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Brownian motion of a dust grain in a plasma

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Of great interest is the problem of charged particulates kinetic energy in plasma. Numerous experimental works (e.g., [1]) as well as studies based on the kinetic theory [2,3] demonstrated that their kinetic energy may take large values compared to the temperature of the ambient neutral gas, which is much more dense than charged plasma components. The estimation of the kinetic energy of grains is one of the most interesting problems in dusty plasmas with different electron, ion and atom temperatures. Here, we study the characteristics of plasma particle kinetics in the presence of moving dust grain (Brownian motion).

In the present work, we perform numeric simulations to investigate the temporal dependence of a grain kinetic energy. The results of ab initio simulations of dusty plasmas are reported. Two methods of simulations are used. The first one is the method of molecular dynamics (MD). Newton's equations are solved for the set of point charged particles inside a cube with specular walls. Interaction of a particle with all others is taken into account. The second method is a particle-in-cell (PIC) algorithm adopted for a problem of grain charge shielding by plasma [4]. We use MD and PIC simulation methods to calculate the mean kinetic energy (temperature) of a dust grain in two temperature plasma.

The research of classical Coulomb plasmas by computer simulation showed that the kinetic energy of grains is greater then that corresponding to the ion temperature. The PIC simulation results agree well with MD runs. In the recent papers it was shown that the velocity grain distribution is described by an effective temperature different from those of the plasma subsystem. Computer simulation results confirm this statement. The time scale for the change of the grain kinetic energy is of the same order as that of the change mass.

The next topic is connected with the ion flow. One provides not only a direct dragging influence (supporting, in particular, the formation of dust voids), but is also responsible for the generation of associated collective plasma processes such as the formation of plasma wake which can strongly affect the interactions of dust grains between themselves and with the plasma. The complete problem of plasma dynamics around a macroscopic body in the presence of plasma flows is highly nonlinear and therefore its numerical analysis is of major importance. Among various numerical methods, direct integration of the equations of motions of plasma particles represents a numerical experiment whose significance approaches experiments in the laboratory. We study the characteristics of grain particle kinetics in the presence of flowing ions around dust grain moving in potential well. The problem was studied by using the MD method.

We have already studied a model problem of the Brownian movement of a grain in an ideal gas for various laws of interaction of atoms with the grain surface. The question of interest in these studies was the average kinetic energy of a grain including rotational degrees of freedom [2, 3]. Although the simple model of the atom-grain inelastic collisions accepted, it demonstrates many interesting features. We confirmed that the translational temperature of the dust component differs from the temperature of the ambient gas. However, we demonstrated that the ‘‘equilibrium’’ temperature is highly sensitive to the details of the inelastic collision. In particular, taking into account the grain mass growth results in appreciable reduction of the dust temperature. It should be noted that the difference between various collisions laws discussed above numerically is very small. The discrepancies in energy balance of the order of a fraction of a tiny mass ratio are accumulated and eventually result in a considerable effect. It is also worth pointing out that the rotational temperature is sensitive even to details of inner structure of a grain.

One of the peculiar features of dusty plasmas is that the average kinetic energy of the dust component, i.e., its translational temperature, may be considerably higher than the temperature of the ambient plasma.

The kinetic description of dusty plasma was discussed in numerous theoretical studies (see [2, 3]). Generally, there are two ways plasma particles interact with dust grains: first, the scattering of a particle by grain electric field and, second, the direct impact of a particle on a grain surface. The latter process results in grain charging due to the higher mobility of electrons, it may change grain mass, heat its surface, etc. In other words, as it is well understood nowadays, the adequate statistical description of the dust component should take into account inner degrees of freedom, the most important among which is the grain charge. Kinetic consideration of charging process shows that absorption of small plasma particles by grains can result in inequality of the grain temperature and the temperatures of the light components even for the case of equal temperatures of electrons and ions. To avoid confusion it should be noted that since the system is open there is no conflict of the latter result with thermodynamics.

Thus, we adopt here a following toy model of the aerosol component absorbing the ambient gas. The dust component consists of spherical rotating grains with variable mass and, consequently, size and moment of inertia. Every atom hitting the grain surface is absorbed by it, transferring, therefore, its momentum, changing the mass of the grain and its angular velocity. The process is inelastic since a part of projectile atom energy is spend for heating the grain surface. It is assumed that the size of grains is small compared to the mean free path of the ambient gas, however, the gas distribution generally depends on the dust component. Our main finding is that although there is no stationary state of this system, the average kinetic and rotational energies of dust eventually tend to certain fixed values, which differ from each other and the temperature of the ambient gas.

The simulations of the Brownian kinetics of a single grain were performed in a following way. The computational area was a three-dimensional cube of unit length on edge in contact with the unbounded equilibrium gas. This contact was simulated by point atoms, which were randomly injected inside the cube from all of its faces and could freely leave the computational area. For each atom leaving the cube, another atom with the random velocity was injected from the random point of the random cube face. The distribution function of the injected atoms was semi-Maxwellian. Since there were no forces acting upon atoms, their trajectories were straight lines. Although the computer facilities allowed us to monitor the motion of the grain for a very long time, up to tens of millions of collisions, it was found that no statistically significant result could be obtained with the time-averaging method. The reason is fairly evident: with growing mass the grain motion slowed down, and it took more and more time for the grain to migrate from one energy subband to another.

Although the simple model of the atom-grain inelastic collisions accepted in this paper ignores some essential processes, it demonstrates many interesting features. We confirmed that the translational temperature of the dust component differs from the temperature of the ambient gas. However, we demonstrated that the ‘‘equilibrium’’ temperature is highly sensitive to the details of the inelastic collision. In particular, taking into account the grain mass growth results in appreciable reduction of the dust temperature. It should be noted that the difference between various collision laws discussed above numerically is very small. The discrepancies in energy balance of the order of a fraction of a tiny mass ratio are accumulated and eventually result in a considerable effect. It is also worth pointing out that the rotational temperature is sensitive even to details of inner structure of a grain.

The important lesson, which may be drawn from the above discussion, is that there is no thermodynamic equilibrium between dust and ambient gas. The statement itself is fairly evident since a dusty plasma is an open system. However, this indicates the inapplicability of the fluctuation-dissipation theorem, which is the basement of the Langevin approach to the theory of Brownian motion. Therefore, the problem of deducing the Langevin equation applicable to dusty plasmas arises. Implementing numeric modeling, here we consider few model problems. Various laws of interaction of Brownian particulate with atoms where studied: elastic collisions, attachment, and more complicated ones. Although this interaction cannot lead to the thermodynamic equilibrium, it was investigated in several theoretic models and corresponds to the Brownian movement of so-called active particulates.

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