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Structure of Dusty Plasma under Microgravity

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The structure of dust particles in dusty plasmas under microgravity has been analyzed by molecular dynamics simulation. The charge neutrality condition satisfied by the system composed of dust particles and ambient plasma is properly taken into account. It is shown that dust particles form shell structures at low temperatures and the number of shells are obtained as a phase diagram in the plane of two parameters characterizing the system: the number of particles and the strength of screening. It is also shown that these structures are almost independent of the strength of screening.

1. INTRODUCTION

Dusty plasma, systems of micron-sized dust particles immersed in ambient plasmas, provides us with a clear example of strongly coupled system whose structure and dynamics can be observed directly by CCD camera and naked eyes without X-ray or neutrons[1]. Their strong coupling is a result of large negative charges on dust particles. On the other hand, the large mass of macroscopic dust particles is not free from the gravity on earth. The experiments under the condition of microgravity are therefore expected to elucidate intrinsic properties of dusty plasmas which are not directly related to the effect of gravity.

In the first experiment on dusty plasmas under microgravity, the geometry of the system is determined by the parallel plate structure and the existence of void has been reported[2]. The formation of the latter itself is an interesting phenomenon and the exploration of its possible origin such as thermophoretic force, ion flow, or thermodynamics, is of much interest. The most important difference in the systems under microgravity and the one on earth, however, may be the isotropy of the environment. It may therefore be worth analyzing the structure of uniform and isotropic dusty plasmas of finite extension under microgravity and propose such experiments which realizes the isotropy of environment as a system.

2. FORMULATION

In this article we consider a system in a volume V composed of N_d dust particles, N_i ions, and N_e electrons and denote the charges of dust particles, ions, and electrons by $-Qe$, e, and $-e$, respectively. We assume that the system satisfies the condition of the charge neutrality

$$(-Qe)n_d + (-e)n_e + en_i = 0, \qquad (1)$$

where $n_d = N_d/V$, $n_i = N_i/V$, and $n_e = N_e/V$ are the densities of components.

When we take statistical average over electron and ion degrees of freedom in adiabatic approximation and neglect the effect of electron-electron, electron-ion, and ion-ion correlation, we arrive at the Yukawa system as a model for dust particles in dusty plasmas[3]. The Helmholtz free energy of the system of dust particles is then given by

$$U_{coh} + U_{sheath}, \qquad (2)$$

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where

$$U_{coh} = \frac{1}{2}\sum_{i\neq j}^{N_d} v(r_{ij}) - 2\pi N_d n_d \lambda^3 \frac{(Qe)^2}{\lambda}, \quad (3)$$

$$U_{sheath} = -N_d \frac{1}{2}\frac{(Qe)^2}{\lambda}, \quad (4)$$

and $v(r)$ is the Yukawa potential

$$v(r) = \frac{(Qe)^2}{r}\exp(-r/\lambda). \quad (5)$$

The parameter λ characterizes the screening by electrons and ions and is given by

$$\frac{1}{\lambda^2} = \frac{4\pi n_e e^2}{k_B T_e} + \frac{4\pi n_i e^2}{k_B T_i}, \quad (6)$$

where T_i and T_e are temperatures of ions and electrons, respectively. The latter temperatures are usually different from (higher than) that of dust particles T_d.

In U_{coh} given by (3), the second term is the internal energy for uniformly distributed Yukawa particles:

$$2\pi N_d n_d \lambda^3 \frac{(Qe)^2}{\lambda} = N_d \frac{n_d}{2}\int d\mathbf{r} v(r). \quad (7)$$

In other words, U_{coh} reduces to zero when dust particles are randomly distributed without correlation.

From the Poisson equation, the charge density $\rho(r)$ responsible for the screening of the Yukawa potential is calculated as

$$\begin{aligned} 4\pi\rho(r) &= -\mathrm{div}\cdot\mathrm{grad}[-\frac{Qe}{r}\exp(-r/\lambda)] \\ &= \frac{1}{\lambda^2}\frac{Qe}{r}\exp(-r/\lambda). \quad (8) \end{aligned}$$

The work which is necessary to form sheaths around N_d dust particles with the charge $-Qe$ is thus given by

$$N_d \frac{1}{2}\int d\mathbf{r}\rho(r)\left(-\frac{Qe}{r}\right) = -\frac{N_d}{2}\frac{(Qe)^2}{\lambda}, \quad (9)$$

where the factor $1/2$ comes from the linearity of the relation between $-Qe$ and ρ in the charging process. The term U_{sheath} is therefore the free energy of the sheath around dust particles. Note that this energy is independent of the correlation between dust particles and can be neglected when analyzing the structure of dust particles.

In what follows, we assume that the volume V is determined by some experimental condition such as the configuration of electrodes and other geometries and analyze the structures formed by dust particles. Under the condition of microgravity, we may assume that the volume take the form of a sphere of radius R.

In order to simulate the system in a sphere of volume V whose potential energy is given by (3), we introduce the uniform negative dust charge density which neutralizes that of dust particles: We note that the second term on the right-hand side of (3) corresponds to the interaction with this uniform negative dust charge density. The potential due to neutralizing negative charge is given by

$$\begin{aligned} &\phi_{ext}(r) \\ &= -n_d(Qe)^2\int_{r'<R} d\mathbf{r}'\frac{1}{|\mathbf{r}-\mathbf{r}'|}\exp(-|\mathbf{r}-\mathbf{r}'|/\lambda) \quad (10) \end{aligned}$$

and is calculated as

$$\begin{aligned} &\phi_{ext}(r) \\ &= 4\pi(Qe)^2\lambda^2 \\ &\quad \times[1-\frac{\lambda}{r}\exp(-R/\lambda)(1+\frac{R}{\lambda})\sinh(\frac{r}{\lambda})], \\ &\quad\quad r<R, \quad (11) \\ &= 4\pi(Qe)^2\lambda^2\frac{\lambda}{r}\exp(-r/\lambda) \\ &\quad \times[\frac{R}{\lambda}\cosh(\frac{R}{\lambda})-\sinh(\frac{R}{\lambda})], \quad r>R. \quad (12) \end{aligned}$$

When the spherical volume V is determined externally, we simulate the structure of dust particles as a system of Yukawa particles interacting via (5) in the potential $\phi_{ext}(r)$. The potential energy part of the Hamiltonian then takes the form

$$\frac{1}{2}\sum_{i\neq j}^{N_d} v(r_{ij}) + \sum_{i=1}^{N_d}\phi_{ext}(r_i). \quad (13)$$

For this system, we have three dimensionless parameters which may be taken as the total number of dust particles N_d, $\Gamma = (Qe)^2/ak_BT$, and $\xi = a/\lambda$, where the mean distance a is defined by $a = (3/4\pi n_d)^{1/3}$. In the limit of high temperatures, the structure may be the uniform distribution in the volume V. With the decrease of the temperature, there appears the correlation and finally we expect to have a solid-like structure of finite extension. In this article, we are interested in structures at low temperatures where our system has two characteristic parameters, N_d and ξ.

3. STRUCTURE OF DUST PARTICLES UNDER MICROGRAVITY

Applying the molecular dynamics, we have analyzed the structures of dust particles at low temperatures: Starting from some configurations, we anneal the system for a sufficiently long time and slowly cool the system. Some examples of resulting structure are shown in Fig. 1.

The radial distribution function is given in Fig. 2 and we observe clear shell structure. The number of shells is determined by parameters N_d and ξ. The phase diagram for the structure is shown in Fig. 3 where the case of Coulomb interaction with $\xi = 0$[4, 5] is also shown.

As is shown in Fig. 3, the number of shells and the positions of shells are almost independent of the strength of screening ξ. This implies that the structure does not strongly depend on ξ. We may interpret this independence as follows: In the shell structure, the intershell distance is nearly equal to the mean distance in the shell and the change in the mutual interaction does not affect the structure as a whole so long as it is isotropic.

When we increase the system size, we eventually have the system whose main part is organized in the lattice structure of infinite Yukawa system[6]. In between, there expected to exist the critical system size for the structural transition from shell structure. In the case of $\xi = 0$, the critical value is determined as $1.1 \times 10^4 \sim 1.5 \times 10^4$[7].

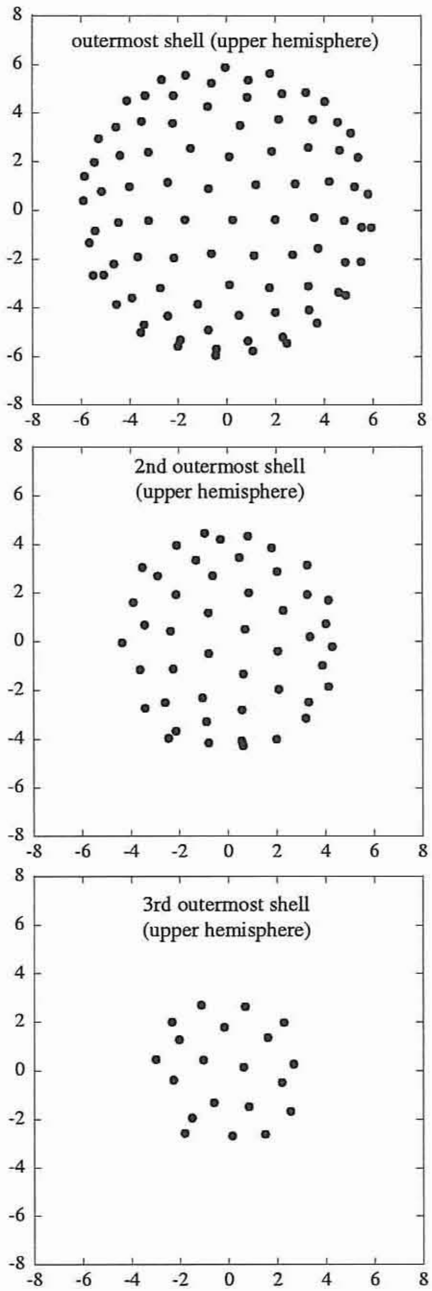

FIG. 1: Structure of outermost three shells with 330 particles for $\xi = 2.0$.

In conclusion, we have obtained the structure of dust particles at low temperatures under the condition of microgravity where there is no specified direction in space. This structure is in sharp contrast with that un-

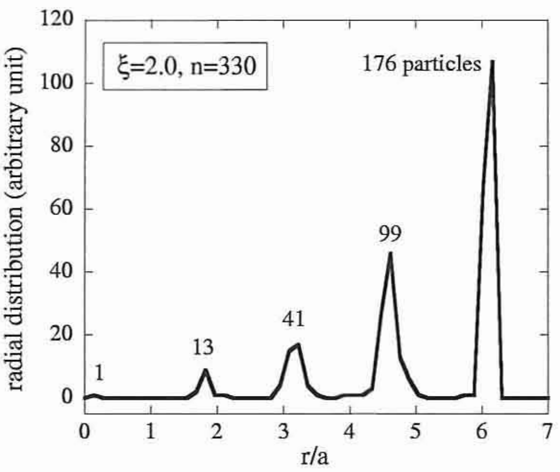

FIG. 2: Radial distribution function of the structure shown in Fig.1.

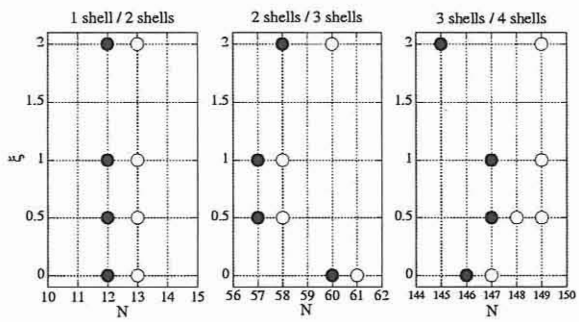

FIG. 3: Number of shells as phase diagram of dust particles under microgravity.

der the gravity on earth where we have one-dimensional structures characterized by the total area density and strength of screening[8].

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