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## Dust charge distribution in a plasma afterglow

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Discharging of dust particles in an argon plasma afterglow was investigated. The study was carried out using different approaches. First, we obtained the dust charge distribution function (DCDF)  $F_k$  by solving numerically the master equation [1]:

$$\frac{d}{dt} F_k = \nu_{ed}^{k+1} F_{k+1} - \nu_{ed}^k F_k - (\nu_{id}^k + \nu_m) F_k + (\nu_{id}^{k-1} + \nu_m) F_{k-1}, \quad (1)$$

where  $t$  is the afterglow time,  $\nu_{ed}^k$  and  $\nu_{id}^k$  are the frequencies with which a particle with charge  $Z_d^k = ke$  collects electrons and ions, respectively,  $k$  is an integer and  $e$  is the elementary charge.  $\nu_m$  is the frequency describing electron emission from the dust surface at collisions of dust particles with argon atoms in excited states. The DCDF is normalized by  $\sum_k F_k = 1$ .

We also calculated the mean dust charge  $Z_d$  using the following expression

$$\frac{\partial Z_d}{\partial t} = \nu_{id} + \nu_m - \nu_{ed}, \quad (2)$$

where  $\nu_{id}$  and  $\nu_{ed}$  are, respectively, the frequencies describing collection of ions and electrons by a dust particle with the charge  $Z_d$ .

We also compared the DCDF calculated from Eq. (1) with the Gaussian distribution [1]:

$$F_{Gk} = \frac{1}{(2\pi\sigma_z^2)^{1/2}} \exp\left[-\frac{(-Z_d^k + Z_d)^2}{2\sigma_z^2}\right], \quad (3)$$

where  $Z_d$  is determined by Eq. (2), and the variance  $\sigma_z^2$  as a function of time is found from the following equation [1]:

$$\frac{d\sigma_z^2}{dt} \approx -\alpha_1' \sigma_z^2 + \alpha_2, \quad (4)$$

where  $\alpha_1' = 2(\nu_{ed}' - \nu_{id}')$  with primes indicating derivatives with respect to  $Z_d$ ,  $\alpha_2 = \nu_{ed} + \nu_{id} + \nu_m$ .

Using Eqs. (1) - (4), we calculated the dust charge distribution function, mean dust charge and variance in an argon afterglow plasma, as functions of time. The calculations were

carried out for the plasma with radius  $R=2$  cm and height  $L=3$  cm (the plasma sizes here are the same as in [2]). It was assumed that the plasma contains electrons with density  $n_e$ , singly charged positive argon ions with density  $n_i$ , ground-state argon atoms with density  $n_a$ , metastable argon atoms ( $\text{Ar}_m$ ) with density  $n_m$ , argon atoms in the resonance 4s states ( $^3\text{P}_1$  and  $^1\text{P}_1$ ) ( $\text{Ar}_r$ ) with density  $n_r$  as well as argon atoms in 4p states ( $\text{Ar}_{4p}$ ) with density  $n_{4p}$ . We assumed that at  $t = 0$ ,  $n_e = n_i = 5 \times 10^9 \text{ cm}^{-3}$  and that the plasma contains dust particles with density  $n_d = 5 \times 10^4 \text{ cm}^{-3}$ , as in [2], and radius  $a_d$ . The results were obtained for different dust radii. The study was carried out taking into account for the transition from ambipolar to free diffusion in the plasma afterglow. The electron diffusion was described in the same manner as in [3], while the ion diffusion as in [4]. The neutral gas pressure was taken to be  $P = 0.3$  Torr, as in [2]. In [5], one can find the results for the  $P = 0.9$  Torr case additionally.

The results were obtained taking into account secondary electron emission in the collisions of excited argon atoms  $\text{Ar}^*$  ( $\text{Ar}_m$ ,  $\text{Ar}_r$  and  $\text{Ar}_{4p}$ ) with dust particles (for the secondary emission yield  $\gamma_m=0.035$ ), as well as neglecting by this process ( $\gamma_m = 0$ ). Since the value of  $\gamma_m$  is not known for the conditions considered here, we used in our simulations the value leading to a good agreement with experimental data [2]. More details on our model can be found in [5].

Fig. 1 shows that the initial  $|Z_d|$  increases if  $a_d$  becomes larger, because of larger surface collecting electrons from the plasma volume. The absolute value of mean dust charge decreases faster with time in the beginning of afterglow, if dust size is larger [Fig. 1 (a)], due to larger dust charging time (see Fig. 1 (c) in [3]). Moreover, at late afterglow times, the absolute value of mean dust charge may become larger for smaller  $a_d$  [Fig. 1(a)]. In particular,  $|Z_d|$  for  $a_d = 5$  nm is larger than the absolute values of mean dust charge for  $a_d = 10$  nm and  $a_d = 20$  nm. This is mainly due to smaller  $\nu_{id}$  in the  $a_d = 5$  nm case compared with the frequencies in the  $a_d = 10$  nm and  $a_d = 20$  nm cases. Note that the secondary emission in metastable-dust collisions affects more essentially the charge of larger dust particles. At late afterglow times ( $t = 100$  ms),  $|Z_d|$  is 2.37 (2.37), 4.61(4.56), 3.36(3.2), 3.59(3.2), 6.8(5.17), 10.7(6.04), 16.61(3.24) for  $a_d = 1$  nm, 5 nm, 10 nm, 20 nm, 50 nm, 100 nm, 200 nm at  $\gamma_m = 0$  ( $\gamma_m = 0.035$ ), respectively. Thus, at  $t = 100$  ms and  $\gamma_m = 0.035$ , the absolute value of mean dust charge for  $a_d = 200$  nm is smaller than  $|Z_d|$  for  $a_d = 5, 50$  and 100 nm because of the secondary emission. It is not the case for  $\gamma_m = 0.0$ .

At late afterglow times, the mean charges of dust particles with different  $a_d$  may be nearly the same (see  $|Z_d(t)|$  in Fig. 1 (a) for  $a_d = 10$  nm, 20 nm and 200 nm), while the variances are very different [Fig. 1 (b)]. Similarly, the variances for different  $a_d$  may be nearly the same

(see  $\sigma_z^2$  in Fig. 1 (b) for  $a_d = 5$  nm and 10 nm), while the mean charges differ essentially [Fig. 1 (a)].

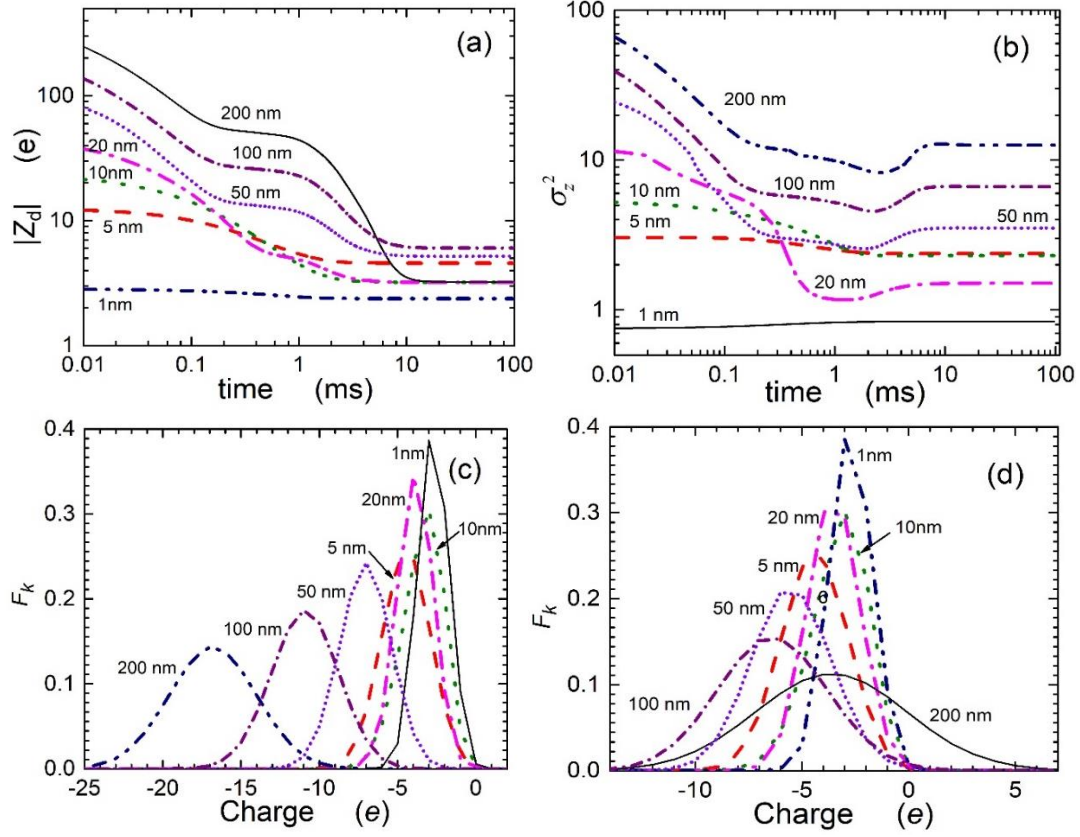


Fig. 1. The mean dust charge (a) and the variance (b) for  $\gamma_m=0.035$ , and the dust charge distribution function obtained from Eq. (1) at  $t = 100$  ms for  $a_d = 1$  nm, 5 nm, 10 nm, 20 nm, 50 nm, 100 nm and 200 nm in the  $\gamma_m=0$  (c) and  $\gamma_m=0.035$  (d) cases.

In our opinion, this is due to changing the dust charging time and the variance at a variation of  $a_d$ . For large dust particles ( $a_d \geq 20$  nm) and  $t \geq 0.3$  ms, the variance increases with growth of  $a_d$  [Fig. 1 (b)]. This conclusion can be also obtained using the OML approach for the steady-

state case at  $\gamma_m = 0$  ( $\sigma_z^2 \approx \frac{(1 + v_{ed}/v_{id})a_d T_e}{2e(\tau/(1 + \tau|z|) + v_{ed}/v_{id})} \propto a_d$ , where  $\tau = T_e/T_i$ ,  $T_e$  and  $T_i$  are the

electron and ion temperatures, respectively, and  $z = eZ_d/a_d T_e$ ). The variance depends also on

$\gamma_m$ , and at late afterglow times for large dust particles,  $\sigma_z^2$  in the case of  $\gamma_m=0.035$  is larger than that in the case of  $\gamma_m=0$ . At  $t=100$  ms, the variance is 0.83 (0.83), 2.34 (2.37), 2.21 (2.3), 1.28 (1.5), 2.67 (3.52), 4.51 (6.65) and 7.66 (12.57) for  $a_d = 1$  nm, 5 nm, 10 nm, 20 nm, 50 nm, 100 nm and 200 nm at  $\gamma_m=0$  ( $\gamma_m=0.035$ ), respectively.

Note that at late afterglow times, most dust particles in the  $\gamma_m = 0$  case are negatively charged, independently on their size [Fig. 1(c)]. In the  $\gamma_m = 0.035$  case, rather large amount of dust particles with  $a_d = 200$  nm are positively charged, while the particles of smaller size are mainly negatively charged. This is due to the fact that for large dust particles,  $\sigma_z^2$  is larger and  $|Z_d|$  is smaller in the  $\gamma_m = 0.035$  case compared with the corresponding values obtained at  $\gamma_m = 0$  [5]. For small  $a_d$  ( $\leq 10$  nm), the DCDF in the  $\gamma_m = 0.035$  case is nearly the same as the one obtained for  $\gamma_m = 0$ , because  $\sigma_z^2$  and  $|Z_d|$  are also nearly the same in the both cases.

We also calculated the dust charge distribution functions at  $a_d = 190$  nm (as in the experiments [2]) and compared them with the measured DCDF [Fig. 2(a)]. It was found that the calculated DCDF agrees well with the one obtained in experiments [2], if our model accounts for the secondary emission with  $\gamma_m = 0.035$  [Fig. 2(a)]. At  $\gamma_m = 0$ , the calculated DCDF is shifted to the region of smaller charge (larger  $|Z_d|$ ) compared with the charge distribution function measured in the experiment. The charge distribution calculated from Eq. (1) at  $\gamma_m = 0.035$  was also compared with the Gaussian distribution obtained using Eqs. (2)- (4). It was found that  $F_{Gk}$  approximates rather well the DCDF obtained from the master equation (1) [Fig. 2(b)].

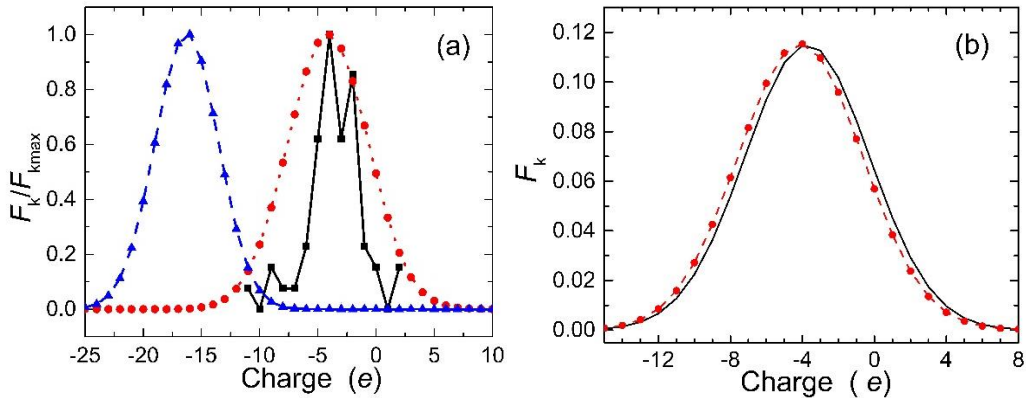


Fig. 2. The normalized DCDFs calculated at  $t = 100$  ms in the  $\gamma_m = 0$  (dashed curve) and  $\gamma_m = 0.035$  (dotted curve) cases and the DCDF obtained in experiments [2] (solid curve) (a). The dust charge distribution functions calculated at  $\gamma_m = 0.035$  from Eq. (1) (dashed curve) and the Gaussian distribution obtained from Eq. (3) (solid curve). Here,  $a_d = 190$  nm and  $F_{k_{\max}}$  corresponds to the DCDF maximum.

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