega_{el}}{A^{3/4}}, \tag{12}$$

$$\omega_i = \frac{\sqrt{3}}{2^{4/3}}\left(\frac{k_\perp}{k}\right)^{2/3}\left(\frac{\omega_{pi}}{\Omega_{el}}\right)^{1/3}\frac{\Omega_{el}}{A^{3/4}}, \tag{13}$$

where $A = 1 + 1/k^2\lambda_{De}^2$. On the other hand, for $\nu_{in} \gg |\omega|$ and $\nu_{in} \ll k_\parallel u_{i0}$, we obtain from equation (11)

$$\frac{\omega}{\Omega_{el}} \simeq \frac{k}{k_\perp}\frac{1+i}{\sqrt{2}}\left(\frac{\omega_{pi}}{\nu_{in}}\right)^{1/2}\frac{1}{A^{3/4}}, \tag{14}$$

which predicts an oscillatory instability in a collisional dusty plasma.

3. Magnetized plasmas

Here, we consider a dusty plasma containing nonspherical elongated rod-like grains in an external magnetic field $\boldsymbol{B}_0 = B_0\hat{z}$. The dispersion properties of electrostatic waves in our dusty magnetoplasma are governed by $\epsilon(\omega, \boldsymbol{k}) \equiv 1 + \chi_e + \chi_i + \chi_d = 0$, where the plasma susceptibilities for electrons and ions ($j = e, i$) are now given by [1]

$$\chi_j(\omega, \boldsymbol{k}) = \frac{1}{k^2\lambda_{Dj}^2}\left[1 + \sum_{n=-\infty}^{\infty} \xi_{jn} Z(\xi_{jn})\Gamma_n(b_j)\right]\left[1 + \sum_{n=-\infty}^{\infty} \frac{\mathrm{i}\nu_{jn}}{\sqrt{2}k_\parallel v_{tj}} Z(\xi_{jn})\Gamma_n(b_j)\right]^{-1}. \qquad (15)$$

In equation (15), $\xi_{jn} = (\omega - \boldsymbol{k}\cdot\boldsymbol{u}_{j0} + \mathrm{i}\nu_{jn} - n\omega_{cj})/\sqrt{2}k_\parallel v_{tj}$, $\omega_{cj} = |Q_j B_0/m_j c|$ is the gyrofrequency, c is the speed of light in vacuum, $\Gamma_n = I_n(b_j)\exp(-b_j)$, with I_n being the modified Bessel function of order n, $b_j = k_\perp^2\rho_j^2$ and $\rho_j = v_{tj}/\omega_{cj}$ is the thermal gyroradius.

3.1. Cold plasma limit

In the cold plasma limit for magnetized electrons and ions, the approximations $k_\parallel v_{te} \ll |\omega - k_y u_0 + \mathrm{i}\nu_{en,in}| \ll \omega_{ci} \ll \omega_{ce}$ with $b_e, b_i \ll 1$ are usually valid. Then, the dispersion relation becomes

$$1 + \frac{k_\perp^2}{k^2}\frac{\omega_{pi}^2}{\omega_{ci}^2} - \frac{k_\parallel^2}{k^2}\frac{\omega_{pe}^2}{(\omega - k_y u_0)(\omega - k_y u_0 + \mathrm{i}\nu_{en}} - \frac{k_\perp^2}{k^2}\frac{\Omega_{el}^2}{\omega^2} \approx 0. \qquad (16)$$

Neglecting the streaming of electrons and ions and collision frequencies, and assuming $k_\parallel \ll k_\perp$ and $\omega_{pi}^2 \gg \omega_{ci}^2$, we obtain from equation (16) a new mode which we call the 'oscillon-ion-lower-hybrid (OILH)' wave whose frequency is

$$\omega_r \approx \frac{\Omega_{el}\omega_{ci}}{\omega_{pi}}\left(1 + \frac{k_\parallel^2}{k_\perp^2}\frac{\omega_{pe}^2}{\Omega_{el}^2}\right)^{1/2}. \qquad (17)$$

The damping rate of the OILH mode including electron–neutral collisions is

$$\omega_i = -\frac{1}{2}\frac{k_\parallel^2}{k_\perp^2}\frac{\nu_{en}\omega_{pe}^2\omega_{ci}^2}{\omega_r^2\omega_{pi}^2}. \qquad (18)$$

For negligible electron–neutral collision frequency, namely $|\omega - k_y u_0| \gg \nu_{en}$ and assuming $\omega \equiv k_y u_0 + \delta$ with $\delta \ll k_y u_0$, equation (16) reduces to

$$1 - \frac{\omega_{OD}^2}{\delta^2} - \frac{\omega_{osc}^2}{k_y^2 u_0^2} + \frac{2\omega_{osc}^2\delta}{k_y^3 u_0^3} = 0, \qquad (19)$$

where

$$\omega_{OD} = \frac{k_\parallel}{k}\frac{\omega_{pe}}{\left(1 + k_\perp^2\omega_{pi}^2/k^2\omega_{ci}^2\right)^{1/2}}, \qquad (20)$$

and

$$\omega_{osc} = \frac{k_\perp}{k}\frac{\Omega_{el}}{\left(1 + k_\perp^2\omega_{pi}^2/k^2\omega_{ci}^2\right)^{1/2}}. \qquad (21)$$

Balancing the first and third terms in equation (19), we have $k_y u_0 \simeq \omega_{osc}$ and $\omega_r = \Omega_{el}\omega_{ci}/\omega_{pi}$ for $k_\perp \sim k$. This is the real part of the OILH mode frequency. Balancing the small second and fourth terms, we obtain the growth rate of the OILH mode as

$$\gamma = \frac{\sqrt{3}}{2^{4/3}} \left(\frac{k_\parallel}{k_\perp} \frac{\omega_{pe}}{\Omega_{el}} \right)^{2/3} k_y u_0. \tag{22}$$

3.2. Hot electrons

For hot electrons, cold ions and elongated charged dust particles, only the ions can be considered magnetized and drifting due to the presence of a dc electric field ($u_0 = cE_{0x}/B_0$). Electrons are assumed to satisfy the conditions $|\omega - k_y u_0| \ll \nu_{en} \ll k_\parallel v_{te}$ with $b_e \ll 1$. Hence, electrons are rapidly thermalized along the external magnetic field direction and establish a Boltzmann distribution. The corresponding electron susceptibility is $1/k^2\lambda_{De}^2$. On the other hand, ions can satisfy $|\omega - k_y u_0| \gg \nu_{in} \gg k_\parallel v_{ti}$ with $b_i \ll 1$. Thus, using equation (15), the dispersion relation of a dusty magnetoplasma is of the form

$$1 + \frac{1}{k^2\lambda_{De}^2} + \mathrm{i}\sqrt{\frac{\pi}{2}} \frac{\omega - k_y u_0}{k^2\lambda_{De}^2 k_\parallel v_{te}} + \frac{k_\perp^2}{k^2}\frac{\omega_{pi}^2}{\omega_{ci}^2} + \frac{k_\parallel^2}{k^2}\frac{\omega_{pi}^2}{(\omega - k_y u_0)^2} - \frac{k_\perp^2}{k^2}\frac{\Omega_{el}^2}{\omega^2} = 0. \tag{23}$$

For nearly perpendicular propagating OILH mode ($k_\parallel \ll k_\perp$), the real and imaginary parts of the frequency are

$$\omega_r \simeq \frac{k_\perp C_{re}}{\sqrt{1 + k^2\lambda_{De}^2 + k_\perp^2\rho_s^2}}, \tag{24}$$

and

$$\omega_i = \sqrt{\frac{\pi}{8}} \left(\frac{\omega_r}{k_\parallel v_{te}} \right) \frac{k^2\lambda_{De}^2 (k_y u_0 - \omega_r}{1 + k^2\lambda_{De}^2 + k_\perp^2\rho_s^2}, \tag{25}$$

where $\rho_s = \omega_{pi}\lambda_{De}/\omega_{ci}$. Hence, the oscillon-ion-lower-hybrid wave grows when u_0 exceeds the wave phase speed (ω_r/k_y) in the azimuthal direction.

4. Discussion

In this paper, we have presented the linear wave modes and their instabilities in a dusty plasma containing electrons, ions, and elongated charged dust grains having a finite dipole moment. Various conditions of the plasma parameters in the presence of external electric and magnetic fields have been considered. The linear dispersion relations for ultra-low-frequency electrostatic modes associated with elongated dust grains are presented both in collisionless and collisional regimes. It is shown that 'dipole oscillons' can become unstable due to the free energy of streaming ion motions in an unmagnetized dusty plasma. Physically, oscillon instabilities are due to the two-stream instability or attributed to the wave-ion resonance interaction in an unmagnetized dusty plasma. The presence of an external magnetic field gives rise to a new 'oscillon-ion-lower-hybrid' mode. The latter is a flute-like mode and arises due to the dust dipole oscillation in the perpendicular wave electric field that causes the polarization of ions in an external magnetic field. In a collisionless cold magnetoplasma, the OILH mode becomes unstable when one considers the magnetic field aligned electron dynamics and equilibrium electron streaming under the combined influence of equilibrium cross-electric and magnetic fields. On the other hand, a Cherenkov resonance instability of the OILH occurs when the electrons are treated kinetically and the cold ions and dust follow the fluid-like motions. The present instabilities should help to identify the origin of nonthermal fluctuations in cosmic and laboratory plasmas where irregular charged dust particles are ubiquitous. Specifically, nonthermal fluctuations may play a decisive role in determining the polarization of cosmic electromagnetic waves when they are scattered from turbulent environments containing 'dipole oscillons'.

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References

[1] Shukla P K and Mamun A A 2002 *Introduction to Dusty Plasma Physics* (Bristol: Institute of Physics Publishing)
[2] Mendis D A 2002 *Plasma Sources Sci. Technol.* **11** A219
[3] Rosenberg M 2002 *J. Plasma Phys.* **67** 235
[4] D'Angelo N and Merlino R L 1996 *Planet. Space Sci.* **44** 1593
[5] Rosenberg M and Shukla P K 1998 *Phys. Plasmas* **5** 3786
[6] Voshchinnikov N V and Semenov D A 2000 *Pis'ma Astronomicheskii Zh.* **26** 787 (2000) (Engl. Transl. 2000 *Astron. Lett.* **26** 679)
[7] Bingham R and Tsytovich V N 2001 *Astron. Astrophys.* **376** L43
[8] Bingham R, Tsytovich V N and Resendes D P 2002 *Dust Plasma Interaction in Space* ed P K Shukla (New York: Nova Science Publishing) pp 249–68
[9] Blum J, Wurm G, Kempf S, Poppe T, Klahr H *et al* 2000 *Phys. Rev. Lett.* **85** 2426
[10] Mohideen U, Rahman H U, Smith M A, Rosenberg M and Mendis D A 1998 *Phys. Rev. Lett.* **81** 349
[11] Tskhakaya D D and Shukla P K 2001 *Phys. Lett.* **A 279** 243
[12] Tskhakaya D D, Shukla P K and Tsintsadze N L 2001 *Zh. Eksp. Teor. Fiz* **120** 340 (Engl. Transl. 2001 *JETP* **93** 301)
[13] Shukla P K 2001 *Phys. Lett.* A **289** 89
[14] Mahmoodi J, Shukla P K, Tsintsadze N L and Tskhakaya D D 2000 *Phys. Rev. Lett.* **84** 2626
[15] Shukla P K and Tskhakaya D D 2001 *Phys. Plasmas* **8** 370
[16] Fried B D and Conte S D 1961 *The Plasma Dispersion Function* (New York: Academic)