Interactions of charged dust particles in clouds of charges

Mrs.K.Swapna Kumari , Abdul Gaffor

[1]Assistant Professor, [2] Professor
1,2, Department of H&S
1,2 Global Institute of Engineering and Technology,Moinabad,RR District, Telangana State

Abstract:

Two charged dust particles inside a cloud of charges are considered as Debye atoms forming a Debye molecule. Cassini coordinates are used for the numerical solution of the Poisson-Boltzmann equation for the charged cloud. The electric force acting on a dust particle by the other dust particle was determined by integrating the electrostatic pressure on the surface of the dust particle. It is shown that attractive forces appear when the following two conditions are satisfied. First, the average distance between dust particles should be approximately equal to two Debye radii. Second, attraction takes place when similar charges are concentrated predominantly on the dust particles. If the particles carry a small fraction of total charge of the same polarity, repulsion between the particles takes place at all distances. We apply our results to the experiments with thermoemission plasma and to the experiments with nuclear-pumped plasma. ®c Central European Science Journals. All rights reserved.

Introduction

The study of a plasma in which charged particles of micrometer size play a significant role (so-called dust plasma) is interesting from the fundamental and applied points of view [16]. Of special interest is the observation of collective effects caused by dust coupling. A number of experiments show that micron size particles can form spatial-ordered structures in thermoemission plasma [3] in gas-discharge plasma and in nuclear-pumped plasma [4].

The properties of strong-coupled plasma are often considered in the framework of the so-called one-component model (see, for example, the review by [10]. According to this model, one of the charged components is treated as homogeneous in space. Polarization effects are taken into account in the form of corrections, in some cases.

Apparently, the physics of processes occurring in dust plasma differs from the onecomponent model. A dust particle surrounded by a shell (or cloud) of charges (with masses much smaller than the mass of the dust particle) should be the object of detailed consideration, first of all. A charged dust particle surrounded by a cloud of charges of the opposite sign is an analogue of an atom in gas kinetics.

In general, the charged cloud of such a \dust atom" may not be in thermodynamic equilibrium. However, we shall consider here the situation in which the charges in a cloud are Boltzmann-distributed. It is natural to call such a dust atom a Debye atom [15] in contrast to a Thomas-Fermi atom, in which a charged cloud is a degenerate electronic gas. Similarly, we can introduce the concept of a Debye molecule [17] and a Debye crystal. The Boltzmann distribution and the Poisson equation (that is, the Poisson-Boltzmann equation) describe mathematically the properties of such Debye systems.

It is natural to assume the presence of attractive forces caused by polarization of the charge shells of Debye atoms. However, reliable theoretical results demonstrating an attraction of Debye atoms do not yet exist. The exact solution of the Poisson-Boltzmann equation shows that the repulsion always takes place for the charged planes both in an electron cloud and in a plasma [2], [20]. Numerical simulation of Debye atoms interaction [17] were not quite reliable, as were the results of analytical calculations [5], [11].

The problem of particle interactions in dusty plasma is similar to the problem of colloidal particle interactions in electrolytes. The very concept of a Debye radius for plasmas was borrowed from the theory of electrolytes. The physics of colloid particle interactions in electrolytes has been investigated for a long time (see, for example, [2]. Until now, however, the problem of attraction forces has not been solved, at least for the case in which the colloid particle radius is smaller than the Debye radius.

Below, we attempt to reliably demonstrate the existence of polarization forces of attraction between Debye atoms and to determine the conditions under which attraction appears. This work differs essentially from other publications devoted to an analysis of charged dust particle interactions in plasmas and in electrolytes (see, for example, [1], [13] and [14]).

First, in contrast to a number of publications, we consider a situation in which the total charge of dust particles is not negligibly small compared with the total charge of the cloud particles of one sign. Moreover, we show here that the essential attraction takes place in an opposite limiting case, that is, when almost all the charge of one of sign is concentrated on dust particles, and the clouds consist of charges of only one (opposite) sign. (See [7-9] for preliminary results.)

Second, based on Debye molecule properties, a Debye atom has definite structure. The Debye atom has a core of a charged cloud close to the surface of a dust particle, when a dust particle has a high charge. In particular, the charge of a dust particle cannot, as a rule, be considered as an approximate delta function, even if its radius is much smaller than the Debye radius.

Third, we calculate directly the resulting force on the dust particle from another particle and the charged cloud. The dependence of the potential energy of interaction on dust particle separation is calculated by integration of this force. In our case, the Poisson-Boltzmann equation is solved in an infrequently used coordinate system based on Cassini ovals. It allows a highly accurate calculation of an electric field near a small particle surface and reliably obtains the force of a particle interaction.

We apply our results to thermoemission plasma and to nuclear pumped plasma.

Boundary conditions.

We will use the term \Debye atom" for a single charged dust particle surrounded by a cloud of lighter charges in thermodynamic equilibrium; two or more dust particles will be referred to as a Debye molecule. Formally, the analyses of a Debye atom and a Debye molecule differ only in the geometry of the problem. While analyzing a Debye atom, we can get by with the solution of the one-dimensional Poisson equation, assuming that the electron cloud is spherically symmetric. In an analysis of a diatomic Debye molecule, we can assume that the problem is symmetric about the x-axis connecting the nuclei (dust particles). Therefore, it is enough to consider the two-dimensional Eq. 3 in plane coordinates (x, y). When analyzing a Debye molecule, the problem is complicated considerably by the choice of boundary conditions.

In a real physical problem, the charge Zpe of a dust particle and its radius rp are specified. Hence, one boundary condition is the field intensity on the surface of dust particles S:

$$\mathbf{E}_0 = -\nabla\varphi|_S$$

Thus, the charge of a dust particle is determined by the expression

$$Z_p = \frac{-r_D^2}{4\pi e}\int_S \nabla\phi ds, \quad z_p = \frac{1}{4\pi}\int_S \mathbf{E}ds.$$

Here z p is a dimensionless particle charge, connected to a particle charge in terms of an electronic charge Z p by the expression Zp = 4¼ ¢ zp ¢ nD; the area of the surface S is normalized with r $^{2\,D}$.

The second boundary condition should be the zero-field value on a boundary surface S 0:

$$\nabla\varphi|_{S'} = 0.$$

The zero-field intensity on the Debye atom or molecular boundary follows from quasineutrality of the system of charges. The basic purpose of Debye molecule consideration is to find resulting dependence of the particles' interaction force on the distance d between particles. In this case, it is more convenient to use other boundary conditions instead of Eq. 4, that is, to set a constant potential on a surface of dust particles,

$$\varphi|_S = \varphi_0 = const.$$

One can get the field intensity E0 on a surface of a dust particle by solving the PoissonBoltzmann equation. The calculations with different values of '0 give the necessary value of E0 and charge value z p (Eq. 5). The resulting force of interaction of the dust particles is determined by integration of the electrostatic pressure on a surface of a dust particle. In one case the force is directed along an axis x, and its projection is determined by the expression

$$F = \frac{1}{8\pi}\int_S (\nabla\phi)^2|_S ds_x, \quad f = \int_S E_0^2 ds_x$$

Here dsx is a projection of surface element ds on an axis x ; the force F is connected to dimensionless force f by the expression F = (T 2/8¼e 2)¢f ; the electric pressure is directed along the outward normal to the surface of dust particles.

Conclusion

Let us summarize the results of the above consideration.

(1) A Debye atom consists of a charged dust particle and shell (cloud of charges). For the large charge of the dust particle, the high-density region (core) of the electron cloud screens considerably the large charge of the dust particle near its surface. In this connection, while considering the interaction of Debye atoms, we cannot ascribe the unscreened value of charge to a dust particle. The dust particle charge screened by the core has a universal value determined by the distance between dust particles. The electron shell of the Debye atom screens it.

(2) Attractive forces are associated with the polarization of charge shells of Debye atoms. The force of attraction is formed by polarization of a large fraction of electrons of the charge shell. The polarization of the core is insignificant.

(3) Forces of attraction between dust particles emerge at a comparatively large distance, approximately equal to the mean separation

between dust particles. In this case, the Debye radius must be approximately equal to half the mean distance between dust particles.

(4) Attraction takes place if like charges are concentrated predominantly on dust particles. If dust particles carry a small fraction of the charge of some polarity, repulsion is observed at any distance.

(5) The electrostatic forces of interaction between dust particles vanish when a certain relation between the electron density and the density of dust particles converges. In this case, the Debye "liquid" is in equilibrium. Since attractive forces appear at large distances, the problem of the formation of dust liquids and crystals can be solved correctly only if many-particle interactions are taken into account. However, we can draw the following two conclusions concerning the criteria for the emergence of collective phenomena based on the results presented by us here:

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