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The reactive ion-drag force in dusty plasmas

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1. Introduction

In paper [1] in was found for the first time that the number of bound ions located on orbits around the dust particle (and correspondingly their effect on screening) do not practically depend on the frequency of ion-atom collisions. Under conditions typical of dust plasma experiments the collisional relaxation with atoms leads to the formations of a cloud of bound ions around negatively charged dust particle, which has a notable effect on dust particle charge screening. Furthermore, bound ions increase the ion flow onto the dust particle, and accordingly its charge is reduced [2 - 4].

The possibility of the appearance of a negative friction force for Coulomb collisions is discussed in papers [5], the ion drag force in a screened potential is considered in paper [6]. The friction force due to ion-atom collisions with resonance charge exchange is analyzed for the first time in present paper.

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.

Number collisions $\Delta N_{st}(r) = n_i v \Delta V \ \Delta t/\lambda_{st}$ will occur within time interval Δt in a small volume ΔV near a point at a distance r from a dust particle centre, n_i is ion density, v is ion velocity, and λ_{st} is the ion mean free path before resonance charge exchange with atom. The average momentum of ions produced from atoms upon charge exchange is equal to zero because gas atoms have an isotropic velocity distribution function (the dependence of charge exchange cross section on velocity can be ignored because of the mall atom velocity). Therefore a dust particle does not change its momentum when trapped ions recombined on its surface. 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

$$F_x \approx -\pi r_0^2 n_{i0} T_e \frac{6a}{\lambda_{st}}. \qquad (1)$$

The main consequence of the obtained estimate of the reactive friction force (1) 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.

Another interesting consequence of (1) is that the reactive friction force is independent of the flow velocity. One should bear in mind that because of the trajectory curvature in the vicinity of the dust particle a weak dependence does exist, and a more accurate calculation will evidently give a larger friction force value.

3. Comparison with other forces

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

$$r_0 = a\frac{e|\varphi(a)|}{T_a} \sim 3a\frac{T_e}{T_a}. \qquad (2)$$

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 [2], and the ion focusing – all this factors can complicate substantially the determination of the volume V_0. For instance, a strong screening can give $r_0 \sim \lambda_D$. Substituting (2) to (1), we come to

$$F_x \approx -\pi a^2 n_{i0} T_e \frac{60a}{\lambda_{st}}\left(\frac{T_e}{T_a}\right)^2 \propto a^3 \qquad (3)$$

The friction force due to scattering in Coulomb field of dust particle is equal

$$F_{Coul} = n_{i0}\frac{2\pi e^4 Z^2}{K_\infty}\Lambda \sim 18\pi a^2 n_{i0}\frac{T_e^2}{K_\infty}\Lambda \propto a^2. \qquad (4)$$

The gravitational force is $F_g = \frac{4\pi a^3}{3}\rho g \propto a^3$. An interesting feature is that besides the reactive friction force (3), the gravitational force alone is proportional to dust particle volume, while all the other forces are proportional to its area.

4. 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 [7]. The statement of the problem is described in detail in paper [7], 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 [4, 8]. Figures present the calculated ion densities from paper [7] 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 [7] 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.

5. Conclusions

The mechnism of the occurence of the reactive force actin on a dust particle in a plasma flow is described. This force is associated with the resonance charge exchange collisions of ions and a parent gas atoms near the dust particle. Its magnitude does not depend on the flow velocity, is proportional to the dust particle volume and to the frequency of the ions charge exchange collision.

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7. References

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