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Macrospin of the Dust Granule

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The experimental researches of the single dust granule spin in conditions of the stratified glow discharge are carried out. The new technique of the angular velocity measurement by means of the coordinate tracing of light scattered by the hollow transparent particle is offered. The registered angular velocity turned out to be about 1-2 orders higher than the ones observed earlier. It depends on the particle individual peculiarities. The linear law dependence of the angular velocity on discharge current is found out. The mechanism of the single particle rotation is described. The numerical estimations agree with experimental data.

Keywords: complex plasmas, single dust particle, spin motion, macrospin.

1. Introduction

Dusty plasmas have become progressive field of research after the dust crystals had been discovered in the experiments [1,2]. The dusty (complex) plasma [3-6] is open dissipative system. Large charge (up to 10^6 e) of each dust grain is caused by intensive fluxes of electrons and ions recombining on the particle surface. Also dust particles intensively interact with the neutral component in laboratory plasma. This leads to the particle cooling and to attenuation of its movement. Both external force fields and plasma particles fluxes affect the dust grain and cause its onward, oscillatory and rotary movement. The grain rotation (spin) was observed for the first time in [7].

The rotation of the dust grain around its center of inertia is interesting for a number of reasons. First, the spin is connected to the plasma flux onto the dust particle surface. This allows to measure the charge by the contactless optical techniques [8]. Second, the charged spinning particle has a magnetic moment, so there is a possibility for studying of magnetic properties of the dust component. For example, investigations [9] with grains, having intrinsic magnetic moments, have indicated a number of new phenomena: a modification of levitation conditions; a particles agglomeration in an external magnetic field. Third, the spin examination is necessary for the properly understanding of dusty plasma behavior in the external magnetic field [10-17]. Under certain conditions the total spin momentum of all dust particles S may exceed the impulse momentum L of dust structure rotating in the magnetic field [8]. In addition, this problem has the astrophysical applications.

The revealing the spin of particles in experiments [7,18] and [19] was followed by appearance of the theoretical models of this phenomenon. The models include the magnetic field affection [20,21] or other factors [22-24] as the reasons of rotation. An adequacy of models must be checked experimentally. Such experiments are difficult enough. As authors know, there are only two informative experimental investigations. In [7] the rotation of spherical particles was detected by high-speed motion detector. The particles of 30 – 35 μm diameter rotate with the angular frequency 40 – 80 Hz. In the following reports [18,25] authors denote the complication of detection and point that the rotation was registered due to the non-spherical shape of particles. In [19] a standard registration was applied; the fiber-like particles were used. Their motion was interpreted as rotation with frequency 20 – 30 Hz. To accept the adequate model the additional experimental investigations are demanded. It is necessary do determine the dependence of angular velocity on following factors: plasma conditions (power input, pressure and a kind of gases), particle characteristics, asymmetry of discharge flows.

The investigation of the single particle spin mechanism is a purpose of present work. The researches are carried out in the stratified glow discharge; the plasma parameters are typical for such experiments. During the measurements only one particle is injected in stratum. So the plasma fluxes upon the grain are not affected by other nearest particles. The optical method of observation requires rather large particle sizes. So we applied the hollow transparent glass microspheres. The size distribution of grains levitated in strata has been examined preliminarily. It was found that it is possible to register the spin of such particles without using a high-speed video camera. Suggested method includes the coordinate tracing of light scattered by spinning particle.

We point out next obtained results. The fact of single particle spin in condition of stratified glow discharge was registered. The spin frequency magnitude appears more than one registered in [7,19]. The spin depends on the

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particle individual features and also on the discharge current. Obtained results allow to choose the physical mechanism of spin. The quantitative estimations are given.

2. Experiment

The discharge chamber is presented at Fig. 1(a). The vertical tube of the chamber had length of 10 cm and radius 1 cm. The narrow diaphragm was placed in the left bottom horizontal appendix of the chamber. It was possible to control the stratum position in vertical tube by means of diaphragm replacing. The container with particles was situated in the upper horizontal appendix. When the chosen stratum had right vertical position the levitated particles were observed in microscope which was situated above the end window of tube. Direct optical observation requires application of particles with the size not less than 15 μm. The hollow glass microspheres with density 0.1 – 0.4 g/cm^3 and radii from 5 to 60 μm were used.

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

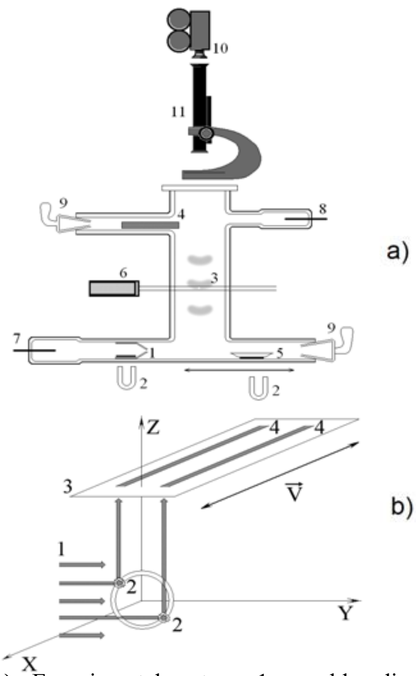

Fig. 1 **(a)** Experimental setup. 1-movable diaphragm, 2-magnet, 3-stratum, 4-container with microspheres, 5-dust collector, 6-laser, 7-cathode, 8-anode, 9-vacuum ports, 10-videocamera, 11-microscope. **(b)** Formation of coordinate tracing. 1-laser beam, 2-particle surface areas scattering light to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

The majority of particles rotates 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) [26,27]. When the registering system (microscope and a video camera rigidly connected) is moving the temporal tracing of scattered light is developed on CCD matrix. Let us accept the direction of illuminating light along y axis; the direction of the registered scattering light along z axis; the direction of the motion of the registering system along x axis, see Fig. 1(b). The image on the CCD-matrix of standing transparent hollow spherical particle (in parallel laser beam) is two spots. The image of onward moving particle is two strips. The distance between them is less than particle diameter, so they can be detailed by observation with rather good optical magnification (50-fold and more). Thin-walled glass spheres have the surface defects scattering the laser light more intensively. The scattered light is modulated with frequency equal the frequency of particle rotation.

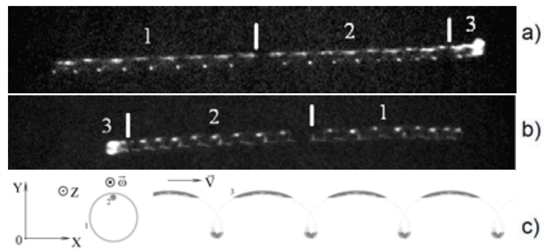

Fig.2: **(a)**, **(b)** examples of coordinate tracing. Images of three consecutive frames. Gaps in a trajectory are caused by "dead time" between frames. **(a)** Image of particle moves from the left to the right. **(b)** Image of particle moves from the right to the left. Conditions: neon, p = 0.7 Torr, i = 1.5mA. Horizontal size of both images is 1.1 mm. **(c)** explaining sketch for **Fig.2(a,b)**; 1-particle surface, 2-defect, 3-result trajectory (cycloid).

Depending on a relative direction of the illumination, the particle angular velocity vector and the optical system shift, the various structure of strips appears on tracing signal. The sample of signal structure for a case of perpendicularly oriented spin, illumination and tracing direction is shown in Fig. 2. Fig. 2(a) shows three consecutive frames corresponding to the particle movement from the left to the right relative to registering system. The following structure of the track is observed: the top strip is a set of sections, while bottom strip is a set of points. The change of shift direction causes interchanging the position of drawings on strips (Fig. 2(b)). The explanation of this observation is presented in Fig. 2(c). The movement of the defect point is the superposition of its rotation and onward movement relatively to registering system (the vector of particle angular velocity is directed on axis *z*). The track has a cycloid shape. Real photos (Fig. 2(a) and 2(b)) show only sites, occurred in the lighted strips (i.e. a set of sections and points).

The registration of rotation diffusion by the modulation of particle shine is used in researches of aerosols [28]. The application of coordinate tracing and the using of transparent hollow microspheres allow to determine both the magnitude and the direction of angular velocity. Probably the coordinate tracing technique is presented for the first time.

The used registration system allows to write down a signal of modulation with the frequency up to 2 kHz.

3. Results

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

1. Each particle has its own angular velocity ω. Equal sized particles may have different ω. Angular velocities values of different particles in the same conditions are between 0 and 12000 rad/s. They exceed values of velocities discovered before [7,19]. Particles with a shape differing from sphere as a rule have greater frequencies.

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

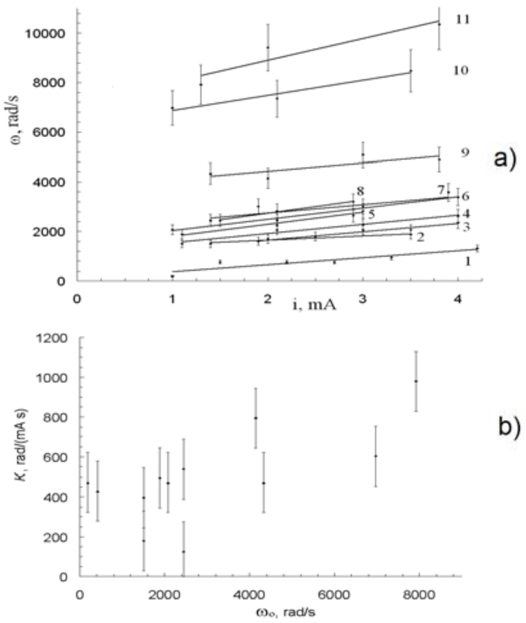

Fig. 3: (a) Dependence of angular velocity on discharge current for several particles (1 – 11). Conditions: neon, p = 0.7 Torr. Percentage error of 10% is caused by "dead time" between frames. (b) Dependence of coefficient K on frequency ω_0 at i=1.5 mA for particles of Fig. 3(a).

3. The angular velocity does not depend on position of particle in a horizontal section. At equilibrium the single particle settles down in the center of horizontal section of stratum. We displaced particles from the center to a half of tube radius by means of thermophoretic force [4, 6].

4. The value of angular velocity increases with discharge current rise. The dependence of angular velocity on discharge current has linear character,

$$\Delta\omega = K \cdot \Delta i \qquad (1)$$

This dependence was measured for 30 particles and is presented for 11 grains at Fig. 3(a). The coefficient *K* dependence on angular velocity for different particles (current was fixed) is presented at Fig. 3(b).

5. No definite direction of particle rotation ω was found. The direction of the angular velocity for the majority of particles does not change with a time. It was revealed however that rotational direction of some particles could turn with angular velocity **Ω** which is essentially smaller than ω; the relation Ω/ω is 0.01–0.1. These particles have the shape deviated from the sphere (oblong ellipsoid). Their figure axes are oriented in the horizontal plate. The rapid rotation (with frequency ω) occurs around these axes.

4. Discussion

Both measured quantitative dependences and qualitative regularities allow to discuss the possible reasons of grain rotation in the glow discharge. The connection of angular velocity with individual particle peculiarities (point 1 in Section 3) means the importance of plasma flux interaction with its surface. Probably, tangential component of impulse of plasma flux falling on asymmetrical particle spins up the grain. Such a model, including particle shape asymmetry, has been proposed in [22]. Conditions of applicability of the other models [20,21,23,24] in our opinion are distinct from conditions of present experiments.

Let us consider almost spherical grain. We associate existence of its rotation with nonzero impulse moment M_{id} [29] transmitted by positive ions encountering its surface per time in the process of stationary particle charge support. Probably this moment arises due to existence of tangential component in the ion flow towards the particle. Appearance of the tangential component could be caused by presence of defect points on the particle surface. Similar electron flux effect (electron drag) is negligible. Let us introduce the coefficient η specifying ion flux tangential component (the relation of tangential component to full ion flow). The stationarity of spin indicates the compensation of M_{id} by moment of neutral drag force M_{fr} [30] (in the assumption of an immovability of neutral gas). Setting M_{id} equal to M_{fr} for the particle with angular velocity ω and radius *a* gives:

$$\omega = \frac{9\eta e n_i q_d}{2\pi\varepsilon_o \rho_n V_{Tn} a^2}, \quad (2)$$

where n_i – ion concentration, q_d – dust grain charge, ρ_n – gas density, V_{Tn} – thermal gas velocity, e – elementary charge, ε_o – dielectric constant in vacuum.

Let us execute an estimation of angular velocity value in accordance with the equation (2). We choose the particle №4 in Fig. 3(a). Its radius is a = 10 μm, angular velocity is 2000 rad/s at current value 2 mA. For particles with radius a = 10 μm one can take $q_d = 3\cdot10^5 e$ from work [31] which was implemented in the same conditions. If $n_i = 5\cdot10^{14}$ m^{-3} then ω value is $19800\cdot\eta$ rad/s. This estimation agrees with experimentally measured values of ω in assumption $\eta \approx 0.1$.

The linear law dependence ω on i could be interpreted too. The equation (2) shows the angular velocity growth with q_d and n_i increasing. Coefficient η has constant value for each grain and does not depend on discharge current. According to the OML-theory particle charge depends on electron temperature T_e [3-6]. T_e slightly varies in our current range in strata [32, 33]. So particle charge variation is negligible. On the contrary, n_i increases with discharge current growth. The dependence n_i on i in gas discharge is controlled by many factors and as far as we understand it is unknown in whole current interval. However, there is linear dependence in current range 1 – 5 mA [32, 34], $\Delta i \sim \Delta n_i$. Using the relation between n_i and i we explain particle frequency increasing observed experimentally. It is possible to estimate the coefficient of proportionality between ω and i. If we use the obtained above value η = 0.1 the estimation for chosen particle (particle №4 on Fig. 3(a)) agrees the slope ratio $K = 4\cdot10^5$ rad/(s·A).

So, both angular velocity absolute value and its linear law dependence on current are in agreement with hypothesis about spinning of single particle by ions.

5. Conclusion

The experimental researches of a single dust granule spin in the conditions of the stratified glow discharge are carried out. The technique of angular velocity measurement by means of coordinate tracing of light scattered by hollow transparent particle is offered. The technique allows to define both magnitude and direction of the angular velocity of the single particle. It does not demand the high optical magnification therefore it is convenient in the case where the distance from object to optical system cannot be small enough. The registered angular velocity has turned out about 1-2 orders higher than ones observed in [7,19]. It depends on particle individual peculiarities. The linear law dependence of angular velocity on a discharge current is found out.

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