*33rd EPS Conference on Plasma Phys. Rome, 19 - 23 June 2006 ECA Vol.**30I**, P-4.035 (2006)*

Influence of the ion collisions on the interaction between dust grains and drag force

S.A. Maiorov

A.M. Prokhorov General Physics Institute of RAS, Moscow, 119991, Russia

1. Introduction. We consider here a new phenomenon, namely, the appearance of a reactive force accelerating the dust particle against ion flux. The mechanism of this force rests on collisions of ions of flow with buffer gas atoms and on the momentum transfer from the flow of ions accelerated additionally in the dust particle field to gas atoms (upon resonance charge exchange of ion and parent gas atom). As a result, the atoms (that were ions before resonance charge exchange) take off a larger momentum from the "ions + dust particle" system than they had carried in, which creates a reactive force directed against the flux (negative friction force) [1 - 3].

The forces acting between dust particles due to resonance charge exchange of ions is considered in paper [4]. Radial flow of atom is generated due to resonance charge exchange collisions of trapped ions. This atom flux in effect represents an repulsive force between grains, which has been called the recombination force. This force is an inverse square force, like the bare Coulomb force.

2. Reactive friction force. Let there exist a flow of singly positively charged ions with charge $e>0$ and mass m incident from infinity along axes x onto motionless negatively charged sphere having radius a and charge $Q=-eZ<0$. We shall assume that dust particle radius, the screening length, and the mean free path of the ion before charge exchange with atom satisfy the conditions $a \ll \lambda_D \ll \lambda_{st}$ and the temperatures of electrons, ions, and atoms satisfy the conditions $T_e \gg T_i \approx T_a$.

In experiments with dust particles levitating in the near-electrode layer the kinetic energy of incident ions flux is approximately equal in the order of magnitude to the electron temperature and, accordingly $K_\infty = \frac{1}{2} m \mathrm{v}_\infty^2 \gg T_a$. The ion that was formed from the atom as a result of resonance charge exchange has the mean kinetic energy $\frac{3}{2} T_a \ll K_\infty$ and velocity distribution determined by the atom temperature. Consequently, the resonance charge exchange decreases the total ion energy on the average by the quantity $K_\infty - 3T_a/2$.

A dust particle is so charged that its charge creates a considerable Coulomb barrier for electrons. The surface potential of the dust grain has the value $e|\varphi(a)| \sim (2 \div 4)T_e$. Hence, when $T_e >> T_a$, a certain volume V_0 exists near a dust particle, such that the ion that was formed from the atom appear to be trapped in the potential well of the dust particle. In this case, consequent collisions the ion most likely to reach the dust particle surface and to recombine on it.

The momentum conversation law implies that the resultant change dust particle momentum is determined by the difference between the ion momentum at infinity and the momentum of atoms produced upon charge exchange collision $\Delta p_x(r,\Delta V) = \Delta p_{1x}(r)\Delta N_{st}$, where a momentum transfer to the dust particle in one act of charge exchange is equal $\Delta p_{1x}(r) = mv_\infty - mv_x$.

From the law of conversation of the total energy of ion moving in the potential field of a dust particle it follows that its kinetic energy is $K(r) = K_\infty - e\varphi(r)$. Using the linear path approximation of moving in the Coulomb potential $\varphi(r) = Q/r$, we obtain the following estimate for the mean momentum transfer to the dust particle due to a single collision at an arbitrary point of the volume V_0: $\Delta p_{1x} = mv_\infty - \sqrt{2mK(r)} \approx -\left|\frac{e\varphi(r)}{v_\infty}\right|$. The reactive friction force is defined as momentum transfer per unit time and is obtained as a result of integration over the volume V_0: $F_x = \int_{V_0} \frac{n_i v}{\lambda_{st}} \Delta p_{1x} dV$ .Assuming that the volume is bounded by the sphere of radius $r_0 >> a$ the potential inside which varies by the Coulomb law and the values of ion density and velocity $n_i(r) \approx n_{i0}, \mathrm{v}(r) \approx \mathrm{v}_\infty$ we obtain $F_x = \int_a^{r_0} \frac{n_{i0} v_\infty}{\lambda_{st}} \frac{eQ}{r v_\infty} 4\pi r^2 dr \approx -2\pi r_0^2 n_{i0} \frac{e^2 Z}{\lambda_{st}}$. Assuming $e|\varphi(a)| \sim 3T_e$ we obtain $F_x \approx -\pi r_0^2 n_{i0} T_e \frac{6a}{\lambda_{st}}$. The main consequence of the obtained estimate of the reactive friction force is its sign. The reactive friction force is directed against the ion flux incident on the dust particle, i.e., under the action of such a friction force the dust particle speeds up against the flux.

For a comparative analysis it is necessary that the volume V_0 be estimated. The simplest way of doing this is its determination in terms of the radius on which the potential energy in the dust particle field is of the order of the atom temperature. Assuming $e|\varphi(a)| \sim 3T_e$, we arrive at $r_0 = a\dfrac{e|\varphi(a)|}{T_a} \sim 3a\dfrac{T_e}{T_a}$. It should be taken into account, however, that the screening effects, non-Debye behaviour of the potential at large distances, the presence of the external electric field, and the ion focusing – all this factors can complicate substantially the determination of the volume V_0. For instance, a strong screening can give $r_0 \sim \lambda_D$. As result, we come to $F_x \approx -\pi a^2 n_{i0} T_e \dfrac{60a}{\lambda_{st}}\left(\dfrac{T_e}{T_a}\right)^2 \propto a^3$.

3. MD simulations. The results obtained were checked by the method of molecular dynamics. All the parameters and the statement of the problem are the same as in paper [5]. The statement of the problem is described in detail in paper [5], but we allowed additionally for collisions with atoms and for the appearance, as a result of charge exchange, of ions with a temperature of cold gas.

Results of calculations using the MD method are presented in [1, 2]. Figures present the calculated ion densities from paper [5] and the same with an additional allowance for the ion-atom resonance charge exchange collisions. As should be expected, the ion-atom resonance charge exchange collisions induce the appearance of a large number of bound ions, which in turn leads to a change in the character of the ion density distribution. From the typical wake tail of the ion focus in [5] a transition is observed to the distribution close to the spherically symmetric distribution. The result of calculation of the friction force is even more impressive. The ion-atom resonance charge exchange collisions being included, the sum friction force decreases almost a hundred times and even reverses sign to become negative.

4. The recombination force. Let there exist a motionless negatively charged sphere having radius a and charge $Q=-eZ<0$. Around a negatively charged dust particle a cloud of bound (trapped) 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. But independence of the number of bound ions (and, accordingly, of their influence upon screening) on the collision frequency was first discovered in paper [1] (also see [6]). Consequently, a large number of bound ions can be accumulated even in a collisionless plasma because of arbitrarily rare collisions.

The momentum transfer by atoms in radial direction (that were ions before a resonance charge exchange collision) through unit area (recombination pressure): $P_{rec} \approx \frac{\Delta p_1 J_{i\,rec}}{4\pi r^2}$.

We obtain the following estimate for the mean momentum transfer due to a single collision at an arbitrary point of the volume V_0 : $\Delta p_{1s} = \sqrt{2MK(r_s)} - Mv_0 \sim |2e\varphi(r_s)M|^{1/2}$.

A momentum transfer due to one act of trapped ion recombination is equal $\Delta p_1 \sim \sqrt{2MT_e}$,

recombination flux to the grain is defined by collisions near grain

$J_{rec} = \int_a^{r_0} \frac{n_i \mathrm{v}}{\lambda_{st}} 4\pi r^2 dr \approx \frac{4\pi r_0^3 n_{i0} \mathrm{v}_0}{3\lambda_{st}}$, where $r_0 = a\frac{e|\varphi(a)|}{T_a} \sim 3a\frac{T_e}{T_a}$

and recombination pressure is equal

$$P_{rec} \approx n_{i0} T_e \frac{a^3 z^3 \tau^{5/2}}{\lambda_{st} r^2}$$

Repulsion of grains due to recombination pressure is $F_{rec} = \pi a^2 P_{rec} \propto a^5$

The mechanism of the occurrences of the recombination force between dust particles in a plasma is described. This force is associated with the resonance charge exchange collisions of trapped ions and a parent gas atoms near the dust particle. This force is an inverse square force, like the Coulomb force.

5. Acknowledgments. I am thankful to the Russian Foundation for Basic Research and the N.W.O. (The Netherlands) for financial support.

References

[1]. S. A. Maiorov // Plasma Physics Reports, Vol. 31, No. 8, 690 (2005)

[2] S.A. Maiorov, Bulletin of the Lebedev Physics Institute, No. 6, 27 (2004).

[3] I.V. Schweigert, A. Alexandrov, F.M. Peeters, IEEE Trans. Pl. Sc. 32(2), 623 (2004).

[4]. S. A. Maiorov, Bulletin of the Lebedev Physics Institute, No. 5, 14 (2005).

[5] S.A. Maiorov, S. V. Vladimirov, N. F. Cramer, Phys. Rev. E. 63, 017401 (2001).

[6]. S. A. Maiorov // Plasma Physics Reports, Vol. 32, (2006).