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To cite this article: E S Dzlueva *et al* 2019 *J. Phys.: Conf. Ser.* **1421** 012030

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Visualization of plasma fluxes by a measurement of own rotation of a dust particle

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Abstract. A research of own rotation of single dust particle which is in a dust trap in the stratified glow discharge under imposed magnetic field is carried out. It is experimentally shown that in the scale of Debye length an action of azimuthal torque from the fluxes of ions and electrons is mutually compensated; an angular velocity of rotation of dusty particle remains invariable up to magnetic fields of 200 G. The found effect was given theoretical interpretation on a basis of consideration of ambipolar diffusion of positive ions and electrons to the particle surface.

1. Introduction

The visualization of plasma fluxes in low-temperature plasma is a relevant, but difficult problem, in particular, because of low ionization degree of plasma (up to 10^{-7}). So the dusty plasma [1-2] which is intensively developing in the last 20 years offers a new technical capability of the diagnostics. At the same time the dust particle works as "the optical probe", which mechanically responds to action of plasma flows and thereby visualizes them. Having information about the plasma fluxes, it is possible to control actively them in discharge chambers and technological systems. Similar researches in the area of heterogeneous electric field, near walls of discharge chambers as well as in magnetic field are especially relevant.

An own rotation of dust particles around the center of inertia was revealed experimentally by N. Sato [3-4]. So far its detailed research is absent for different discharge conditions and particles of any shape. A lot of information on own rotation of dust particles was given by work [5] in which the method of the coordinate tracing allowing to take effective measurements with transparent spherical particles was offered. The dust particles with a diameter up to 40 microns, which have a charge up to 10^6 electrons on a surface and rotate with angular velocity up to 10^4 rad/s, generate magnet moment up to 10^5 Bohr magnetons and define the magnetic properties of complex plasma [6-7]. Dynamic, structural, electrical and thermodynamic properties of complex plasma are rather well studied now, but magnetic properties after emergence of works [4-7] only begin to be studied.

An observation of own rotation of dust particles is a difficult technical problem which demands a significant optical multiplication and application of video recording with a high speed when the observed dust particle is located in a trap in plasma. Observations show that all dust particles possess own rotation (the magnetic moment). However, this rotation appears as threshold effect depending on magnetic induction and the power input [8-9].



In the present work the dependence of angular velocity of rotation of the single dust particle on magnetic field is discussed. The experiment shows extremely weak change of angular velocity in magnetic field. The physical interpretation of rotation taking into account the fluxes of the electrons and ions going on the dust particle in the course of maintenance of its stationary charge in magnetic field is offered.

2. The scheme of the experiment and the optical registration of rotation

The registration of rotation of dusty particles was made by a coordinate tracing method [5-6] which consists in the following. Spherical transparent hollow glass particles (microspheres with the density of 0.4-0.9 g/cm³ with a diameter of 10-120 μm , wall thickness 1-2 μm) were used. On their surface there are spot defects which scatter the light passing through the particle. The setup described in [5] was applied to creation of complex plasma. Particles were injected in the dust trap one by one. Their illumination was carried out sideways by laser radiation; the video recording was implemented from above by video camera with the CCD matrix with parameters: resolution of 1 megapixel and the frequency up to 240 frames per second. Tracing of the image was carried out by reciprocating motion of the system of optical registration (it consisted of a non-magnetic optical head part of microscope MBS-10 providing the a hundredfold increase rigidly connected with the video camera). Illumination and tracing were made in the horizontal plane in mutually perpendicular directions. The scheme is shown in figure 1.

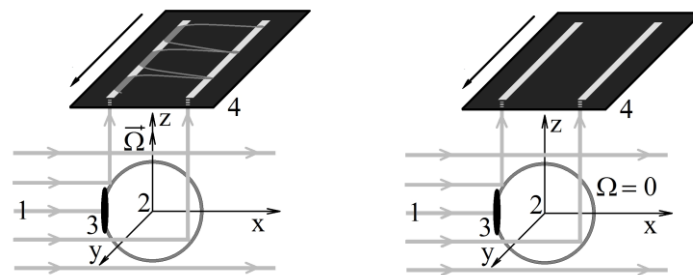


Figure 1. The scheme explaining the method of coordinate tracing. 1 – laser illumination, 2 – transparent particle, 3 – the schematic image of defect on the surface, 4 – the CCD matrix. When the matrix is moved (it is shown by an arrow) and the particle is rotated (it is shown by Ω) the registered signal is a cycloid which parameters depend on characteristics of the movement.

From the obtained results we will give the main one: the extremely weak dependence of angular velocity of own rotation of the particle on vertical magnetic field in the range of 0-200 of G is observed. Examples of dependences for two particles are given in figure 2. The result is of interest because it was expected the fast rotation of dust particles [10-11]. For example in [10], when imposing magnetic field, own rotation of dust particles with an angular velocity up to $\Omega \approx 6 \cdot 10^6 \text{ rad} \cdot \text{s}^{-1}$ was expected.

Without the magnetic field the direction of rotation of the particle and the value of angular velocity are random values. In magnetic field the majority of particles behave similar to atoms of paramagnetic: angular velocity almost does not change, its direction is opposite to vector of magnetic field, and the magnetic moment of a particle is directed along the magnetic field. In some cases the own rotation as function of magnetic field, has threshold character, more detail it was described in [9-10].

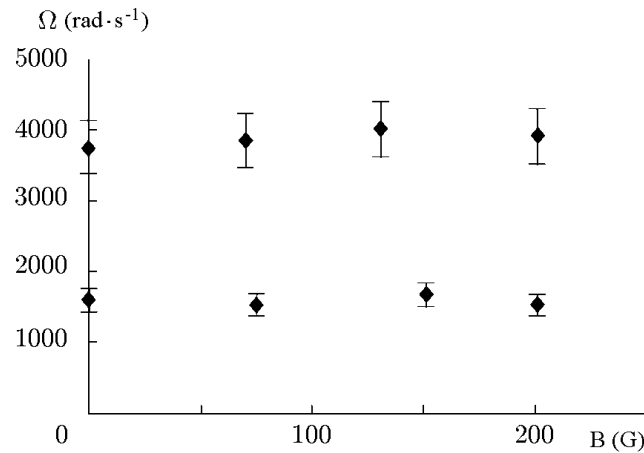


Figure 2. Example of dependence of angular velocity of own rotation on magnetic induction for two particles of spherical shape of 20 microns in size. Conditions: gas neon, pressure is 0.15 Torr, current 1.3 mA.

3. Interpretation of results

In the considered plasma the vertical fluxes of ions and electrons, blowing in the levitated not quite symmetric dust particle, spin it without any magnetic field as windmill blades twist. In this work the dust particles of spherical shape were used. Nevertheless, without magnetic field the considerable angular velocity of rotation up to thousands rad/s were observed. It occurs because the surface charge generally gathers on cambers of the particle and enhances its accidental asymmetry. Probably, also the threshold nature of rotation observed for some particles is explained by asymmetry of electric field of a particle and the field of its environment. In the presented work we are interested only the change of rotation of a dust particle under the influence of external magnetic field. Let's consider fluxes of positive ions and electrons on a particle surface, figure 3.

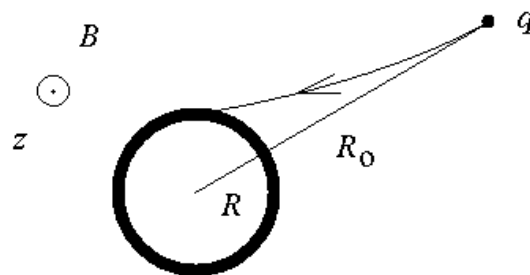


Figure 3. Illustration of the movement of the positive ion to the dust particle in magnetic field.

To simplify the analysis, we will consider that nothing depends on vertical coordinate; therefore we will consider a task only in coordinates of the horizontal plane, and we will look for only a vertical component of angular velocity of particle rotation. Let's consider the movement of the positive ion to the surface of the dust particle with zero starting velocity. In vertical magnetic field the positively charged ion gets the angular momentum in the system connected with the center of the particle. At a collision with the particle this angular momentum is transferred to the particle and twists it. Let r is the distance from the ion to the center of the particle; φ is a corner between the initial direction on the ion from the center of the particle and the current direction on the ion. The projection of ion velocity to the

direction to the center of the particle is $V_{-r} = -\frac{dr}{dt} > 0$. Let's present the ion velocity as the sum of two components $\vec{V} = \vec{V}_{-r} + \vec{V}_{\phi}$; two components of Lorentz force correspond to them: $F_{\phi} = qV_{-r}B$ and $F_{-r} = -qV_{\phi}B$. The second component of the force slows down the movement of the ion to the particle, but it will not interest us as the moment of this force is equal to zero. Moment of force $F_{\phi} = qV_{-r}B$ is equal

$$M = M_z = F_{\phi}r = qV_{-r}Br = -qB\frac{dr}{dt}r.$$

The angular momentum is connected with it:

$$L = L_z = \int M_z dt = -qB \int \frac{dr}{dt} r dt = -qB \int r dr.$$

Limits of integration are defined by initial removal of the ion from the center of the particle R_0 and final removal equal to particle radius R :

$$L = L_z = -qB \int_{R_0}^R r dr = \frac{qB}{2} (R_0^2 - R^2).$$

This angular momentum twists the dust particle.

We found the angular momentum transferred to the particle by one positive ion. Now we will consider the continuous flux of positive ions on the particle surface, this flux is connected with ambipolar diffusion. The angular momentum transferred in unit of time is equal to the moment of forces:

$$M = M_z = \frac{dL_z}{dt} = \frac{d}{dt} \left\{ \frac{qB}{2} (R_0^2 - R^2) \right\} = \frac{B}{2} (R_0^2 - R^2) \frac{dq}{dt} = \frac{B}{2} (R_0^2 - R^2) I,$$

here I is the current of positive ions on the particle surface. As a result, the moment of forces acting on the particle from positive ions does not depend on weight, it is defined by the current I of these ions

$$M = \frac{B}{2} (R_0^2 - R^2) I.$$

In the given consideration we considered that the initial velocity of the charge moving to the dust particle is equal to zero. It is quite fair for positive ions, but it is not fair for electrons. The matter is that electrons are slowing down at the movement to the negatively charged particle therefore their initial velocity is obviously other than zero. The movement of electrons with different initial values of impact parameter will be, as shown in figure 4.

Different electrons untwist the dust particle in different directions, and on average the electrons untwist the particle a little. For an electron at its movement to the particle the same expressions for the Lorentz force, moment of force and change of the angular momentum of the particle, are the same as for the positive ion, only the charge and sizes proportional to it will change the sign. Respectively, change of the angular momentum of an electron during its movement will be equal to the same value on the module

$$\Delta L = \Delta L_z = -\frac{q}{c} B \int_{R_0}^R r dr = \frac{qB}{2c} (R_0^2 - R^2) = -\frac{eB}{2c} (R_0^2 - R^2).$$

If to consider the electron which hits in the particle perpendicular to its surface (that is the final angular momentum of the electron relatively to vertical axis passing through the center of the particle is equal to zero), then the initial angular momentum of an electron:

$$L_0 = \frac{eB}{2c}(R_0^2 - R^2).$$

Thus, the average initial angular momentum of the electrons reaching the particle surface is approximately equal $L_0 = \frac{eB}{2c}(R_0^2 - R^2)$.

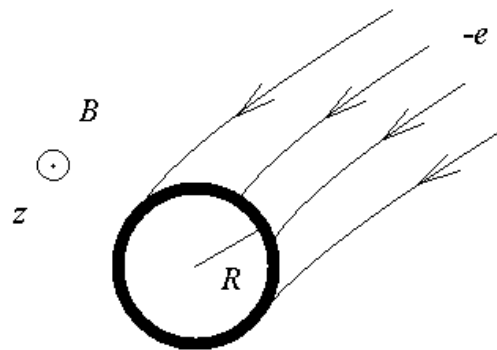


Figure 4. Illustration of the movement of electrons to the dust particle in magnetic field.

Electrons on sufficient removal of R_0 from the particle have isotropic distribution of velocities in the horizontal plane and the zero average angular momentum relatively the particle. A part of electrons with the angular momentum $L_0 = \frac{eB}{2c}(R_0^2 - R^2)$ then sticks to the dust particle and drops out of consideration of the remained electrons. As a result, in a layer of electrons at a distance of R_0 from the particle from each vanishing electron not compensated angular momentum $-L_0 = \frac{eB}{2c}(R_0^2 - R^2)$ is formed. Not compensated angular momentum which is formed in unit of time is equal to the moment of forces

$$M = \frac{B}{2c}(R_0^2 - R^2)I,$$

which in accuracy coincides with the moment of forces acting on the particle from current of positive ions, but differs in the sign because of other sign of current I .

It is possible to assume that the flux of positive ions twists the dust particle; and the flux of electrons twists in the counter direction not the particle, but the gas surrounding it at some distance R_0 from the center of the particle. As a result, the particle has to rotate under the influence of the flux of positive ions, but in an experiment it is not observed. The matter is that positive ions begin the movement not with zero initial velocity as it was considered above, and with some accidental dispersion of initial velocities. As a result of this dispersion the flux of positive ions on the dust particle is similar to figure 4 for electrons, but only with a deviation to the opposite side. Further reasoning for the flux of positive ions is similar to reasoning for the flux of negative electrons. As a result, both fluxes twist not the particle, but the plasma surrounding it in the counter directions, and the twisting of the particle is weak.

Thus, Ampere force acts on the current, flowing to the surface of the dust particle in vertical magnetic field and twist a mote and the plasma surrounding it. At ambipolar diffusion current of positive ions and current of negative electrons on the surface of the mote are equal on the module. Respectively, two Ampere forces untwist not the mote, but surrounding it plasma, with an identical force in the counter directions. Total current of ambipolar diffusion is equal to zero therefore the total moment of forces acting on this current is equal to zero. As a result, the rotation of the mote observed in an experiment is not enough.

4. Conclusion

It is experimentally shown that in the scale of Debye length the action of the azimuthal moments of forces from fluxes of ions and electrons is mutually compensated, the angular velocity of rotation of the dust particle remains almost invariable up to magnetic fields in 200 G. Experiments were carried out in the glow discharge in the neon in the stratified mode. Hollow transparent particles about 20 μm in the diameter were used. The original method of coordinate tracing was applied to diagnostics of their own rotation.

The found effect of extremely weak dependence of angular velocity of rotation of the dust particle on magnetic field was given the theoretical interpretation on the basis of consideration of ambipolar diffusion of positive ions and electrons on the particle surface. In magnetic field the charges at the movement to the surface of the particle get the angular momentum. It is given to the particle and the plasma surrounding it and does not depend on the mass of charged particles of the flux. Respectively, the angular momentum of the flux of ions is generally compensated by the angular momentum of the flux of electrons.

Acknowledgments

The work was supported by RFBR, grant № 18-02-00113. The equipment and materials used were partially acquired through the program of the Development of the Material and Technical Base of Saint-Petersburg State University.

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