Single dust-particle rotation in glow-discharge plasma

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Rotation of a single dust granule (spin) is investigated experimentally in a stratified glow discharge. We employ the technique of measurement of the angular velocity, which is based on coordinate tracing of the light scattered by a hollow transparent particle. The angular velocity measured in the experiment is about 1–2 orders of magnitude higher than observed in previous experiments. We found that the angular velocity depends linearly on the discharge current. The mechanism of rotation of the granule is also described.

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I. INTRODUCTION

Dusty plasmas are complex systems formed by ion-electron plasmas and micrometer-sized particles. Intense fluxes of electrons and ions to the particles and recombination on their surfaces can charge a dust grain up to $10^6 e$, thus resulting in a variety of complex structures (dusty crystals) through particle-particle and particle-ion-electron interactions. Influxes, e.g., the dc of a rf discharge, on one hand, and dissipation due to intense interaction between dust particles and the neutral gas on the other, define a complex plasma as an open dissipative system [1–4].

These structures appear due to *collective* behavior and may disappear in avalanches which are described by power laws typical for self-organized criticality [5] and, more generally, for marginally stable states in plasma [6,7]. Since this complexity has been revealed in experiments [8,9] the area has become an attractive growing field of research.

Besides charging of dust grains the ion-electron fluxes and especially the external force fields effect a variety of motions on the individual, "microscopic" level: translation, oscillation, and rotation. The rotation of a dust grain around its center of inertia (spin), first reported in [10], is important from a number of viewpoints and for various reasons. The grain spin is related to the plasma flux onto the surface of the grain thus, in turn, making it possible to measure the grain's charge by contactless optical techniques [11]. Further, a charged spinning particle possesses a magnetic moment, so there exists the possibility of studying the magnetic properties of the dust component. Inner magnetization of the material of the grains modifies the dynamics significantly and leads to new phenomena on the individual and collective levels of dusty plasma behavior, e.g., it modifies the conditions of levitation, affects agglomeration of particles in an external magnetic field [12], etc. Under certain conditions the total spin momentum of all dust particles, S, may exceed the impulse momentum L of the entire dust structure rotating in a magnetic field [11]. Therefore, spin accounting is necessary for proper understanding of complex plasmas behavior in the presence of an external magnetic field [13–20].

After dust particle spin was revealed in experiments [10,21,22], various theoretical models were suggested. These models involve different mechanisms, like the shear of the ion flow velocity in the plasma sheath which cause self-rotation and subsequent formation of a particle magnetic dipole moment [23], ion gyromotion [24], dust shape asymmetry together with plasma charging flux; inhomogeneity of the ion attachment coefficient at the grain surface [25,26]; and spontaneous breaking of the symmetry caused by asymmetric charging in a flow [27]. However, it is difficult to verify these models experimentally. In the experiments reported in [10], rotation of spherical particles of 30–35 μm diameter with angular frequency 40–80 Hz was detected by a high-speed motion detector. The complications of detection of rotation are stressed in subsequent reports, and it was also pointed out that spin was observable due to the nonspherical shape of the grains [21,28]. In [22] the standard registration for fiberlike particles is used, and the particle motion appears to be a rotation with frequency 20–30 Hz. Therefore, more elaborate experiments, which take into consideration physical details (power input, pressure, particle characteristics, and asymmetry of discharge flows), are required.

The main subject of this paper is an experimental study of the mechanism responsible for the appearance of spin of a single dust grain. The experiment is performed in a stratified glow discharge, and the plasma parameters are typical for such experiments and measurements: the plasma density is 10^{14}–10^{15} m^{-3}; the electron temperature (average electron energy) is about 3–4 eV; the longitudinal electric field is 10–20 V/cm (for Ne the pressure is 0.2–1.0 Torr and the discharge current is in the range of 1–5 mA). A single particle is injected into the stratum during experiments and therefore the plasma fluxes on the injected grain are not affected by nearby particles in the measurements. Since optical methods of observation require rather large particle sizes, we used hollow transparent glass microspheres. The size distribution of grains levitating in the strata was examined before the measurements. The experiments show that it is possible to observe the spin of such particles without using a high-speed video camera. The suggested method employs coordinate tracing of light reflected by spinning particle.

The results obtained are as follows: (1) single particle spin in stratified glow discharge is detected; (2) the spin frequency magnitude appears to be larger than registered in [10,22]; (3) the spin depends on the individual features of the particle as well as on the discharge current. The results obtained allow to establish the physical mechanism of spin. Quantitative estimations are presented.

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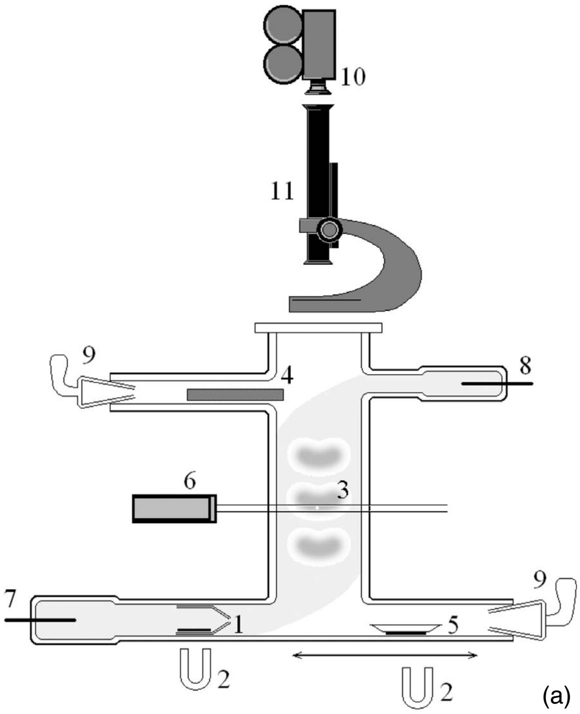

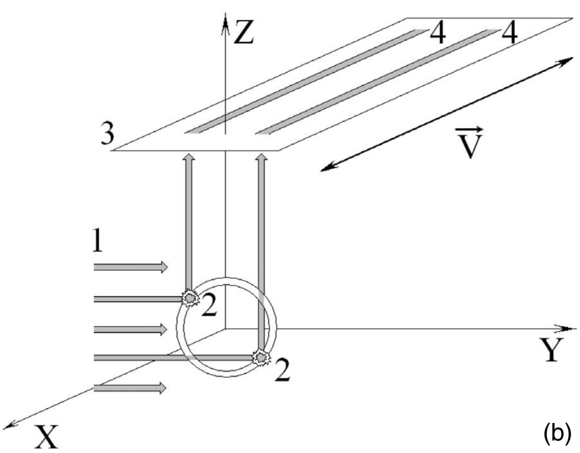

FIG. 1. (a) Experimental setup. (1) movable diaphragm, (2) magnet, (3) stratum, (4) container with microspheres, (5) dust collector, (6) laser, (7) cathode, (8) anode, (9) vacuum ports, (10) video camera, and (11) microscope. (b) Formation of coordinate tracing. (1) laser beam, (2) particle surface areas scattering light to optical system, (3) charge-coupled device (CCD) matrix, (4) image of moving particle on the CCD matrix. Arrow shows the direction of CCD matrix shift.

II. EXPERIMENT

The discharge chamber for extraction of levitating particles from the discharge is presented in Fig. 1(a). The vertical tube of the chamber had a length of 10 cm and a radius of 1 cm. A narrow diaphragm was placed in the left bottom horizontal appendix of the chamber. It was possible to control the stratum position by replacement of the diaphragm. The container with particles was situated in the upper horizontal appendix. When the chosen stratum had the right vertical position, the levitating particles were observed through

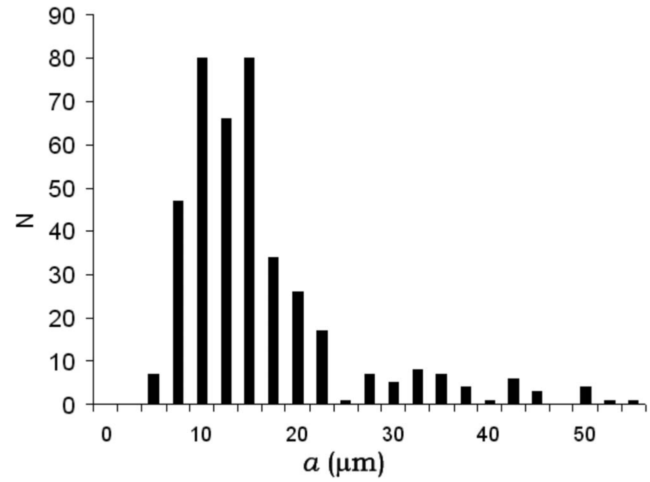

FIG. 2. Particle size distribution. Conditions: air, $p=0.2$ Torr, $i=1$ mA, and a is the radius of the 402 particles sphere.

a microscope which was situated above the end window of tube.

The device consisted of a carriage and glass plate (placed on the carriage) for collection and extraction of the particles from the discharge, placed in the right bottom horizontal appendix. The carriage was driven by a permanent magnet. After switching on the discharge and injecting the dust particle the device was moved under the vertical tube. Then the stratum was pulled down and the discharge was switched off. The process of dust particle collection was monitored by video camera. Then the size distribution of the extracted particles was obtained. In more detail this technique is described in [29]. So the particle levitation conditions in neon, air, and their mixes were determined.

Direct optical observation requires application of particles with size not less than 15 μm. Hollow glass microspheres with density 0.1–0.4 g/cm^3 and radii from 5 to 60 μm were used. The sample of particle size distribution is shown in Fig. 2. One can see that particles of the necessary sizes were present in our conditions.

The granule levitating in the stratum was observed by means of a microscope in transmitted light. Its size and shape were determined. Video shooting with frame rate up to 60 frames/s revealed that only a small part of the particles had a frequency of rotation less than 60 Hz. In addition, there are particles which start to rotate when the discharge current exceeds a value of 2.5–3 mA.

The majority of particles rotate with higher frequencies. In order to detect these frequencies the coordinate tracing technique was applied. The principle of coordinate tracing is shown in Fig. 1(b) [30]. When the registering system (a microscope and a video camera rigidly connected) is moving, a temporal tracing of the scattered light is developed on a CCD matrix. Let us accept the direction of illuminating light along the y axis; the direction of the registered scattered light along the z axis; and the direction of the motion of the registering system along the x axis [see Fig. 1(b)]. The image on the CCD matrix of a stationary transparent hollow spherical particle (in a parallel laser beam) is two spots. The image of an onward-moving particle is two strips. The distance between

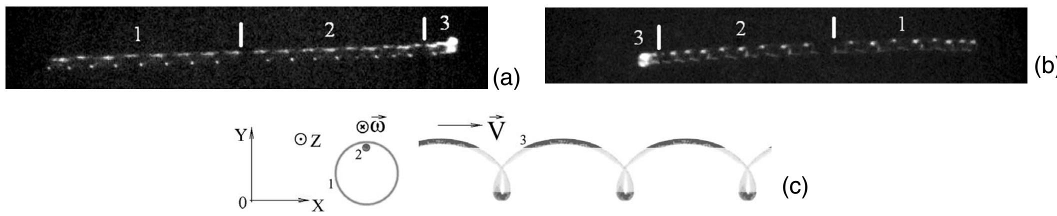

FIG. 3. (a), (b) Examples of coordinate tracing. Images of three consecutive frames. Gaps in a trajectory are caused by "dead time" between frames. (a) Image of particle moves from the left to the right. (b) Image of particle moves from the right to the left. Conditions: Ne, $p=0.7$ Torr, $i=1.5$ mA. Horizontal size of both images is 1.1 mm. (c) Explanatory sketch for (a): (1) particle surface, (2) defect, and (3) resulting trajectory (cycloid).

the strips is less than a particle diameter, so they can be detailed by observation with rather good optical magnification (50-fold and more). Thin-walled glass spheres have surface defects that scatter the laser light more intensely. The scattered light is modulated with frequency equal to the frequency of particle rotation.

Depending on the relative direction of illumination, the particle's angular velocity vector, and the optical system shift various structures of the strips appear in the tracing signal. A sample of the signal structure for the case of perpendicularly oriented spin, illumination, and tracing direction is presented in Fig. 3. Figure 3(a) shows three consecutive frames corresponding to particle movement from the left to the right with respect to the registering system. The following structure of the track is observed: the top strip is a set of sections, while the bottom strip is a set of points. The change of shift direction causes interchange of the positions of the drawings on strips [Fig. 3(b)]. The explanation of this observation is presented in Fig. 3(c). The movement of a defect point is a superposition of its rotation and onward movement with respect to the registering system (the particle angular velocity is along the z axis). The track is a cycloid. The real photos [Figs. 3(a) and 3(b)] show only sites occurring in the lighted strips (i.e., a set of sections and points).

Registration of rotational diffusion by modulation of the particle reflectivity is used in experiments with aerosols [31]. Coordinate tracing combined with use of transparent hollow microspheres allows us to determine the value of angular velocity and its direction. The registration system we constructed allows us to process a modulated signal with modulation frequency up to 2 kHz. To the best of our knowledge this technique of coordinate tracing is presented here for the first time.

III. RESULTS

The spin of a single dust particle was registered in a stratified glow discharge in the following conditions: current 1–4 mA; pressure 0.3–0.7 Torr; gases, Ne, air, and their mixtures. During the measurements there was only one particle in the stratum. The spin has the following properties.

(1) Each particle has its own angular velocity $\boldsymbol{\omega}$. Equal-sized particles may have different ω. Angular velocity values of different particles in the same conditions are between 0 and 12 000 rad/s. They exceed the values of velocities discovered before [10,22]. Particles with a nonspherical shape as a rule have greater frequencies.

(2) The magnitude of the angular velocity of each particle does not change with time in invariable conditions.

(3) The angular velocity does not depend on the position of the particle in the horizontal section. At equilibrium the single particle settles down in the center of the horizontal section of the stratum. We displaced particles from the center to one-half of the tube radius by means of the thermophoretic force [2,4].

(4) The value of the angular velocity increases as the discharge current grows. In Fig. 4 traces of the scattered light of a single particle are presented for current ranging from 1 up to 4 mA. The increase of the number of spots from 11 to 19 means that the angular velocity grows from 1980 to 3420 rad/s. The angular velocity depends linearly on the discharge current (in the range of current 1–4 mA the increase of the velocity is proportional to the increase of the current):

$$\Delta\omega = K\Delta i. \tag{1}$$

This dependence is measured for 30 particles and is presented for 11 grains in Fig. 5(a). The dependence of K on

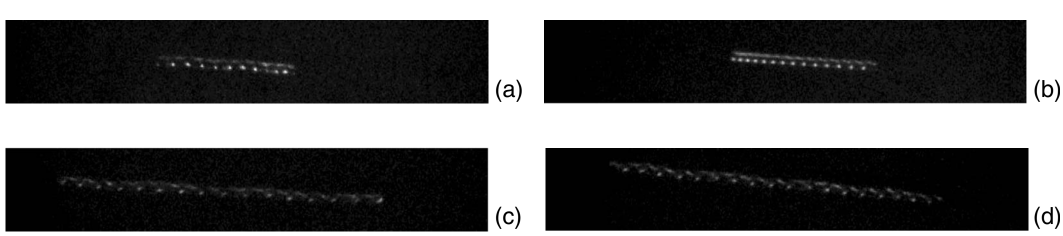

FIG. 4. Coordinate tracing of one particle for different discharge currents. The frame duration is 33 ms. Horizontal size of images is 450 μm. The form of the particle surface is close to a sphere with radius $a=15$ μm. Conditions: Ne, $p=0.7$ Torr. The immovable particle is highlighted by a laser beam perpendicular to the observation direction (vertical in figure). Optical system is moving to the left. Scattered light modulation appears on the tracks: (a) $i=1$ mA, 11 modulation periods, (b) $i=2$ mA, 14 modulation periods, (c) $i=3$ mA, 16 modulation periods, and (d) $i=4$ mA, 19 modulation periods.

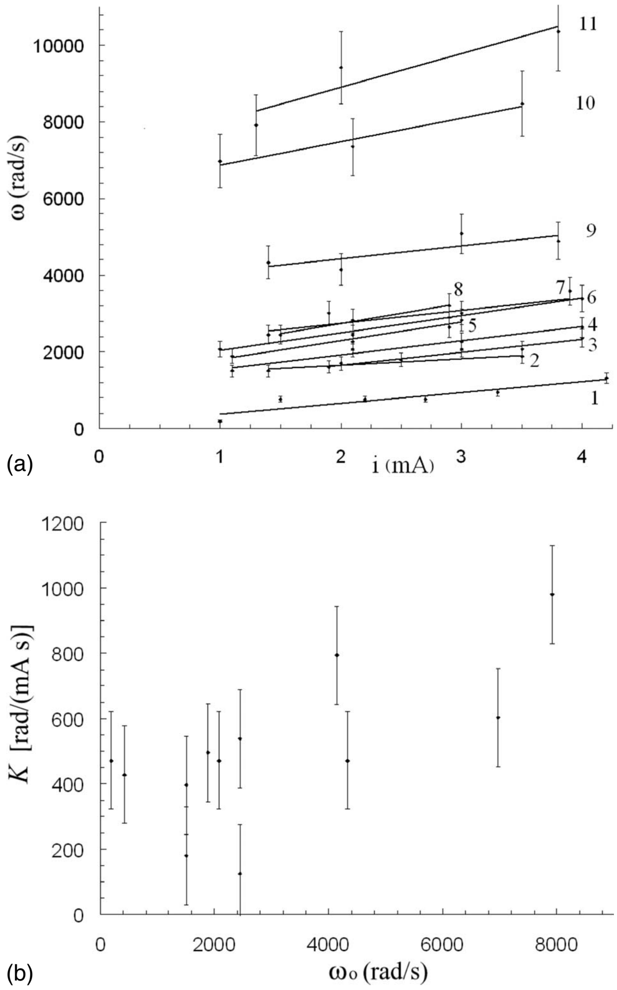

FIG. 5. (a) Dependence of angular velocity on discharge current for several particles (1–11). Conditions: Ne, $p=0.7$ Torr. 10% error is caused by dead time between frames. (b) Dependence of coefficient K on frequency ω_0 at $i=1.5$ mA for particles of (a).

angular velocity for different particles at fixed current is presented in Fig. 5(b).

(5) No definite direction of particle rotation $\boldsymbol{\omega}$ was detected. The direction of the angular velocity for the majority of particles does not change with time though. It was found, however, that the direction of rotation for some particles may change when the angular velocity $\boldsymbol{\Omega}$ is significantly smaller than $\boldsymbol{\omega}$; the ratio Ω/ω is 0.01–0.1. The shape of these particles deviates from a sphere to an oblong ellipsoid. Their symmetry axes are in the horizontal plane. Rapid rotation with frequency $\boldsymbol{\omega}$ occurs around these axes. The symmetry axes rotate slowly with frequency $\boldsymbol{\Omega}$ around the vertical axis clockwise or counterclockwise for different particles. For an oblong ellipsoid, the traces show additional light modulation. Variation of the track width is shown in Fig. 6.

IV. DISCUSSION

The measured quantitative dependencies and qualitative relations listed in items 1–3 of Sec. III allow us to discuss the possible reasons for grain rotation in the glow discharge. The

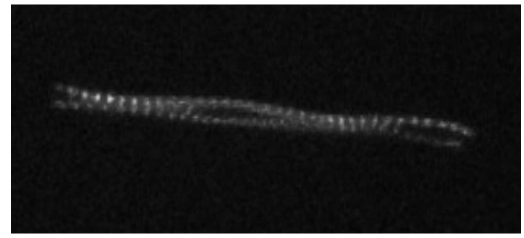

FIG. 6. Coordinate tracing for oblong ellipsoid shaped particle; ellipsoid axis ratio is 1:2. Particle rotates with frequencies $\omega=6600$ rad/s and $\Omega=190$ rad/s. Conditions: Ne, $p=0.7$ Torr, $i=2.5$ mA. Horizontal size of images is 190 μm.

relation between the angular velocity and peculiarities of the individual particle (item 1, Sec. III) shows the importance of the plasma flux interaction with its surface. Probably, the tangential component of the impulse of the plasma flux falling on an asymmetrical particle causes it to spin. A model that takes into account the asymmetry of particle shape is proposed in [25], but the conditions for other models [23,24,26,27], in our opinion, are different from the conditions of the experiments presented here.

For illustration one can consider an almost spherical grain. We associate the existence of its rotation with a nonzero impulse moment M_{id} [32] transmitted by positive ions encountering its surface per unit time in the process of stationary particle charge support. Probably this moment arises due to the existence of a tangential component in the ion flow toward the particle. The appearance of the tangential component may be caused by the presence of defect areas on the particle surface. A similar electron flux effect (electron drag) is negligible. Let us define the coefficient η as the relation of the tangential component to the full ion flow; thus it specifies the ion flux tangential component. Stationarity of the spin indicates the compensation of M_{id} by the moment of the neutral drag force M_{fr} [33] under the assumption that the neutral gas is considered immovable [18,19]. Setting M_{id} equal to M_{fr} for a particle with angular velocity ω and radius a gives

$$\omega = \frac{9\eta e q_d n_i}{2\pi\varepsilon_0 \rho_n V_{T_n} a^2}, \tag{2}$$

where n_i is the ion concentration, q_d is the dust grain charge, ρ_n is the gas density, V_{T_n} is the thermal gas velocity, e is the elementary charge, and ε_0 is the dielectric constant. This formula is valid in a limited range of the current.

Using Eq. (2) let us estimate the angular velocity ω. We take the particle no. 4 in Fig. 5(a) whose radius is $a=10$ μm, so the angular velocity is $\omega=2000$ rad/s at current 2 mA. For particles with radius $a=10$ μm one can take $q_d=3\times10^5 e$ from [34] where the conditions were the same. At $n_i=5\times10^{14}$ m^{-3} and corresponding ρ_n and V_{T_n}, ω is $19\,800\eta$ rad/s. This estimation agrees with experimentally measured values of ω under the assumption that $\eta\approx0.1$.

The linear dependence of ω on i can be explained as well. As Eq. (2) shows, the angular velocity grows as q_d and/or n_i increases. The coefficient η is a constant for a grain and does not depend on the discharge current. According to the orbit motion limited theory the charge of the particle depends on the electron temperature T_e [1–4]. T_e varies slightly in our current range [35,36], so the variation of the charge of the particle is negligible. On the contrary, n_i increases with discharge current growth. The dependence of n_i on i in a gas discharge is controlled by many factors and, as far as we understand, is unknown in the entire current interval. However, there is linear dependence in the current range 1–5 mA [35,37], $\Delta i \approx \Delta n_i$. Therefore, using the relation between n_i and i, one can explain the increase of the particle frequency observed experimentally. It is possible to estimate the coefficient of proportionality between ω and i. If we use the value $\eta=0.1$ obtained above the estimation for the particle no. 4 in Fig. 5(a) agrees with the slope ratio $K=4 \times 10^5$ rad/s A.

Finalizing, we conclude that both the absolute value of the angular velocity and its linear dependence on current are in agreement with our hypothesis about the spinning of a single particle by ions.

V. CONCLUSION

An experimental study of the spin of a single dust granule in a stratified glow discharge has been carried out. The technique of angular velocity measurement by means of coordinate tracing of light scattered by a hollow transparent particle is used.

The technique allows us to define both the magnitude and direction of a angular velocity of single particle. It does not require high optical magnification and therefore is convenient when the distance from the object to the optical system is not very small.

The registered angular velocity turned out about 1–2 orders of magnitude higher than observed in [10,22] and depends on individual peculiarities of the particle. A linear dependence between the angular velocity and the discharge current has been revealed.

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