Effective Interaction Potentials of Particles in Complex Plasmas

Moldabekov Zh.A., Ramazanov T.S., Dzhumagulova K. N.

IETP, Al-Farabi Kazakh National University, 71, Al Farabi av., Almaty 050040, Kazakhstan, ramazan@physics.kz

In this work effective interaction potentials between different types of particles in complex plasmas are presented. In particular interactions between dust-dust, charge-atom and charge-charge in classical and semiclassical cases were considered. For the purpose of taking into account screening effects in interparticle interaction the method of dielectric response function was used.

Introduction. Complex plasma is neutral system consisting different type of the particles such as electron, ion, neutral atom and dust grain. Study of complex plasmas for practical purposes became especially important after finding of dust structures in the plants of the plasma spraying, because such structures have a negative impact on the quality of deposited samples. Later it was known that the complex plasma is widely distributed in the interstellar space. In gas discharge plasma main role have the collective behavior of particles due to long range character of Coulomb potential. Quantum effects in the complex gas-discharge plasma do not play a big role, but are important in space plasma.

Collective effects that appear in the plasma can be studied using effective interaction potentials. Effective interaction potential of particles which takes into account many particle correlation effects can be found by the method of dielectric functions.

For classical plasma screening is important for consideration at large distances, whereas in the semiclassical approximation the diffraction effects at small interparticle distances, which removes the singularity of the interaction, should be taken into account. The interaction micropotentials of the charged particles taking into account the effects of diffraction are presented in Refs. [1,2].

Interaction of an electron and an atom is caused by the polarization of an atom under the impact of an electric field of the charged particle. In Refs. [3,4] the screening potential of Buckingham is used as an effective potential. The interaction of charged particles and charged particles with atoms were considered in detail in Refs [5-10].

The interaction potential between polarized dust grains. Ions and electrons can be described by the model of the point like charged particles. Dust component of complex plasma in comparison with other components have more large size and charge. Additionally most of all complex plasma observed in non equilibrium state under external fields. Thus, different mechanism of the polarization is possible. We do not consider mechanism of the polarization. In general dipole-dipole effective interaction potentials are obtained. The value of the dipole moment which obtained on the basis of the some polarization mechanism can be substituted in the final equation for effective interaction potential. In experimental setup main contribution to the polarization of plasma around dust grain gives by ion component because temperature of the electrons more large than temperature of the ions. Let's consider a system of charges: the dust particles, the ion cloud in an external field of the second dust particle. One can suppose that the field relative to a system of dust particles and the cloud of ions is semihomogeneous.

Interaction micropotential of dust particles (dipoles):

$$\varphi = \frac{eZ}{R}\left(eZ + \frac{m}{R}\right) , \tag{1}$$

where $m = \vec{n}(\vec{d}_1 - \vec{d}_2)$ is the scalar product of unit vector along line between centers of two dipoles $\vec{n}$ and vector difference of dipole moments of grains, Z -charge number of the dust grain.

Its Fourier transform has the following form:

$$\tilde{\varphi} = \frac{4\pi e^2 Z}{k^2} - \frac{2\pi^2 eZm_{ij}}{k} ,$$

The dielectric function is taken as:

$$\varepsilon = 1 + \frac{n_i}{k_B T_i}\tilde{\phi}_{ii} + \frac{n_d}{k_B T}\tilde{\phi}_{di} , \tag{2}$$

where $\tilde{\phi}_{ii} = 4\pi q^2 / k^2$, q -charge of the ion.

We find the interaction pseudopotential in the random phase approximation on the basis of micropotential (1). From linear response theory it is known that Fourier transform of the pseudopotential is obtained from the relation:

$$\tilde{\Phi}(q) = \frac{\tilde{\varphi}(q)}{\varepsilon(q)} , \tag{3}$$

After Fourier transformation one can obtain the formula for effective interaction potential between electron and dust particle:

$$\Phi = \frac{1}{r}\left[Ah\left(K_1 r\right) + Bh\left(K_2 r\right)\right] + \frac{eZm_{ij}}{r^2} . \tag{4}$$

For convenience, we define the following function and the coefficients:

$$h(ar) = \cos(ar)\left(\pi + Si(ar)\right) - Ci(ar)\sin(ar),$$

$$A = 2\pi^2 e^2 Z^2 \left(1 + \frac{1}{\sqrt{1-4\mu^2/r_D^2}}\right) + \frac{eZm_{ij}}{\mu}\left(1 + \frac{1-\mu^2/r_D^2}{\sqrt{1-4\mu^2/r_D^2}}\right), \qquad (5)$$

$$B = 2\pi e^2 Z^2 \left(1 - \frac{1}{\sqrt{1-4\mu^2/r_D^2}}\right) + \frac{eZm_{ij}}{\mu}\left(1 - \frac{1-\mu^2/r_D^2}{\sqrt{1-4\mu^2/r_D^2}}\right),$$

$$K_{1/2} = \frac{1}{2}\left(1/\mu \pm \sqrt{1/\mu^2 - 4/r_D^2}\right).$$

Pseudopotential of the charge-atom interaction. We choose the interaction micropotential between charge and atom in the following form:

$$\varphi_0 = -\frac{e^2\alpha}{2(r^2 + r_B^2)^2}, \qquad (6)$$

where $r_B^4 = \frac{\alpha a_B}{2}$, $a_B = \hbar^2/(me^2)$ is the Bohr radius.

Using the formula (3) for classical and semiclassical cases following expressions was obtained:

$$\Phi = -\frac{e^2\alpha}{2(r^2 + r_B^2)^2} + \frac{e^2\alpha\cos(r_B/r_D)}{4r_B r_D^2}\frac{\left[\pi/2 - arctg(r_B/r)\right]}{r}, \qquad (7)$$

$$\Phi = -\frac{e^2\alpha}{2(r^2 + r_B^2)^2} + \frac{e^2\alpha\left(\cos(r_B C_2) - \cos(r_B C_1)\right)}{4r_B r_D^2\sqrt{1-4\lambda\!\!\!^{-}{}^2/r_D^2}}\frac{\left[\pi/2 - arctg(r_B/r)\right]}{r}, \qquad (8)$$

here:

$$C_1^2 = \left(1 + \sqrt{1-4\lambda\!\!\!^{-}{}^2/r_D^2}\right)/(2\lambda\!\!\!^{-}{}^2),$$

$$C_2^2 = \left(1 - \sqrt{1-4\lambda\!\!\!^{-}{}^2/r_D^2}\right)/(2\lambda\!\!\!^{-}{}^2), \qquad (9)$$

and $\lambda\!\!\!^{-}$ is the wavelength of charged particles.

The quantum pseudopotential for pair interaction of particles. The interaction potential which takes into account the quantum effects of diffraction due to the uncertainty principle and the symmetry effects due to the Pauli bloc principle, was obtained by the equality of the Slater sum:

$$S(r_1,...,r_N) = c\sum_n \Psi_n^* e^{-\beta E_n} \Psi_n \ , \tag{10}$$

where:
$$c = \Pi N_\nu ! \lambda_\nu^{3N_\nu} \ , \tag{11}$$

$$\lambda_\nu^2 = 4\pi\alpha_\nu\beta, \quad \alpha_\nu = \hbar^2/2m_\nu, \quad \beta = 1/kT \tag{12}$$

to the classical Boltzmann factor. In these equations, N_ν is the number of particles of the ν-th sort, which have a mass m_ν and thermal wavelength λ_ν. The wave function is a properly symmetrized eigenfunction for the entire macroscopic system with eigenvalue E_n, where n represents a complete set of quantum numbers.

For the region of temperatures $10^4 K < T < 10^8 K$ and densities $10^{21} cm^{-3} < n \le 10^{24} cm^{-3}$ the following interpolation formula was obtained:

$$u_{ab}(r) = \frac{e_a e_b}{r}\left\{1 - th\left(\frac{\lambda_{ab}^2}{a_0^2 + br^2}\right)\exp\left[-th\left(\frac{\lambda_{ab}^2}{a_0^2 + br^2}\right)\right]\right\}\left(1 - e^{-r/\lambda_{ab}}\right), \tag{13}$$

where $a_0 = (3/4\pi n)^{1/3}$ is an average interparticle distance and $b = 0.033$, which in the limit $T \to \infty$ coincides with the Deutsch potential:

$$u_{ab}\Big|_{T>10^8 K} = \frac{e_a e_b}{r}\left(1 - \exp[-r/\lambda_{\alpha\beta}]\right) \ . \tag{14}$$

For dense plasma $r_s = a_0/a_B \le 3$ potential (13) weakly depend on changing of density and can be expressed in the form:

$$u_{ab}(r) = \frac{e_a e_b}{r}\left\{1 - th\left(\frac{\lambda_{ab}^2}{a_B^2}\right)\exp\left[-th\left(\frac{\lambda_{ab}^2}{a_B^2}\right)\right]\right\}\left(1 - e^{-r/\lambda_{ab}}\right). \tag{15}$$

It should be noted that the potential (13) does not take into account symmetry effect.

Reference

[1] Kelbeg, G., Ann. Phys. **12**, 219 (1963)
[2] C. Deutsch, Ann. Phys. (N.Y.) **115**, 404 (1978).
[3] R.Redmer, Phys. Rev. E **59,** 1073 (1999).
[4] S.Kuhlbrodt, R.Redmer, Phys. Rev. E **62,** 7191 (2000).
[5] W.Ebeling, H.Hache, H.Juranek, R.Redmer, G.Roepke, Contrib. Plasma Phys. **45,** 160 (2005).
[6 T.S.Ramazanov, K.N.Dzhumagulova, Yu.A.Omarbakiyeva, Phys. Plasmas **9,** 092702-1-4 (2005).
[7] T.S.Ramazanov, K.N.Dzhumagulova, Yu.A.Omarbakiyeva, Phys. Plasmas **9,** 092702-1-4(2005).
[8] Baimbetov F.B., Nurekenov Kh.T., Ramazanov T. S., Phys. Letters A, **v. 198** (1995)
[9] Baimbetov F.B., Bekenov M.A., Ramazanov T.S., Phys.Rev., v. **50**, N8 (1994)
[10] T.S. Ramazanov and K.N. Dzhumagulova., Physics of Plasmas. **9**, 3758 (2002)