DUSTY-PLASMA CRYSTALS AND INTERACTION OF DUSTY PARTICLES IN A MAGNETIC FIELD

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Ordered structures and interaction of macroparticles are considered in low-temperature plasma of the gas discharge. Special emphasis is placed on a new class of phenomena in the dusty-plasma system, arising in a magnetic field.

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The present paper is dedicated to a novel line of inquiry, that is "dusty plasma" physics (see [1-3]). The dusty plasma represents low-temperature plasma containing macroparticles or, put very simply, motes. Dusty-plasma gas clouds axe widely abundant in space: dusty interstellar clouds and nebulas, cometary tails, dusty shells of stars, etc. The dusty plasma is of great cosmogonic importance. For instance, according to the contemporary viewpoint, clusters and associations of young stars are formed by the compression of gas-dusty clouds. Another example of the dusty plasma is rarefied low-temperature plasma consisting of neutral gas, micrometer particles (referred to as dusty ones), ions, and electrons. Although further we discuss just such plasma, many properties revealed in it can be applied to the space dusty plasma.

Typical parameters of the dusty plasma studied in terrestrial conditions are the following: pressure about 1 Torr and room temperature in the low-pressure discharge as well as pressure about 10^3 Torr and temperature from 1700 to 2600 $\boldsymbol{K}$ in thermal plasma. Ionization of the latter is insignificant, of order 10^{-7}. Dusty particles introduced into plasma become charged and collect ions and electrons. The particle charge can be extremely high and, depending on the mote sizes, reaches hundreds or thousands of electron charges for micrometer particles. The role of dusty particles in atmospheric phenomena can be played, for instance, by water droplets in thunderstorm clouds. The high charge of dusty particles causes strong interaction between them and with plasma particles. Recent studies showed such an interaction to change substantially dusty plasma properties. One of the clearest confirmations of that is discovery of the dusty-plasma crystal. Conditions of probable dusty plasma crystallization were theoretically formulated by Ikezi. However, almost ten years had passed, before the "plasma" crystal was observed in the high-frequency discharge plasma. This ordered structure is formed in a radiofrequency discharge near a lower electrode at the space charge boundary. The plasma crystal lattice constant amounts to a fraction of a millimeter, which allows its observation by the unaided eye. Figure 1 sketches the experimental setup for studying ordered structures in the gas-discharge plasma.

Plasma crystals have a variety of unique properties making them an irreplaceable tool when studying strongly nonideal plasma and fundamental properties of the crystals. Observation of self-organized dusty structures offers a new line of inquiry, which can be evidently referred to as a "superchemistry" or a physics of "super-condensed" medium where the roles of atoms and simplest molecules are played respectively by dusty particles and their bound states.

Therefore, of paramount interest are forces causing the interaction between motes. First, one should answer the question of what forces cause identically charged motes to attract each other, thus forming a bound system of the dusty molecule or the dusty crystal.

To understand the effect, it is very important to realize that the problem depends on experimental conditions. All experiments with dusty plasma were carried out in terrestrial conditions when three basic forces contribute to the interaction: electrostatic, gravity, and "ionic". In the simplest case, when the discharge is formed between two horizontal electrodes, the cloud of dusty particles is confined by the space charge near the negative electrode where gravity and electrostatic forces are balanced (see Fig. 2). Thus, only two forces contribute to the interaction of dusty particles: electrostatic repulsion and gravity forces. In this case, dusty particles can be considered to be in an electrostatic trap: the electrode repulsive field confines them from below, while horizontal spreading is prevented by the

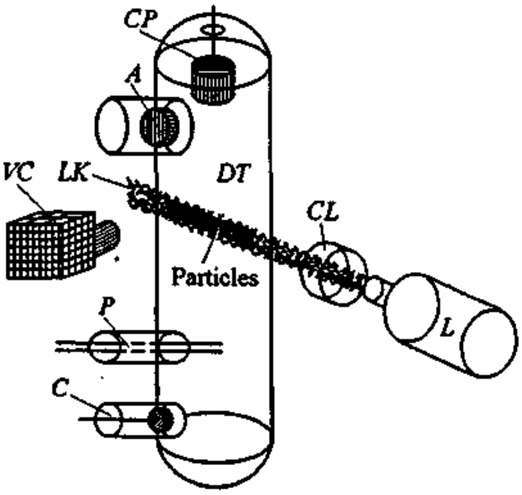

Figure 1. Experimental setup for studying ordered structures in the gas-discharge plasma: laser (L), cylindrical lens (CL), laser knife (LK), discharge tube (DT), container with particles (CP), anode (A), cathode (C), probe (P), and videocamera (VC).

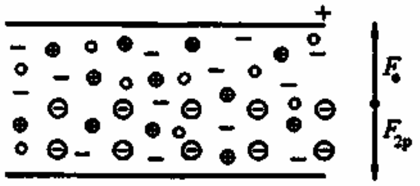

Figure 2. Schematic of the dusty plasma: dusty particle (⊖), positive ions (⊕), electrons (-), and neutral molecules of gas (o) where the discharge is formed.

repulsive field induced by the negative potential of discharge tube walls.

The answer to the question, whether dusty particles in the electrostatic trap are in a gaseous (disordered) or a crystalline (ordered) state, depends on the parameter $\mathbf{g_P} = (ze)^2 / \bar{r}\,T$, where $\boldsymbol{T}$ is the plasma temperature, **ze** is the particle charge, $\bar{r} = (4\pi \boldsymbol{n_p} / 3)^{-1/3}$, and $\boldsymbol{n_p}$ is the particle concentration. The ordered state arises only at $\mathbf{g_P} > 171$. At the dusty-plasma experiment conditions the parameter $\mathbf{g_P}$ is 10^4-10^6, which just leads to the crystallization.

To clear up whether dusty particles crystallize in the absence of electrostatic trap, the experiment should be done under space conditions. In the absence of gravity, the electrostatic repulsion of dusty particles can be balanced only by the ionic force. We examine this attractive force acting at distances exceeding the Debye radius when the electric interaction can be neglected. A prototype of such forces can be found in an ancient and almost forgotten theory. In 1784, Swiss scientist Lesage proposed a simple and elegant mechanistic substantiation of the universal gravity law. According to opinions of that time, the ether consisted of small elementary atoms moving in all directions. Lesage's idea was that ether atoms lose a small fraction of their kinetic energy when penetrating a massive body. In the case of an individual body, it is hit by an identical number of ether atoms from all directions and the total force acting on it is zero. However, if the body neighbors another one, the latter reduces the ether momentum acting upon the former, which leads to efficient attraction of the two bodies (see Fig. 3).

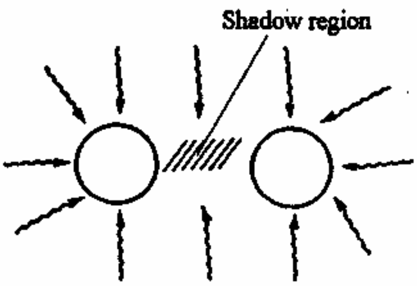

Figure 3. Mechanism of attraction between two bodies according to Lesage.

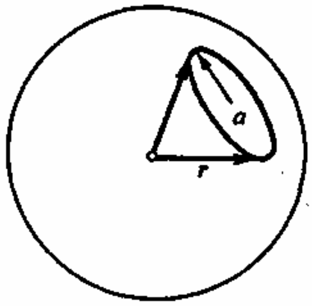

Figure 4. Illustration to the calculation of attraction between dusty particles (see text).

At greater distances the particle flux decrease, hence the attraction, is proportional to the solid angle at which the second body is seen from the first one, that is inversely proportional to the squared distance. Certainly, this simple model cannot explain the real gravitation. The considered gravity mechanism would cause friction between the ether and planets and their final drop onto the Sun. We enlarge on the history because the Lesage model almost exactly reproduces the dusty plasma. There the role of ether atoms is played by electrons and ions, as well as by the neutral plasma component. In the case of a solitary dusty particle, the plasma flux upon its surface is spherically symmetrical and the average bombardment force is zero. Attraction between two dusty particles arises due to the fact that motes mutually shade each other from the plasma flux, which decreases the effective plasma pressure at the mote surface facing the neighbor (see Fig. 3).

To calculate this attractive force, we consider the distance ***ô*** between dusty particles, much exceeding the particle radius $\boldsymbol{a}$. To simplify calculations, we invert the problem, believing an ion hitting the particle to be emitted rather than absorbed. Ions emitted by the particle bombard another particle, thus causing their repulsion. The repulsion force taken with an opposite sign is just the sought-for attractive force between dusty particles. If $\boldsymbol{r}$ much exceeds $\boldsymbol{a}$, the emitting particle can be considered to be a point. We also assume that ions emitted by such a particle have the velocity $\boldsymbol{V}$. We designate the number of ions emitted by the point dusty particle per unit time as $\boldsymbol{I}$. Then the number of ions passing through another dusty particle (see Fig. 4) is given by

$$dI = I\frac{a^2}{4r^2} . \tag{1}$$

To calculate the bombardment force $\boldsymbol{F_i}$ acting upon the second particle, one should multiply the number $\boldsymbol{dI}$(1) by the momentum $\boldsymbol{mV}$ of each ion.

$$\boldsymbol{F_i} = mVdI . \tag{2}$$

Taking into account that at equilibrium conditions with plasma ion concentration $\boldsymbol{n_i}$ the number of ions absorbed by the dusty particle per unit time is $\boldsymbol{I} = p\ n_i V a^2$, from (1) and (2) the repulsion force of dusty particles is written as

$$F_i = \frac{\pi}{4} n_i m V^2 \frac{a^4}{r^2} . \tag{3}$$

Analogous reasons can be extended to electrons and the neutral component. Note that at an equilibrium when temperatures of the neutral component and dusty particle are equal, neutral molecules do not contribute to the total bombardment force. This is due to the fact that the number of these molecules incident onto the particle is equal to the number of emitted molecules at equilibrium. According to (3), the contribution of electrons also much exceeds the contribution of ions, since the electron mass is much less than the ion mass. Hence, the momentum transmitted by electrons is much less than that from ions. The ion bombardment force $\boldsymbol{F_i}$ is substantially weaker than the electrostatic repulsion force of dusty particles if these are spaced by a distance of order of the Debye radius or shorter. Only in the case when the distance between dusty particles much exceeds that radius, does the bombardment force exceed the electrostatic repulsion. Since these forces are small at such distances, the binding energy of dusty particles is not high. Currently, the question whether a dusty crystal with a free boundary exists is open.

The case is radically changed when the dusty plasma is placed into a magnetic field. To understand the changes caused by turning the external field on, we consider the ion motion in plasma as collisionless, neglecting ion collisions with each other, electrons, and neutral component. As earlier, we believe that ions are absorbed by a mote when colliding with it. We also consider that the distance between motes greatly exceeds the Debye radius, that is the ions move mainly in the region where the electric field is absent. Thus, the single force acting upon ions, is the Lorentz one,

$$F = \frac{q}{c} V_{\perp} H \quad , \tag{4}$$

where $\boldsymbol{q}$ is the ion charge, $\boldsymbol{c}$ is the speed of light, $\boldsymbol{H}$ is the magnetic field, $V_{\perp}$ is the ion velocity component perpendicular to that field. The ions in the magnetic field move along a screw line with radius $m V_{\perp} c \,/\, qH$ and step $2\pi mcV\cos\alpha \,/\, qH$, where **a** is the angle between the ion initial velocity and the field. The uniform magnetic field focuses charged particle beams both perpendicular to the field and at a small angle to the line of force.

As in the case of absence of magnetic field, we invert the problem. Let two dusty particles be arranged along the line of force. Then ions emitted by one dusty particle, able to hit another, form a beam with small divergence about the line of force serving as the beam axis (see Fig. 5).

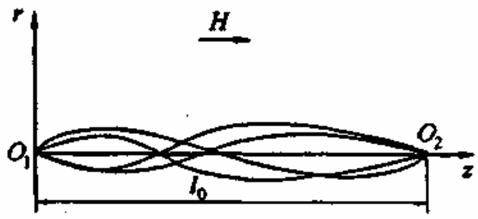

Figure 5. Focusing action of the magnetic field.

Any ion by the time $\boldsymbol{T} = 2\pi mc \,/\, qH$ after emission from the point $\boldsymbol{O_1}$, of the first panicle again crosses the line of force belonging to this point. The distance passed by the ion along the axis, that is the screw line step, is given by (at small angle **a**)

$$l = 2\pi \frac{mc}{qH} V \left(1 - \frac{\alpha^2}{2} \right) . \tag{5}$$

Thus, all ions outgoing from the point $\boldsymbol{O_1}$ at small angles to the line of force are collected again at that line within the narrow section

$$\Delta l = \pi \frac{mc}{qH} V \alpha^2 \tag{6}$$

near the point $\boldsymbol{O_2}$ spaced from $\boldsymbol{O_1}$ by the distance

$$l_0 = \frac{2\pi\, mcV}{qH} \quad . \tag{7}$$

Therefore, the spot of radius ***Äñ*** for ions, emitted from the point $\boldsymbol{O_1}$ within the sector (0, **a**) in the plane perpendicular to the axis and passing through the point $\boldsymbol{O_2}$, is written as

$$\Delta r = \alpha \Delta l \, . \tag{8}$$

The field focusing can many times strengthen the attraction between dusty particles if the second particle is at the point O_2.

To estimate how strongly the force F_H of ion bombardment upon the dusty particle at the focal point O_2 exceeds the corresponding force F_0 with no magnetic field, we consider the weak magnetic fields: $R >> á$, where R = mcV/qH is the Larmor radius. First, we note that formula (8) estimates the maximum angle a_{max} , at which ions emitted by the first particle hit the second one. To do that, the focal spot size should not exceed the dusty particle radius a, hence,

$$\alpha_{max} = \left(\frac{a}{\pi R}\right)^{1/3} . \tag{9}$$

The number of ions emitted by the first dusty particle and hitting the second one is proportional to the ratio of the area cut from a sphere surface by the cone of angle a_{max} to this sphere area,

$$dI = \frac{\alpha_{max}}{4} I . \tag{10}$$

Substituting (9) and (10) into (2), one finds

$$F_H = \frac{mV}{4}\left(\frac{a}{\pi R}\right)^{2/3} I . \tag{11}$$

Comparing (11) and (3), one determines the ratio of bombardment forces acting upon dusty particles spaced by $l_0 = 2\pi R$,

$$\frac{F_H}{F_O} = 4\left(\frac{\pi R}{a}\right)^{4/3} . \tag{12}$$

It follows from (12) that due to the condition $R >> á$ the attractive force F_H in the magnetic field is much stronger than in its absence. Thus, the dusty molecule can be stable in the magnetic field if the distance between dusty particles is multiple to l_0, that is $l = nl_0$, n = 1, 2... Since under the condition of glowing discharge at pressure about 1mm Hg and normal temperature T = 300 **K** the ion pathlength is **ë** $\approx 10^{-2}$ cm, the considered collisionless mode of ion motion with **ë** $\geq l_0$ is satisfied in magnetic fields $H \geq 10^3$ Oe. It also follows from (12) that the ratio of the force of ion bombardment in the field to that in its absence grows as the magnetic field decreases, $F_H/F_0 \propto H^{-4/3}$, therefore, at first glance, the effect should be strongest just in weak fields. In fact, this is not the case. Formula (12) is derived for dusty particles at distance $R \propto H^{-1}$ from each other. According to (3), the force is $F_0 \propto R^{-2}$. Substituting this into the ratio F_H/F_0, one finds the force F_H of ion bombardment to be proportional to $H^{2/3}$, that is it grows with the magnetic field. The effect is maximum in the strong fields, when the Larmor radius R is much less than the dusty particle radius a, as is illustrated in Fig. 6.

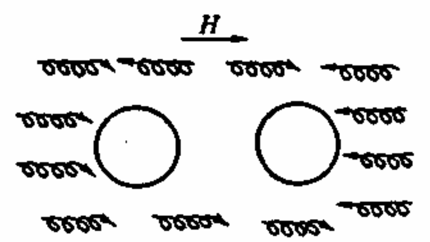

Figure 6. Attraction of dusty particles in the strong magnetic field.

In the absence of dusty particles, ions in the strong external magnetic field cannot move freely perpendicular to lines of force. The trajectory of each ion is spirally wound onto the line of force, therefore their motion is sharply anisotropic. As it follows from Fig. 6, in the considered case all ions hitting dusty particles push them to each other. In the weak magnetic field, such an attraction involves a small fraction of ions hitting the dusty particle, namely those within the small angle á shown in Fig. 5.

It also follows from Fig.6 that the attractive force between dusty particles in a strong field is given by

$$F_i = \frac{1}{4} m V I = \frac{1}{4} \pi n_i m V^2 a^2 . \qquad (13)$$

Thus, in this limiting case, the attractive force between particles is maximum and independent of their spacing. From (13), it is evident that this force is also independent of the magnetic field, totally corresponding to the sketch of Fig. 6. For dusty particles of radius á ≈ 10ìm the condition of strong field, when formula (13) is valid, is satisfied for fields H ≥ $10^4 \sqrt{A}$ [Oe], where $\boldsymbol{A}$ is the ion atomic mass.

It is expedient to compare the force $\boldsymbol{F_i}$ to Coulomb repulsion of two dusty particles $\boldsymbol{F_c} = z^2e^2/l^2$, where l is the distance between particles. It follows from (13) that the attractive force $\boldsymbol{F_i}$ caused by ion bombardment becomes equal to the Coulomb repulsion force $\boldsymbol{F_c}$ at the distance

$$l = \frac{2ze}{\sqrt{\pi n_i m V^2 a^2}} . \qquad (14)$$

For the particle with $\boldsymbol{á}$ = 10 *ìm* and dusty plasma parameters $\boldsymbol{n_i} = 10^{10}$ cm^{-3}, $\boldsymbol{V} = 2.5 \times 10^5$ $cm \cdot s^{-1}$ (hydrogen plasma), $\boldsymbol{m} = 1.8 \times 10^{24}$ g, $\boldsymbol{e} = 4.8 \times 10^{-10}$ cgse, and $\mathbf{z} = 10^4$, from (14) one finds the equilibrium distance as $\boldsymbol{l}$ = 0.16 cm.

In fact, the electrostatic repulsion of dusty particles in plasma is weakened by the Debye screening. For the above dusty plasma parameters, the Debye radius is $r_D = \sqrt{T/4\pi n_i e^2} \approx 10^{-3}$ cm, which would be much shorter than the calculated distance $\boldsymbol{l}$. Thus, equilibrium distances between particles in the actual dusty plasma in the strong magnetic field are approximately equal to the Debye screening radius.

Just this fact complicates studying the impact of external magnetic field on dusty molecules and crystals. As we indicated in the beginning, a dusty crystal in terrestrial conditions is in an electrostatic trap and the distance between dusty particles is of the order of the Debye radius. In this case, turning the external field on does not change the crystal structure. Quite different are space conditions, when the equilibrium distance between dusty particles can considerably exceed the Debye radius. There the role of the external magnetic field can be governing.

Returning to the dusty-plasma clouds in interstellar space, one can state that the considered interaction in the terrestrial dusty plasma can have also cosmogonic importance. For instance, the very first stages of stellar system formation from these clouds axe currently not quite clear. It is not excluded that only gravity forces are insufficient to initiate gravitational compression in such a rarefied system as interstellar gas clouds. The interstellar magnetic field seems to play an important role in this process.

REFERENCES

1. Nefedov A.P., Petrov O.F., and Fortov V.E. Usp. Fiz. Nauk 1997, 167 (11), 1215 (Phys.-Usp.).
2. Advances in Dusty Plasma. Eds. P.K. Shukla, D.A. Mendis, and T. Desai. Singapore: World Scientific, 1997.
3. Fortov V.E., Molotkov V.I., and Nefedov A.P. Progress in Physics of Clusters. Eds. V.D. Lakhno, A.P. Nefedov, and G.N. Chuev. Singapore: World Scientific, 1998.