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Simulation Studies on Grain Charging / Coagulation in Dusty Plasmas

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Abstract

We have developed a new particle simulation code for grains which are dynamically charged by the background plasma. Here, not only the regular attachment effect of the electrons and ions, but also the effects of the secondary electron emission and the coagulation of grains are taken into account. Simulation results show that all the grains change their charge randomly from negative to positive, or positive to negative in the way of "flip-flop" as the time passes by. The flip-flop effect is outstanding when the radius of the grains is of the order of 10nm, and such grains with opposite charges coagulate with each other to grow.

Keywords:
dust plasma, simulation, charging, coagulation, flip-flop effect

1. Introduction

The dust grains are found in planetary plasmas. They are considered to play an important role in the formation of the structure, e.g., the rotating radial spokes of the Saturn's rings. The dust grains also become important and interesting in various processing plasmas.

The dust grains are usually considered to be charged negative because electrons of the background plasma attach to the grains more frequently than ions due to the difference between their thermal speeds. Meyer-Vernet, however, pointed out that it is possible for the grains to change their charges from negative to positive or from positive to negative in the way of "flip-flop", when the secondary electron emission effect from the grains is taken into account [1]. His theory is static one, but it can be extended to the dynamic one. In this study, we are investigating the dynamic charging process of the dust grains and the detailed feature of the charging and coagulation processes.

Our final goal is to clarify the physical mechanism of the ordered structure formation from the viewpoint of "Self-organization". For this purpose, we have developed a dynamical charging scheme and a new dust particle simulation code in which a dynamic charging process of the grains including the secondary electron emission effect and the coagulation effect between the grains are taken into account.

2. Simulation Scheme

The average number of attachment per unit time is given by the background plasma distribution function.

$$\text{if} - q_\alpha \phi > 0,$$

$$N_\alpha = 4\pi\alpha^2 n_\alpha \sqrt{\frac{kT_\alpha}{2\pi m_\alpha}} \left[1 - q_\alpha \phi / kT_\alpha\right], \quad (1)$$

$$\text{if} - q_\alpha \phi < 0,$$

$$N_\alpha = 4\pi\alpha^2 n_\alpha \sqrt{\frac{kT_\alpha}{2\pi m_\alpha}} \exp\left[-q_\alpha \phi / kT_\alpha\right], \quad (2)$$

where ϕ and a are the surface potential and the radius of

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the grain, respectively, and α indicates electron or ion, n_α, q_α, T_α, m_α are the density, charge, temperature and mass of α species, respectively. Here, the background plasma distribution is assumed to be Maxwellian.

The attachment of electrons and ions to dust grains is considered to occur according to Poisson process [2]. Therefore, using above average number, namely, the average probability for Poisson process, the time intervals of the attachment to each grain are determined by the random number at every time step in the simulation.

In addition to the above regular attachment effect, the secondary electron emission is taken into account when the kinetic energy of the colliding electron is larger than a certain critical value, E_C. The number of the secondary electrons is given by [3]

$$N_{SE} = \delta(E) = A\, E \exp[-2\sqrt{E/E_M}], \tag{3}$$

if $\phi > 0$,

$$N_{SE} = \delta(E) \exp[\frac{q_e\phi}{kT_s}] \left(1 - \frac{q_e\phi}{kT_s}\right), \tag{4}$$

where E is the kinetic energy of the colliding electron; A and E_M are constants; T_s is the temperature of the secondary electrons.

Thus, the number of the electrons of the background plasma decreases due to the attachment to grains, and increases due to the secondary electron emission from the grain.

When the distance between the dust grains with opposite charge becomes less than a critical length, r_C, it is considered in this simulation model that they make coagulation and the change of the mass and radius of the coagulated grain as well as the change of the charge will occur. Namely, the mass and charge of such a grain is given by the summation of the coagulating grains, and the radius becomes large as to be proportional to 1/3 powers of the coagulated grain's mass.

It should be noticed that the rates of electron (ion) attachment, Eqs. (1) and (2), are depending on the potential and radius of each grain as well as the background plasma density. Therefore, depending on the conditions both of the grains and of the background plasma due to the effects of the attachment, secondary electron emission, and coagulation, the probability of the attachment itself is modified, In other words, the charging process is a nonlinear feedback system in itself.

The electrostatic potential field given by each grain at the distance of r is proportional to

$$Q_j / r \cdot \exp\{-r/r_d\}. \tag{5}$$

Here, Q_j and r_d are the charge and the Debye length of the j-th grain, respectively.

The dust grains, which are initially located around the center of the simulation box randomly without velocity and charge, are charged due to the background plasma and moved by the electrostatic potential field in the 2-dimensional open boundary system, as the time passes by.

The flow chart of the simulation procedure is shown in Fig. 1, where $r^{(j)}$, $v^{(j)}$, $Q^{(j)}$, $t_{atch}^{(j)}$ and are, respectively, the position, velocity, charge and the time when the electron or ion attachment to the j-th grain occurs next, and N_{ion} and N_{ele} are the total number of the ions and electrons of the background plasma.

3. Simulation Results

The temporal charge evolutions of 6 dust grains in the typical simulation run are shown in Fig. 2. Each panel corresponds to the each grain, and the charge is taken in the vertical axis from –200 e to +200 e.

It is clearly seen that the charges of all the grains change randomly from negative to positive, or positive to negative in the way of "flip-flop" as the time passes by. The lowest (negative) charge is determined by the balance between the attachment of the electrons and ions, while the highest (positive) charge is determined by the balance between the electron attachment and the secondary electron emission.

When the grain size is small enough, all the grains stay negatively charged as is shown in Fig. 3. The reason is as follows. Since the grain size is small, there are not so many electrons which attach to the grains. Then, the high energy electrons which can make secondary electron emission seldom collide with the grains.

In contrast with the small grain case, when the grain size is large enough, many electrons collide with the grains. Under the simulation parameters used here, the grains are positively charged which is shown in Fig. 4.

In the small and large grain cases, the grains, all of which are charged in negative or positive respectively, are repulsing each other to be scattered away from the simulation box, and thus, the simulation is ended at the earlier time.

When the grain size is appropriate, both the positively and negatively charged grains can exist simultaneously. Thus, such grains gather to coagulate

due to the attractive force between them.

In Fig. 5, the temporal evolutions of the spatial distribution of grains are shown. In the earlier stage, the grains which are located around the center of the simulation box are going toward the boundary (left panel). As the time goes, the grains are moving slowly towards the outer region of the system (center panel), and in the final state of the simulation run (right panel), the grains, especially, those around the center of the system, coagulate with each other. The position of the grains are indicated by "○" (the circle becomes large as the coagulation proceeds, but does not correctly reflect the size of the grain, which is much smaller).

Since the mass of the grain becomes larger than those of the others when the grain coagulates with the other grain, the coagulated grain plays a role of a nucleus for more coagulation. In the final stage of this simulation run, the largest grain consists of about 50 grains. Thus, the mass becomes 50 times larger than the original one, while the grain size becomes 3.7 times larger.

4. Summary

We have developed a new particle simulation code for dust grains which are dynamically charged by the background plasma. Here, not only the regular attachment effect of the electrons and ions, but also the effects of the secondary electron emission and the coagulation of grains are taken into account.

If the grain size is appropriate all the grains change

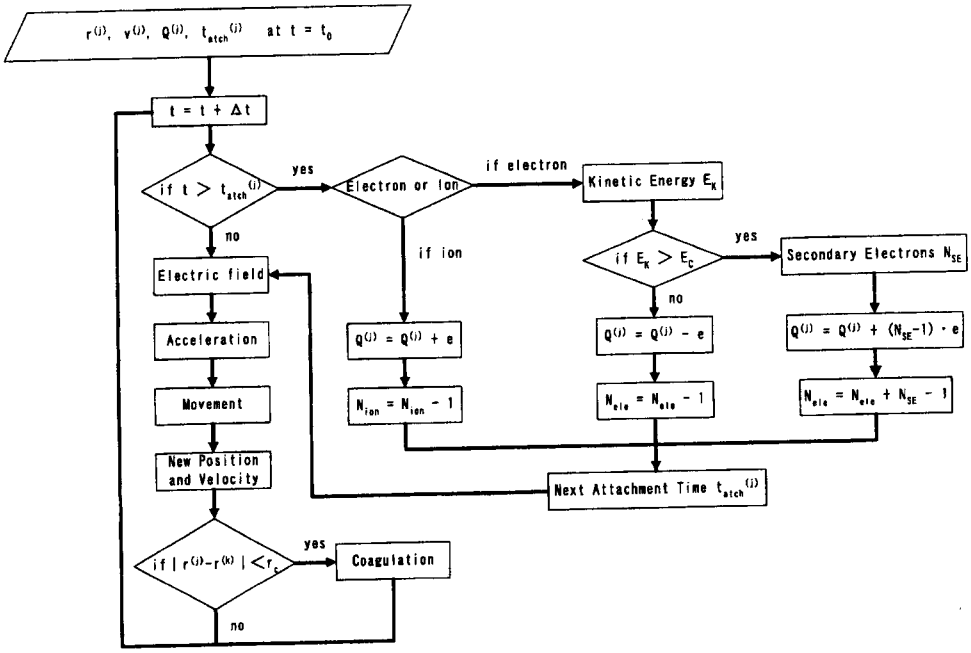

Fig. 1 The flow chart of the simulation procedure

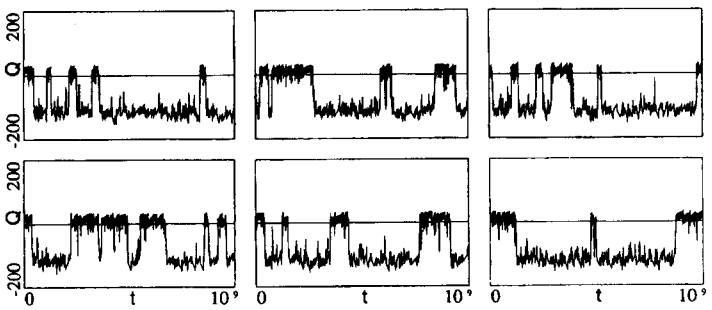

Fig. 2 The temporal charge evolution of the grains

their charge randomly from negative to positive, or positive to negative in the way of "flip-flop" as the time passes by. Such oppositely charged grains make a coagulation to grow. In the typical simulation parameters, the "flip-flop" effect, and hence, coagulation is outstanding when the grain size is of the order of 10nm. When the grain becomes large enough, the grain stops growing due to the following reasons. First, since the mass of the large grain is large, the coagulation between the large grains is almost impossible, and the coagulation between the small and large grains can not change much the size of the large grain. Second reason is that the attachment of single electron to the large grain does not affect much on the surface potential of the grain, and the "flip-flop" effect can not play a significant role.

Therefore, there is a suitable grain size for the rapid growth of the grains. This fact shows a good agreement with the experiments, in which grains grow farstest when the grain size is 10nm, and stop growing when the grain size becomes 100 ~ 200nm [5].

Since the secondary electron emission effect plays a significant role in this simulation, the precise treatment is quite important. For the number of secondary emission electrons, we employed the formula given by Sternglas [3]. It is pointed out by Chow that the secondary electron emission effect would be enhanced more than that given by Sternglas (Eqs. (3) and (4)), when the grain size is of the order of 10nm as is treated here [4]. If this enhancement is taken into account, the flip-flop effect shown in the present work becomes more active for the wider range of grain parameters.

References

[1] N. Meyer-Vernet, Astron. Astrophys **105**, 98 (1982).

[2] C. Cui and J. Goree, IEEE Trans. Plasma Phys. **22**, 151 (1994).

[3] E.J. Sternglas, *Sci. Pap. 1772*, Westinghouse Res. Lab., Pittsburgh (1957).

[4] V.W. Chow, *Dust-Plasma Interactions*, University of California, San Diego (1996),

[5] Y. Watanabe *et al.*, J. Vac. Sci. Tech. **A14**, 540 (1996).

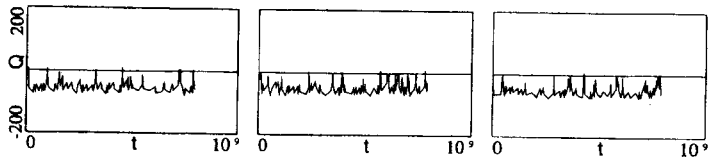

Fig. 3 The temporal charge evolution of the small grains

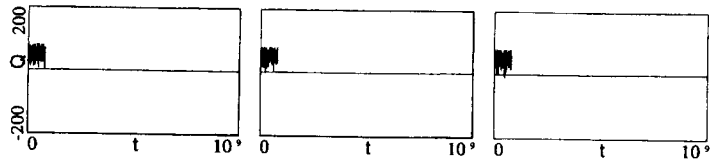

Fig. 4 The temporal charge evolution of the large grains

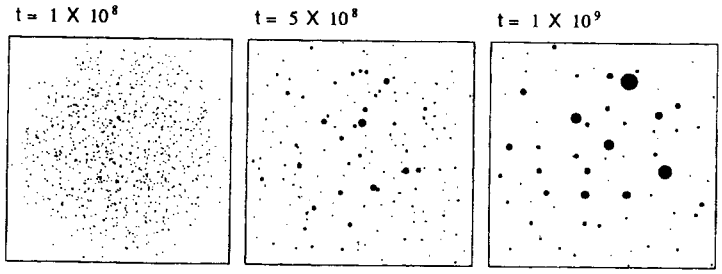

Fig. 5 The spatial distribution of grains at $t = 0$, $t = 5 \times 10^8\ \omega_{pe}^{-1}$, and $t = 1 \times 10^9\ \omega_{pe}^{-1}$. The circle becomes large as the coagulation proceeds.