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Oscillations of Magnetized Grains in Complex Plasmas

V. V Yaroshenko and A. A. Minakov

The Institute of Radio Astronomy of the National Academy of Sciences of Ukraine,
4, Chervonopraporna st., Kharkiv, Ukraine 61002
E-mail: yarosh@ira.kharkov.ua

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Vertical vibrations of a single magnetized charged dust grain and a one-dimensional string of magnetized particles in a gas-discharge plasma immersed in an external almost vertical magnetic field are studied. It is shown that the magnetic force associated with gradients of the magnetic field results in a novel type of oscillations of a single particle. Such vibrations can be either stable or unstable, depending on the magnetic field distribution inside the gas-discharge chamber. In a one-dimensional particle string, the magnetic force causes a new low-frequency oscillatory mode, which is characterized by dispersion similar to the optical phonon branch in the long-wavelength range. The possibilities of using the vertical vibrations of magnetized grains for determining complex plasma parameters are discussed.

1. Introduction

Complex plasmas are multicomponent systems consisting of several charged components (electrons, ions and microparticles) and neutral gas. The microparticles (dust grains) are very massive and highly charged (usually negative) due to interaction with plasma electrons and ions. In the last decade such complex plasmas have aroused a keen interest as a new progressive field in plasma physics closely interrelated with other research areas, such as strong coupling phenomena, colloid physics, environmental research, astrophysics [1], plasma processing technologies, etc. The most surprising discovery was the observation of crystal-like structures, which arise spontaneously when charged microparticles are trapped in a sheath electric field [2-9]. Such plasma crystal structures can sustain longitudinal and transverse vibrational modes, which have been extensively studied in recent years [6-16]. However, the ground based complex plasma experiments deal with either a monolayer or a cloud of a few layers (quasi-two dimensional systems). Three-dimensional structures can be obtained either in experiments under microgravity conditions, using very small (sub-micron) particles, or when some other nonelectric force compensates gravitation. The idea of gravity compensation by a nonelectric force seems very promising from a standpoint of recent experimental research. In particular, experiments involving the thermophoretic force, which lifts the particles above the sheath region, were characterized by strong plasma inhomogeneities and ion flows [17] and allowed an opportunity to study a complex plasma structure (e.g. void formation) even under gravity [18,19]. At the same time, the nonlinear temperature distribution produces specific vibrational modes [20] which can provide a tool for determining the complex plasma parameters.

Recently, multilayer complex plasma structures were observed in an external magnetic field [21]. Measurements were carried out in a capacitively-coupled radio-frequency discharge with paramagnetic microspheres of radius $a = 2.25\mu m$, magnetic permeability $\mu \sim 4$, and material density $1.5 g/cm^3$. Magnetic coils located above the discharge chamber created a magnetic field coaxial with the chamber. The field gradient pointed upwards, exerting a levitating force on paramagnetic particles. For further technical details we refer to the recent paper [21].

When dust grains were injected into the discharge in the absence of the magnetic field, they charged up and levitated forming a few-layer structure in the plasma sheath of the lower electrode. As soon as the magnetic field was applied, the main particle cloud rised somewhat higher. Increasing the magnetic field strength allowed to lift the macroparticles into the central part of the discharge chamber or even to the upper sheath of the discharge. Hence, contrary to the electrostatic levitation in the sheath electric field, the levitation height in the magnetic experiments can be controlled by variations of the electric current in the magnetic coils. This means that magnetic forces open new opportunities for studying complex plasmas at the kinetic level.

Among the novel features demonstrated by the magnetized particles was dust agglomeration: some particles coalesce into chains oriented vertically, in parallel to the field lines of the external magnetic field. This phenomenon is well studied both in theory [22] and in the laboratory [21]. This paper will focus on the grain levitation in an external magnetic field and on the vertical particle vibration. Until now, oscillatory modes of magnetized particles in a gas discharge plasma have been considered only for the case of homogeneous magnetic fields [23], i.e. the magnetic force levitation as well as the impact of inhomogeneous magnetic field on the particle dynamics have not been discussed yet.

The paper is organized as follows. In section 2 we first discuss levitation of the magnetized particles and consider the vertical oscillations of a single grain in discharge plasmas, before turning in section 3 to the existence of new collective modes in a string of paramagnetic particles. Finally, our conclusions are given in section 4.

2. Vertical Oscillations of a Single Dust Particle

In this section, we consider the vertical motion of an individual charged dust particle embedded in a combination of the sheath electric field and an external magnetic field, thus modeling the configuration realized in the recent magnetic experiment [21]. The static magnetic field **B** is assumed to be almost vertical $\mathbf{B} \approx B\mathbf{e}_z$, so that $B_z \gg B_x, B_y$. As shown below, in this case the particle is magnetized mainly along the vertical z-axis, and the magnetic force impact on the horizontal motion of the grain can be neglected.

The equation describing the vertical motion of a dust particle in gas discharge plasmas can be written in a form

$$\ddot{z} + 2\gamma\dot{z} = \frac{F}{M} - g, \qquad (1)$$

where F is the z-component of the total electromagnetic force acting on the particle of mass M, g denotes the gravitational acceleration, and γ the damping rate due to neutral gas friction [24].

In the experiments, which do not invoke a magnetic field, the particles are suspended near the lower electrode due to the balance of gravitational and electrostatic forces. Since to a good approximation the absolute value of the sheath electric field $E(z)$ increases almost linearly with z [12, 13], there is always a position where gravitation can be compensated by the electrostatic force, viz.

$$Mg = Q_0 E_0. \qquad (2)$$

Here $Q_0 = Q(z=0) < 0$ is the particle charge, and $E_0 = E(z=0) < 0$ the electric field at the point $z = 0$ corresponding to the equilibrium position. Relation (2) implies that the particles with different ratios Q_0/M will be suspended at different positions: the grains of larger Q_0/M (smaller sizes) levitate higher due to the electric force, while the larger grains require stronger electric fields and therefore can only levitate in the vicinity of the electrode, where the electric field is strong enough.

If the particle is perturbed from its equilibrium and the oscillation amplitude is sufficiently small, one can expand

$$E(z) \cong E_0 + E_0' z \tag{3}$$

(the prime denotes the derivative $\partial E/\partial z$ at the equilibrium $z = 0$).

The charge accumulated by a grain is usually determined by the balance of the electron and ion fluxes on its surface. Values of these fluxes are functions of the discharge parameters. As a result of a non-uniformity of the plasma in the sheath-region, the equilibrium dust charge becomes a function of the distance from the electrode, i.e. $Q = Q(z)$ [25]. However, typically the particle charge does not change crucially over the scales of the small vertical oscillations near equilibrium and thus we can use only the linear expansion for $Q(z)$,

$$Q(z) \cong Q_0 + Q_0' z. \tag{4}$$

Substituting (3) and (4) into (1) gives in the linear approximation

$$\ddot{z} + 2\gamma\dot{z} - \frac{Q_0 E_0' + Q_0' E_0}{M} z = 0,$$

and, correspondingly, the characteristic frequency is

$$\Omega_E^2 = -\frac{(QE)_0'}{M}. \tag{5}$$

Recent experiments have demonstrated that the equilibrium dust charge is practically independent of the vertical position only in the bulk plasma and in the pre-sheath region, but its value increases rapidly in the sheath, achieving a maximum and then starts to decrease in the vicinity of the lower electrode [25]. In laboratory complex plasmas, the particles usually levitate near the sheath edge, where $(QE)_0' \cong Q_0 E_0' < 0$, so that the vertical oscillations described by (5) are stable. Recently, excitation of the vertical vibrations and the measurement of the frequency (5) have been used to estimate the dust charge and spatial distributions of the electric field $E(z)$ in the plasma sheath [8, 26, 27]. Note that our present analysis does not include the "delayed" charging effect and the related specific instability of the vertical vibrations predicted by Nitter et al. [28] and observed in a discharge plasma at low gas pressure [29-31].

Now we consider another limiting case when the grain levitates mainly due to the magnetic force. A spherical particle of radius a and magnetic permeability μ immersed in an external magnetic field $\mathbf{B}$ gets a magnetic moment [32]

$$\mathbf{m} = a^3 \frac{(\mu - 1)}{(\mu + 2)} \mathbf{B}. \tag{6}$$

Such a magnetized grain is subjected to a magnetic force, $\mathbf{F_m} = \nabla(\mathbf{mB})$. Apparently, the vertical component of the magnetic force,

$$F_m = \frac{\partial (mB)}{\partial z} = -2\alpha B \frac{\partial B}{\partial z}, \tag{7}$$

is the highest one, because $m \cong m_z \gg m_x, m_y$. The introduced coefficient α is defined as $\alpha = a^3(\mu - 1)/(\mu + 2)$.

Expanding the magnetic force (7) in the vicinity of the equilibrium position, $z = 0$, and taking $F_m \cong F_0 + F_0' z$ yields

$$F_0 = -2\alpha B_0 B_0',$$

$$F_0' = -2\alpha (B_0'^2 + B_0 B_0'').$$

Once again subscript "0" denotes the quantities at the equilibrium position $z = 0$. Contrary to the condition of electrostatic levitation (2), both sides of the force balance, $Mg = -2\alpha B_0 B_0'$, are now proportional to a^3, and spherical grains of various sizes are suspended at the same height, which can be completely specified by the vertical gradient of the external magnetic field. Substituting F_0 and F_0' into (1) and using the balance equation gives in the linear approximation

$$\ddot{z}+2\gamma\dot{z}+\frac{2\alpha}{M}\left(B_0'^2+B_0B_0''\right)z=0. \quad (8)$$

The characteristic frequency of vertical oscillations is now

$$\Omega_m^2=\frac{2\alpha}{M}\left(B_0'^2+B_0B_0''\right). \quad (9)$$

Since the particle mass can be written as $M=4\pi\rho a^3/3$ (ρ is the material density), (9) reduces to

$$\Omega_m^2=\frac{6(\mu-1)}{4\pi\rho(\mu+2)}\left(B_0'^2+B_0B_0''\right). \quad (10)$$

It follows immediately that all magnetized grains have the same frequency of vertical vibrations (10), independently of their sizes: Ω_m^2 is specified by the vertical profile of the external magnetic field and the magnetic properties of the grain material. As a result, the value Ω_m^2 can be positive or negative depending on B_0, B_0' and B_0'' at the initial levitation height. When the electric current in the coils is fixed, these values are mainly determined by the position of the discharge chamber relative to the magnetic coils. We have calculated the values of the magnetic induction, its first and second spatial derivatives along the axis of the magnetic coils produced by a 17-cm thick coil with 30-cm bore at the current of 1 kA used in real experiments [21]. The values of B_0, B_0' and B_0'' for different distances from the magnetic coils are shown in Table 1. The latter illustrates that when the distance between the lower electrode and the magnetic coils is small enough (e.g., less than 0.1 m), B_0'' becomes strongly negative, leading to negative values of Ω_m^2 and thus an instability of the vertical oscillations (in the case $|\Omega_m|>\gamma/2$). Nevertheless, the major conclusion is that an appropriate choice of the magnetic field distribution can always allow the squared frequency Ω_m^2 be positive to stabilize vertical particle vibrations.

To obtain a numerical estimate of the frequency Ω_m, we consider typical parameters in the magnetic experiments corresponding to the distance between the lower electrode and the bottom edge of the coils of about $25\div30$ cm [21]. Particle levitation was observed for average magnetic fields, $B_0\sim0.1=0.15$ T, and field gradients, $|B_0'|\sim0.75=1.15$ T/m. Taking $B_0''\sim5\div7.5$ T/m² (Table 1) then yields $\Omega_m\sim50\div70$ s–1. Such values are similar to the frequencies of vertical vibrations in a sheath electric field Ω_E [14-16] and can be easily measured.

Finally, when both the magnetic and electric forces contribute to balancing gravitation, the frequency of vertical oscillations can be written as a combination of (5) and (9):

$$\Omega_v^2=\Omega_m^2+\Omega_E^2=\frac{6(\mu-1)(B'B)_0'}{4\pi\rho(\mu+2)}-\frac{(QE)_0'}{M}. \quad (11)$$

This describes either stable or unstable vertical vibrations, depending on the contribution of Ω_m^2 and Ω_E^2. While the electrostatic squared frequency $\Omega_E^2\sim-(QE)_0'$ can be either positive

Table 1. *Magnetic induction, its first and second spatial derivatives along the axis of the magnetic coils at the current of ~1 kA*

Distance from the coils, m	0.05	0.1	0.15	0.2	0.25	0.3	0.35
B_0, T	0.75	0.4	0.28	0.2	0.15	0.1	0.7
B_0', T/m	–1.5	–2.35	–2.2	–1.5	–1.15	–0.75	–0.4
B_0'', T/m²	–22.3	–4.3	8.3	10.5	7.5	5.2	4.5

or negative within the sheath region [25], the magnetic term Ω_m^2 can be always allowed positive (by varying the magnetic field distribution) and exceeding $\left|\Omega_E^2\right|$ and thus stabilizing the vibrations which would be unstable in the absence of the magnetic field.

Now the question is what parameters of the complex plasma can be recovered from measurements of the characteristic frequencies (10) or (11). As the frequencies of the vertical vibrations are accurately measured and the values of B_0, B_0' and B_0'' are determined numerically, expression (10) immediately gives the value of the magnetic permeability μ, and thus from Eq. (6) the magnetic moment can be found. If the levitation is due to the combination of electrostatic and magnetic forces, then using Eq. (11) the $(QE)_0'$ profile can be determinated at μ, B_0, B_0' and B_0'' given. Varying the current in the magnetic coils (and also B_0, B_0' and B_0''), it is possible to calculate the values of $(QE)_0'$ even in the close vicinity of the lower electrode, where $Q_0 E_0' > 0$, and the oscillations appear unstable in the absence of the magnetic field. There is another possibility when the magnetic force (7) lifts up the particle in the pre-sheath region, where the charge is nearly constant and $\Omega_E^2 = \left|Q_0 E_0'\right|/M$. Then by measuring (11), either the equilibrium charge Q_0 at μ, B_0, B_0' and B_0'' given or the equilibrium gradient E_0' for the Q_0 known can be found. Such measurements could be of importance in understanding how the particle charge or the sheath structure is impacted by an external magnetic field. Hence, the observations of the vertical oscillations of a single particle in an inhomogeneous magnetic field seem very promising for complex plasma diagnostics.

3. Vibrational Modes in a Horizontal String of Paramagnetic Grains

In order to describe the collective vertical modes in complex plasmas with magnetized grains, we consider an often-invoked model of a one-dimensional infinite linear chain of grains (the so called horizontal 1D-string [11, 14]). In this model, each spherically symmetric grain is considered as having an electric charge Q, and mass M. We assume that in equilibrium, the particle centers are separated by the average distance Δ along the horizontal x-axis. Like in the previous section, an inhomogeneous external magnetic field is applied along the vertical z-direction, leading to the particle magnetization ($\mathbf{m}$ is a magnetic moment of the grains).

The interparticle forces include the Coulomb electrostatic force, the magnetic force due to interactions of magnetic moments between the grains and with the external magnetic field. Since the dust grains are shielded by the surrounding plasma, the interparticle charge interaction is governed by the Debye-Huckel potential

$$\Phi_n = \frac{Q_n}{\left|\mathbf{r}_n\right|}\exp\left(-\frac{\mathbf{r}_n}{\lambda_D}\right),$$

with λ_D being the plasma Debye length. Note that under the discharge conditions, the electron temperature is usually much higher than the temperature of plasma ions, and thus λ_D is mainly determined by the ions, i.e. $\lambda_D \approx \lambda_{Di}$.

The energy of electrostatic and magnetic interactions between the n-th and m-th grains of the string can be written as

$$U_{n,m} = \frac{Q_n Q_m}{\left|\mathbf{r}_{n,m}\right|}\exp\left(-\frac{\left|\mathbf{r}_{n,m}\right|}{\lambda_D}\right) - \frac{\mu_0}{4\pi}\left[\frac{\mathbf{m}_n\mathbf{m}_m}{\left|\mathbf{r}_{n,m}\right|^3} - 3\frac{(\mathbf{m}_n\cdot\mathbf{r}_{n,m})(\mathbf{m}_m\cdot\mathbf{r}_{n,m})}{\left|\mathbf{r}_{n,m}\right|^5}\right], \quad (12)$$

where the second term in the right-hand side Eq. (12) accounts for interactions of two magnetic dipoles [33], and $\mathbf{r}_{n,m}$ denotes the distance between the grains. The corresponding force acting on the n-th particle is then given by $\mathbf{F}_{n,m} = -\partial U_{n,m}/\partial \mathbf{r}_n$.

The ground-based experiments on complex plasmas have demonstrated that the typical particle separation in dust structures, Δ exceeds the screening length λ_D, giving $\Delta/\lambda_D \sim 1.5 \div 2.5$ [12-16]. The dipole forces are also short-ranged, so that we can only consider the nearest neighbor particle interactions. Taking all this into account, the equation of motion for the n-th particle becomes

$$\ddot{\mathbf{r}}_n + 2\gamma\dot{\mathbf{r}}_n = M^{-1}(\mathbf{F}_{n,n+1} + \mathbf{F}_{n,n-1} + \mathbf{F}_{n,ext}). \qquad (13)$$

Here $\mathbf{F}_{n,n\pm1} = \mathbf{F}(\mathbf{r}_{n,n\pm1} - \mathbf{r}_n)$ and $\mathbf{F}_{n,ext} = -\partial U_{ext}/\partial \mathbf{r}_n$ are the forces acting on the n-th grain in the external magnetic and electric fields. The external potential $U_{ext}(\mathbf{r})$ can be approximated by a parabolic potential in the z-direction, just as in the case of a sheath electric confinement [14], namely

$$U_{ext} = \frac{1}{2}M\left(\Omega_m^2 + \Omega_E^2\right)z^2, \qquad (14)$$

with Ω_m^2 and Ω_E^2 being the vertical characteristic frequencies defined by (11).

Using (12) and (14) and considering only small vertical oscillations, $z \ll \Delta$, around the equilibrium position, $z = 0$, one can find from (13) that the equation of motion in the linear approximation is given by

$$\ddot{z}_n + 2\gamma\dot{z}_n = -\left(\Omega_m^2 + \Omega_E^2\right)z_n +$$

$$+\left(\Omega_\perp^2 + 9\frac{m_0^2}{\Delta^5}\right)(2z_n - z_{n+1} - z_{n-1}) = 0, \qquad (15)$$

where z_n is the vertical displacement of the n-th particle and m_0 stands for the equilibrium magnetic moment of the grains, $m_0 = (\mu - 1)a^3 B_0/(\mu + 2)$. Furthermore, the quantity $\Omega_\perp$ denotes the frequency of the transverse dust-lattice waves [34], namely

$$\Omega_\perp^2 = \frac{Q^2}{M\Delta^3}\exp\left(-\frac{\Delta}{\lambda_D}\right)\times\left(1 + \frac{\Delta}{\lambda_D}\right)$$

Finally, note that to derive (15) we have neglected the small corrections, $\sim (a/\Delta)^3$, associated with variations of the magnetic moments over the scales of the particle displacement around the equilibrium position and added the phenomenological friction $2\gamma\dot{z}_n$, proportional to the particle velocity.

Provided that z_n varies as $\sim \exp(-i\omega t + ikn\Delta)$, Eq. (15) gives a dispersion relation describing transverse dust lattice waves in the external electric and magnetic fields:

$$\omega^2 + 2i\gamma\omega = \Omega_m^2 + \Omega_E^2 - \left(\Omega_\perp^2 + 9\frac{m_0^2}{\Delta^5}\right)\sin^2\frac{k\Delta}{2}. \qquad (16)$$

If $\Omega_m^2 + \Omega_E^2 > 0$, then (16) is similar to the dispersion dependence for the vertical vibrational mode found in the sheath region [14]: the wave is characterized by the optical phonon dispersion in the long-wavelength range (the maximum frequency is achieved at $k = 0$, then the frequency decreases with the growing wavenumber k). The main difference is in the increase of the total characteristic frequency of vertical vibrations $\Omega_v^2 = \Omega_m^2 + \Omega_E^2$ for positive Ω_m^2 or its decrease if $\Omega_m^2 < 0$. It is even possible for Ω_v^2 to become negative $\left(\Omega_E^2 < \left|\Omega_m^2\right|\right)$, and then the vertical mode reveals instability due to the magnetic interaction. An opposite situation is also possible, when the magnetic term Ω_m^2 exceeds the absolute value of negative Ω_E^2 and thus plays the stabilizing role.

When a particle levitates mainly due to the magnetic force (7) outside the sheath region, $\Omega_E^2 \to 0$, and then the electrostatic interaction of dust charges are given simply by the term proportional to $\Omega_\perp^2$ in (16) describing a vertical dust-lattice mode.

Finally, note that just as in the case of vertical vibration of a single particle, the measurements of the wave dispersion $\omega(k)$ corresponding to (16) allow to estimate some important complex plasma parameters: an equilibrium charge in the pre-sheath or bulk plasmas (via determining $\Omega_\perp$), magnetic moment of the grain (magnetic permeability), or even the vertical profile of (QE) (by estimation of Ω_E^2 at different values of the magnetic field).

4. Conclusions

We have demonstrated the possibility of a novel type of vertical vibrations of a single magnetized particle in discharge plasmas when an external magnetic field is applied. Such vibrations can be stable or unstable, depending on the magnetic field distribution inside the particle cloud. Moreover, it is shown that the vertical oscillations of a one-dimensional string of grains supported by the magnetic force give rise to a new low-frequency mode, which is characterized by the optical-phonon dispersion when the wavelength far exceeds the intergrain distance. The identification of a vertical mode can provide a tool for determining the electric field profile, particle charge or magnetic moment of the grains. The characteristics of the mode are specified by the gradients of the external magnetic field and thus can be effectively controlled under experimental conditions. This opens new possibilities for the investigation of the particle behavior at the kinetic level as well as for stimulating phase transition in the system, and for the study of self-organized structures in the experiments.

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Осцилляции намагниченных частиц в пылевой плазме

В. В. Ярошенко, А. А. Минаков

Исследованы вертикальные осцилляции одиночной намагниченной заряженной пылевой частицы, а также цепочки намагниченных частиц, находящихся в газовом разряде и во внешнем почти вертикальном магнитном поле. Показано, что сила, связанная с градиентом магнитного поля, приводит к новому типу осцилляций одиночной частицы. Эти осцилляции могут быть как устойчивыми, так и неустойчивыми в зависимости от распределения магнитного поля внутри газоразрядной камеры. Магнитная сила, действующая на одномерную цепочку пылинок, вызывает появление новой низкочастотной моды с дисперсией, аналогичной оптической фононной ветви колебаний в длинноволновом диапазоне. Обсуждаются возможности использования вертикальных осцилляций намагниченных пылевых частиц для определения параметров комплексной плазмы.

Осциляції намагнічених частинок в пиловій плазмі

В. В. Ярошенко, А. О. Мінаков

Досліджені вертикальні осциляції поодинокої намагніченої зарядженої пилової частинки та ланцюжка намагнічених частинок, що є в газовому розряді і в зовнішньому майже вертикальному магнітному полі. Показано, що сила, пов'язана з градієнтом магнітного поля, викликає новий тип осциляцій поодинокої частинки. Ці осциляції можуть бути як стійкими, так і нестійкими залежно від розподілу магнітного поля всередині газорозрядної камери. Магнітна сила, що діє на одновимірний ланцюжок пилинок, викликає нову низькочастотну моду з дисперсією, аналогічною оптичній фононній гілці коливань в довгохвильовому діапазоні. Обговорюється можливість використання вертикальних осциляцій намагнічених пилових частинок для визначення параметрів плазми.