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Modelling of Grain Kinetics in Dusty Plasmas

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1. Introduction.

Here, we numerically investigate various kinetic characteristics of micron-sized dust grains in plasmas of gas discharge. We consider two-temperature stationary and moving plasma. For the simulation we employ particle-in cell (PIC) method when a heavy macroparticle is placed in the center of the simulation box and Newton equations are solved for the system involving also plasma particles. We simulate the process of charging of grain absorbing all electrons and ions colliding with its surface and obtain kinetic characteristics of the transitional and stationary regimes. We investigate the statistical properties of the charge fluctuations and their time correlations, the ion drag force and force between grains. The resonance charge exchange collisions are included in our code. The simulations made for two-temperature plasmas of argon and neon with various pressure and temperature of gas.

Under certain conditions, around a negatively charged dust particle a cloud of bound ions may appear which may have a considerable effect on the dust particle charge screening. The effect of weak collisional relaxation of the ion component in a gas-discharge plasma on the dust particle charge screening has recently drawn great attention [1-5], although the possibility of the formation of bound ions was first pointed out in paper [6].

The possibility of accumulation of bound ions on the orbits around a negatively charged dust particle has been considered in many papers [1-5]. But independence of the number of bound ions (and, accordingly, of their influence upon screening) on the collision frequency was first discovered in paper [4]. Consequently, a large number of bound ions can be accumulated even in a collisionless plasma because of arbitrarily rare collisions.

The equations of the self-consistent OML model with an additional inclusion of bound ions were solved in paper [3]. A linear integro-differential equation was derived describing the balance of bound ions. The numerical solution was based on the iteration method, and the influence of bound ions on the screening was examined. It was found that in most dust plasma experiments bound ions play a significant part. But the model used there included no parameter describing the intensity of collisional relaxation, that is, the limit of infinitely weak relaxation was considered. It was revealed the presence of even a weak relaxation leads to a qualitative change in the character of behavior of the potential, and the OML approximation ignoring bound ions becomes invalid. The calculations showed that the electron and ion distributions are close to the Debye distribution.

The effect of bound ions on the screening was also investigated in paper [5] within the self-consistent OML model. As in paper [3], it is noticed that the presence of even a very weak relaxation makes the potential close to the Debye potential. The present paper continues the studies [7-9], and its results are partially presented in [10].

Let us consider a plasma consisting of singly charged ions with a positive charge *e* and mass *M* and of electrons with mass *m* and charge *-e*. Let in plasma there also exist a motionless negative point charge $Q = -Z_0 e < 0$. According to the Mott-Smith model for ions, the particle flux onto a dust particle is

$$J_i(a) = \pi a^2 n_{i0}\sqrt{\frac{8T_e}{\pi M}}(1 - e\varphi / T_i) \equiv J_{i0}[1-\psi(a)]\,.$$

2. PIC simulation results.

Table 1 presents the results of calculations of a two-temperature motionless argon plasma with ion temperature $T_i = 0.025\ eV$ and electron temperature $T_e = 1\ eV$, and with ion density $n_i = 10^9\ cm^{-3}$. Different columns of the table correspond to different values of the ion free path before collision with neutral atoms.

No run	1	2	3	4	5
λ_{st}, μm	∞	1000	500	200	100
-Q/e	4871	3393	2924	2337	1934
J_i / J_{i0}	16.6	34.7	45.4	62.3	74.2
$J_i / J_{i\,MS}$	0.118	0.37	0.55	0.955	1.379
$-\chi_{PIC}(a)$	3.413	2.32	1.99	1.593	1.319
$\chi_{Deb}(a)$	3.331	2.32	1.99	1.597	1.322
$\chi_{\backslash Coul}(a)$	3.508	2.44	2.10	1.683	1.392

Tabl. 1. Characteristics of dust particle charging for different ion free paths λ_{st}. The following time-average values are given: *-Q/e* - the dust particle charge in electron charge units; J_i / J_{i0} - the ion flow (obtained in a numerical experiment) onto a dust particle normalized to the unperturbed flow value $J_{i0} = \pi a^2 n_{i0}(8T_e / \pi M)^{1/2}$; $J_i / J_{i\,MS}$ - the ion flow normalized to the flow value obtained within the Mott-Smith model, $J_{i\,MS} = J_{i0}[1-\psi_{PIC}(a)]$, calculated using the simulated surface potential value $\varphi_{PIC}(a)$; the

surface potential $-\chi_{PIC}(a) = -e\varphi_{PIC}(a)/T_e$ normalized to the electron temperature and its Debye $\chi_{sDeb} = e\varphi_s/T_e$ and Coulomb $\chi_{sCoul} = e\varphi_s/T_e$ values.

The results of calculations demonstrate a qualitative change in the character of screening when collisional relaxation is taken into account. We observe a transition from the distribution corresponding to the OML model (run No 1) to the Debye distribution. A detailed analysis shows that the ion distribution is practically coincident with the Debye distribution (4) or (7), (9) even at the particle surface. So, a conclusion can be drawn that as expected the relaxation causes an enhancement of screening rather than its decrease. A considerably increasing ion flow onto a dust particle reduces its charge (in the absolute value), while the screening increases at small distances.

The influence of bound electrons on the screening in a two-temperature plasma with cold ions has led to the hypothesis of importance of bound ions for moving plasma as well. Although the kinetic energy of ions in a flow is of the order of the electron temperature, the cold ions produced upon charge exchange have a temperature of the buffer gas atoms. Therefore, when bound ions are numerous, they can make a decisive contribution to the dust particle charge screening.

T_i, eV	-Q/e	J_i / J_{i0}	$-\chi_{PIC}(a)$	χ_{sDeb}
1	2805	48.8	1.902	1.996
0.025	2924	45.4	1.997	1.999

Table 2. Characteristics of dust particle charging for the ion free path λ_{st} = 500 μm . The average charge, the ion flow, and the surface potential are presented.

To verify this hypothesis, a calculation was performed using parameters of run No 3 of Table 1, but with the ion temperature equal to the electron temperature 1 eV. The temperature of ions produced upon charge exchange was assumed to be equal to the gas temperature T_a = 0.025 *eV*. Table 2 presents the results of this computation and the data of run No 3 of Table 1 are given in the second row for comparison. The data presented, the same as the analysis of the distribution functions of ion and electron densities show that the characteristic of screening is the Debye radius determined by the gas temperature.

3. Conclusions

The results of numerical simulation made it possible to analyze the kinetic processes leading to dust particle screening in a gas-discharge plasma and to verify the existing theoretical models.

We have revealed that the presence of even weak collisional relaxation is responsible for a radical deviation from the widely used model of orbital motion limited.

The electric field potential distribution and the ion density become very close to the results of the Debye model if the resonance charge exchange collisions are taken into account.

The electron distribution is well described by the Boltzmann model with a Debye potential. But the particle flows onto a dust particle depend strongly on the ion-atom collision frequency (gas pressure) and, accordingly, the dust particle charge cannot be determined correctly using the Mott-Smith model. This fact should be regarded, for instance, in interpretation of the results of experimental measurement of the interaction force between dust particles.

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5. References

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