

CONFERENCES AND SYMPOSIA

PACS number: 01.10.Fv

Scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences (27 September 2000)

A scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences (RAS) was held on 27 September 2000 at the P L Kapitza Institute for Physical Problems, RAS. The following reports were presented in the session:

(1) **Ignatov A M** (Institute of General Physics, RAS, Moscow). *Quasigravitation in dusty plasma*;

(2) **Gulyaev R A** (Institute of Terrestrial Magnetism, Ionosphere and Wave Propagation, RAS, Troitsk, Moscow region), **Shcheglov P V** (P K Sternberg Astronomical Institute, M V Lomonosov Moscow State University, Moscow) *Observations of the resonance glow of atoms in region of solid material sublimation in the near circumsolar space*.

Summaries of the two papers are given below.

PACS number: **52.90.+z**
DOI: 10.1070/PU2001v044n02ABEH000913

Quasigravitation in dusty plasma

A M Ignatov

1. Introduction

Different processes leading to the attraction of like charged macroparticles in dusty plasma will be briefly discussed in this report.

Low-temperature plasma often contains some quantity of solid macroparticles or dust grains, whose characteristic size can vary widely (from tens of Angstroms in installations of plasma processing to tens of centimeters in Saturn's rings). A separate grain of dust behaves like a floating Langmuir probe, i.e. due to the high mobility of the electrons it turns out to be negatively charged with a charge which can be $10^3 - 10^4$ times more than the charge of the electron, depending on the conditions of the surrounding plasma. This medium consisting of several sorts of charged particles (electrons and ions with fixed charge and grains variable charge) as well as of neutral atoms is called a dusty plasma. It is worth of mentioning that the charging of the dust grains sometimes depends on various additional factors such as the thermo-emission and radioactivity of the dust grains which can alter the sign of the charge.

The first laboratory observations of aerosols in a gas discharge were made in 1924 [1]; a systematic study of dusty plasma started only about 20 years ago. Many aspects of dusty plasma physics are discussed in the collective volume [2]; the *Uspekhi Fizicheskikh Nauk* journal (*Physics – Uspekhi*) has also published several detailed reviews [3, 4].

Recently, along with the dusty plasma, the subject of intensive studies has been the very similar colloidal plasma [5] which is a natural (biological liquid) or artificially prepared suspension of macroparticles in a solvent, usually water. The charge of the macroparticles, also called macroions, is due to the corresponding electrochemical reactions. It is essential that in contrast to dusty plasma, colloidal suspensions are in thermodynamical equilibrium. Though the absolute magnitudes of the macroion charges are, as a rule, less than the charges of the grains of dust in plasma, colloidal suspensions can be more nonlinear systems. Really, it is not the charge which is of crucial importance, but the dimensionless ratio $\eta = e\phi/T$, where ϕ is the macroparticle potential, and T is the temperature of the solvent or electron component of the plasma. In colloidal solutions this magnitude can be of some tens, but in a dusty plasma $\eta \leqslant 6$.

Because grains of dust have like charges, it seems at first sight that they should repel each other. At the same time there are convincing experimental data in favor of forming various structures, in particular, dusty clusters. For this, attraction is necessary between the macroparticles. A similar situation is met in the physics of colloidal plasma. That is why one interesting problem in the theory of dusty plasma and colloidal suspensions is the search for mechanisms of interaction between particles. Many processes able to provide attraction were predicted theoretically. Some of them which can apparently be observed in nature are discussed below.

2. Electrostatics of equilibrium plasma

Let us consider first a purely electrostatic interaction in an ultimately idealized model. The main question in this case is in the basic possibility that the nonlinear shielding of the field in plasma can bring about the attraction of like charges. In the bibliography one can find a lot of references to studies in which in the framework of one model it is possible to achieve attraction as well as repulsion. Having no way to discuss them in detail, I only note that all authors use some or other series expansions and approximate solutions of the Poisson equation. So it is worth discussing the statement of the problem and, without solving it — this hardly can be done analytically — to try to understand qualitatively the nature of the solution.

Let two equal spherical particles of the radius a and charge Q be placed in an equilibrium plasma. For the sake of simplicity let us suppose that the particles are ideal conductors and the plasma is collisionless. Under such

Uspekhi Fizicheskikh Nauk **171** (2) 213 – 219 (2001)
Translated by Yu A Danilov; edited by M S Aksent'eva

conditions the plasma is described by the Vlasov equation

$$\frac{\partial f_\alpha(t,\mathbf{r},\mathbf{p})}{\partial t}+\frac{\mathbf{p}}{m_\alpha}\,\frac{\partial f_\alpha(t,\mathbf{r},\mathbf{p})}{\partial \mathbf{r}}+e_\alpha\mathbf{E}(\mathbf{r})\frac{\partial f_\alpha(t,\mathbf{r},\mathbf{p})}{\partial \mathbf{p}}=0\,, \qquad (1)$$

where index α denotes various plasma components. The Vlasov equation for the potential ϕ can be written as

$$\Delta\phi=-4\pi\left[\sum_\alpha e_\alpha n_\alpha(\phi)-\rho_{\mathrm{b}}\right], \qquad (2)$$

where the density ρ_{b} of the neutralizing background enters, and

$$n_\alpha(\phi)=\int \mathrm{d}\mathbf{p}\,f_\alpha(\mathbf{r},\mathbf{p})\,. \qquad (3)$$

The boundary condition for equation (2), corresponding to a constant charge of the particles, is

$$\oint_{\Sigma_{1,2}}\mathrm{d}\mathbf{s}\nabla\phi=-4\pi Q\,, \qquad (4)$$

$$\phi\big|_{r\to\infty}\to 0\,, \qquad (5)$$

and the integral should be taken over the surfaces of both spheres $\Sigma_{1,2}$.

Let us suppose that the plasma particles are reflected specularly from the surface of the grains of dust. In this case the boundary condition for the Vlasov equation can be written as

$$f_\alpha|_{\Sigma_{1,2},\,p_{\mathrm{n}}>0}=f_\alpha|_{\Sigma_{1,2},\,p_{\mathrm{n}}<0}\,, \qquad (6)$$

where p_{n} is a normal with respect to the sphere surface component of the momentum of the plasma particle. The distribution functions at infinity are considered to be Maxwellian with nondisturbed densities $n_{0\alpha}$ and temperatures T_α:

$$f_\alpha|_{r\to\infty}\to f_{0\alpha}=n_{0\alpha}(2\pi m_\alpha T_\alpha)^{-3/2}\exp\left(-\frac{p^2}{2m_\alpha T_\alpha}\right).$$

Equations (1), (2) ensure the conservation of the total momentum, which in a stationary plasma can be written as $\nabla_j\Pi_{ij}=0$, where the stress tensor is

$$\Pi_{ij}=\Pi_{ij}^{(f)}+\Pi_{ij}^{(p)}\,,$$
$$\Pi_{ij}^{(f)}=\delta_{ij}\phi\rho_b+\delta_{ij}\,\frac{(\nabla\phi)^2}{8\pi}-\frac{\nabla_i\phi\,\nabla_j\phi}{4\pi}\,, \qquad (7)$$

$$\Pi_{ij}^{(p)}=\sum_\alpha\int\mathrm{d}\mathbf{p}\,\frac{p_ip_j}{m_\alpha}\,f_\alpha(\mathbf{r},\mathbf{p})\,. \qquad (8)$$

The force exerted on a grain of dust is, by definition, equal to the momentum flux through its surface. Evaluating the momentum flux, for example, for the upper grain of dust, it is convenient to divide the integration surface into an upper hemisphere of sufficiently large radius R_0 and a disc of the same radius in the plane $z=0$ (Fig. 1). Doing so, we achieve the resulting force which is obviously parallel to the z-axis and can be written as

$$F_z=\int_{\sqrt{x^2+y^2}<R_0}\mathrm{d}x\,\mathrm{d}y\,\Pi_{zz}\big|_{z=0}-R_0^2\int_{z>0}\mathrm{d}\Omega\,\Pi_{rz}\big|_{r=R_0}\,. \qquad (9)$$

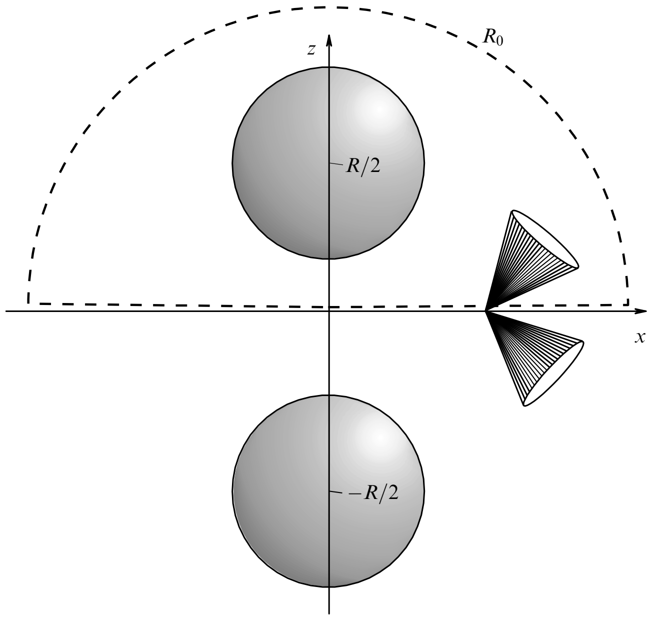

Figure 1. Evaluation of the attraction force between two grains of dust. The distribution function for momenta, belonging to the dashed cones, is zero.

It is worth mentioning that the force (9) in general is not proportional to the derivative of the total energy over the distance between the centers of the spheres.

The stationary Vlasov equation with boundary condition (6) can be easily solved:

$$f_\alpha(\mathbf{r},\mathbf{p})=f_{0\alpha}(\mathbf{r},\mathbf{p})\exp\left(-\frac{e_\alpha\phi}{T_\alpha}\right), \qquad (10)$$

and the stress tensor (8) is diagonal

$$\Pi_{ij}^{(p)}=\delta_{ij}\sum_\alpha n_{0\alpha}T_\alpha\exp\left(-\frac{e_\alpha\phi}{T_\alpha}\right). \qquad (11)$$

Because of the obvious symmetry of the problem $E_z(z=0)=0$, in the limit $R_0\to\infty$ the relation for the force (9) can be written as

$$F_z=2\pi\int_0^\infty\rho\,\mathrm{d}\rho\left\{\phi(\rho,0)\rho_{\mathrm{b}}+\sum_\alpha n_{0\alpha}T_\alpha\right.$$
$$\left.\times\left[\exp\left(-\frac{e_\alpha\phi(\rho,0)}{T_\alpha}\right)-1\right]+\frac{1}{8\pi}\left(\frac{\partial\phi}{\partial\rho}\right)^2\right\}. \qquad (12)$$

To make the boundary condition (5) compatible with the Poisson equation (2), the plasma at infinity should be neutral, i.e. $\rho_{\mathrm{b}}=\sum_\alpha e_\alpha n_{0\alpha}$. It is easy to verify that taking this fact into account, the integrand in (12) becomes non-negative. So, it follows necessarily from the law of momentum conservation that the electrostatic interaction between two identical macroparticles in plasma is always repulsive.

Which effects could change the character of the interaction? First, a dispersion in the particle size could bring about attraction — like charged spheres of various size under certain conditions can attract each other even in vacuum [6].

Moreover, when there is a sufficiently large dust concentration, the densities of electrons and ions in the surrounding plasma are not the same. In a more realistic model the description of the interaction should include equations (1), (2) with $\rho_b = 0$, and the charge neutrality is ensured by the other grains of dust. The boundary condition (5) becomes inapplicable, and it is impossible to pass to the limit $R_0 \to \infty$ in equation (9). The force (9) can become negative though it cannot be evaluated. It seems that this mechanism ensures an effective attraction between macroions in colloidal plasma (7), but the necessary value of the potential of the macroparticle is fairly high and could hardly be achieved in a dusty plasma.

3. Le Sage force

One more idealization in the model discussed above is the supposition of specular reflection of the plasma particles from the macroparticle surface (6). The real picture is far more complicated. In the stationary state the macroparticle charge is determined by the equality of electron and ion currents on its surface. For each ion hitting the surface of the grain of dust strikes one electron. As a result the charge of the grain of dust does not change, but its mass can change and this happens, for example, in the process of plasma synthesis of macroparticles. On the other hand, in many experiments the grains of dust prepared beforehand interact with a plasma of inert gases. Here, the reaction of recharging occurs, the neutral atom leaving the surface of the grain of dust so that its mass does not increase. In any case the plasma is absorbed on the surface of the macroparticle. How this influences on the dust interaction, one can understand considering the other idealization.

Let us suppose that the influence of the electric field of the grain of dust on the plasma particles can be neglected. To some extent this supposition can be justified assuming that the dust size exceeds the Debye radius. If the dust absorbs everything hitting its surface then instead of (6) for solution of Vlasov equation (1) one should use the boundary condition

$$f_\alpha\big|_{\Sigma_{1,2},\, p_n > 0} = 0\,. \tag{13}$$

It is naturally that on superimposing these conditions the solution of equation (1) would not be a Maxwellian distribution any more. For example, in the plane $z = 0$ there exist two cones in the velocity space, shown in Fig. 1; the distribution function inside these cones is zero. Moreover, as $R_0 \to \infty$ an anisotropic additional term arises in the Maxwellian distribution proportional to $1/R_0^2$. The momentum flux tensor (8) is also anisotropic. As a result of fairly cumbersome calculations, the details of which can be found in [8], the force (9) turns out to be attractive and equal to

$$F_z = -\frac{3}{4}\,\pi n_{0i} T_i\,\frac{a^4}{R^2}\,, \tag{14}$$

where R is the distance between the centers of the dust grains. It should be emphasized that for total absorbtion (13) the stationary state of plasma becomes possible only when it is created continuously. Here we suppose that the plasma sources are located enough far from the grains of dust. In the contrary case it is necessary to introduce the sources into equation (1) explicitly.

The physical sense of the force (14) is quite clear. Because the plasma is absorbed by grains of dust, the gas-kinetic pressure on the surface, for example, of the upper grain of dust (see Fig. 1) is less from below than from above. It is obvious that the reduction of the pressure is proportional to the solid angle subtended by one grain of dust as seen from the surface of the other one, this is reflected in (14).

More than two centuries ago Le Sage [9, 10] proposed the theory of universal gravitation. Le Sage assumed that the aether atoms, interacting with massive bodies, lost a certain part of their *vis viva* and derived from this the attraction proportional to $1/R^2$. Because the case in point above was the same effect (up to a non-essential difference in terms), the force (14) in a series of studies has been now called 'Le Sage force'. Moreover, the words 'bombardment force' as well as the somewhat mystic term 'shadow force' are used as synonyms.

In the opposite limit of grain size less than the Debye radius the situation became rather more complicated, because the plasma particle trajectories differ from straight lines even at considerable distance from the grain of dust. Nevertheless, the asymptotic relation for the Le Sage force for distances which exceed the Debye radius can be derived in another way, which enables one to look at the physics of the process from another point of view. Because each grain of dust absorbs plasma, in its neighborhood a spherically convergent flow is formed. Due to the equation of continuity at large distances the velocity changes as $1/R^2$. A drag force, proportional to the flow velocity, is exerted on any object which is in the flow. So, using the known relation for the drag force, one can estimate the attraction force which arises [11] which turns out to be (14) as much as one.

The boundary condition (13) brings out that the electric potential of the absorbing body in plasma at large distances behaves as $1/R^2$, and the electric field as $1/R^3$. One can expect that the resulting force between two grains of dust at small distances is due to Coulomb repulsion, and at large distances the Le Sage force dominates. Though there is no analytical theory which takes into account the Coulomb interaction in a compatible way, numerical modeling confirms this character of the force dependence on distance [12].

The Le Sage attraction is of quite universal character and can be due not only to matter flows, but to any conserved quantity as well. So, if for some reasons the temperature of the grain surface is lower than that of the surrounding plasma, for example, due to radiative cooling, then in the neighborhood of each grain of dust a convergent heat current forms and as result of thermophoresis, an attraction arises [13].

It is easy to verify that in the case of total absorbtion (13) the net momentum flux through the surface surrounding both particles is zero. In other words, in this case the third Newtonian law is valid. In general this is not so. If the attraction is due to the heat flows and the grains of dust have different temperatures, then nonequal forces are exerted on various particles. The total momentum flux from the plasma to the system of macroparticles can differ from zero — this is an analogue of the well-known radiometric effect.

One more difference of the Le Sage gravitation from the usual interaction is its non-parity. For example, if we put one more grain of dust under the lower one at Fig. 1, then the force exerted on the upper grain of dust will remain unchanged. In addition, the Le Sage force is determined by the form of the surface of the dust grain. All this means that in spite of the formal similarity with the gravitational interaction, the field concept can not be applied to the Le Sage force.

Recently experiments have been carried out on direct measurement of forces between two macroscopic bodies in low-temperature plasma [14]. Carrying out these measurements, the experimentalists used an electroscope-type construction, immersed in a glowing discharge. It turned out that in a certain range of parameters the leaves of the electroscope attract each other in spite of the like charges on them. Though there is no complete theoretical analysis of this experiment, the Le Sage force is the only present explanation of the observed interaction.

4. Ensemble of macroparticles

A statistical description of an open system — ensemble of macroparticles, exchanging matter and charge with the surrounding plasma has been used for a long time (for example, [15, 16]). The systematic derivation of the kinetic equations on the basis of the Bogolubov hierarchy was published only this year [17]. The essential feature of the kinetic description of the dusty component is the increase of the dimensionality of the phase space. Because the charge of the dust grain is a variable magnitude which is determined by the surrounding plasma, it is necessary to take into account the dependence of the distribution function of the dust not only on the coordinates and momenta, but on the charge as well.

The plasma absorbtion with the dust and processes of dynamic charging bring out a series of interesting kinetic effects, for example, specific damping of low-frequency waves [3]. Moreover, in the stationary state the translational temperature of the dust, i.e. the kinetic energy of Brownian motion, turns out to be higher than the temperature of the surrounding plasma [17]. Sometimes in kinetic description it is necessary to take into account the growth of the macroparticle mass, which, on the contrary, leads to a reduction of the temperature [18].

Le Sage gravitation can bring about the development of instability of the homogeneous state like a Jeans instability and to the formation of dissipative structures. In particular, the ensemble, consisting of a large, but finite number of dust grains strives to obtain the form of a spherical cloud. Skipping the details of the kinetic description of this process, let me note one interesting peculiarity — when the thermal fluctuations are neglected the dust cloud is not a diffuse object, but has a sharp frontier [16].

5. Interaction with particle currents in plasma

Up till now the point at hand was the interaction of macroparticles in quasiequilibrium plasma without macroscopic flows of particles. Many experiments are carried out with the grains of dust, levitating over an electrode purposely inserted in the gas discharge chamber. In this case the electrode turns out to be negatively charged, and the electric field near its surface balances the gravity. Plasma in the near-electrode layer is essentially nonequilibrium, and this brings out many interesting effects.

If the electrons in the near-electrode layer are distributed according to Boltzmann (usually $T_e \gg T_i$), then the ions are accelerated in the electric field. In the domain where the grains of dust are kept, the directed velocity turns out to be comparable with the ionic sound speed or higher. It is natural that in such a medium the static dielectric permittivity can be negative. In the linear approximation the distribution of the electric field appears like a ship's wake [19]. Downstream from the dust a Mach cone forms, inside which the potential oscillates; but upstream the potential drops exponentially. The potential oscillations have been observed in computer simulations [20] as well. In addition, downstream a domain with surplus ion density forms, for this reason this effect is called ionic focusing.

If two macroparticles are in the flow, one of which is in the Mach cone of the other, then due to ionic focusing the lower particle strives to position itself at a certain distance strictly below the upper particle. In this case the action exerted by the upper macroparticle on the lower one is considerably greater than the force of the counteraction. An ensemble of a large number of macroparticles self-organizes into a two-dimensional hexagonal crystalline structure consisting of vertical chains of grains of dust. A considerable part of the modern experimental and theoretical work on dusty plasma is dedicated to research of the properties of this dusty crystal.

In conclusion I would like to note that recently the physics of dusty plasma has become to a considerable extent an interdisciplinary science. If only some years ago it was permissible to consider a dusty plasma as a multicomponent one with an additional sort of particles, then now it has been recognized that effects which according to tradition were studied in the physics of aerosols and physical chemistry play an important role. Moreover, in laboratory conditions the gravitational field of the Earth plays an anomalously great role in comparison with a traditional plasma. In this respect a rich harvest of data can be expected from experiments with dusty plasma planned to be carried out on the board the International Space Station as well as from the Cassini spacecraft approaching Saturn.

References

1. Langmuir I, Found G, Ditter A *Science* **60** 392 (1924)
2. *Dusty and Dirty Plasmas, Noise, and Chaos in Space and in the Laboratory* (Ed. H Kikuchi) (New York: Plenum Press, 1994)
3. Tsytovich V N *Usp. Fiz. Nauk* **167** 57 (1997) [*Phys. Usp.* **40** 53 (1997)]
4. Nefedov A P, Petrov O F, Fortov V E *Usp. Fiz. Nauk* **167** 1215 (1997) [*Phys. Usp.* **40** 1163 (1997)]
5. Löwen H *Phys. Rep.* **237** 249 (1994)
6. Saranin V A *Usp. Fiz. Nauk* **169** 453 (1999) [*Phys. Usp.* **42** 385 (1999)]
7. Schram P P J M, Trigger S A *Contrib. Plasma Phys.* **37** 251 (1997)
8. Ignatov A M *Fiz. Plazmy* **22** 648 (1996) [*Plasma Phys. Rep.* **22** 585 (1996)]
9. Le Sage G L *Neuveaux Mémoires de l'Académie Royale* (Berlin) 404 (1782)
10. Rosenberger F *Die Geschichte der Physik in Grundzögen* Bd. 3 (Braunschweig: F. Vieweg und Sohn, 1890) [Translated into Russian (Moscow-Leningrad: GTTI PCHI SSSR, 1935)]
11. Ignatov A M *Kratkie Soobshch. Fiz.* (1 – 2) 58 (1995) [*Bull. Lebedev Phys. Inst.* (1–2) 18 (1995)]
12. Khodataev Ya K et al. *Fiz. Plazmy* **22** 1028 (1996) [*Plasma Phys. Rep.* **22** 932 (1996)]
13. Tsytovich V N et al. *Comm. Plasma Phys.* **18** 281 (1998)
14. Dubinov A E et al. *Pis'ma Zh. Tech. Fiz.* **25** (13) 73 (1999) [*Tech. Phys. Lett.* **25** 538 (1999)]
15. Vladimirov S V *Phys. Plasmas* **1** 2762 (1994)
16. Ignatov A M *Fiz. Plazmy* **24** 731 (1998) [*Plasma Phys. Rep.* **24** 677 (1998)]
17. Schram P P J M et al. *Phys. Rev. E* **63** 016403 (2001)
18. Ignatov A M, Trigger S A, physics/0006072
19. Vladimirov S V, Nambu M *Phys. Rev. E* **52** R2172 (1995)
20. Melandsø F, Goree J *J. Vac. Sci. Technol. A* **14** 511 (1996)