S6-2

Configurations of Coulomb Clusters in a Complex Plasma
セミマクロなダスト系プラズマの構造形成と制御

Osamu Ishihara
石原　修
Faculty of Engineering, Yokohama National University,
79-5 Tokiwadai Hodogaya-ku, Yokohama 240-8501 Yokohama, Japan
横浜国立大学大学院工学研究院，〒240-8501 横浜市保土ヶ谷区常盤台79-5

A complex plasma, known also as a dust plasma, is characterized by a plasma which includes fine particles of nano to micron meters in size. Fine particles in a plasma are either positively or negatively charged depending on the environment. In many laboratory experiments, dust particles are highly charged negatively due to the large mobility of electrons. Since the Coulomb potential of dust particles is much more than the dust thermal energy, dust particles form strongly coupled Coulomb clusters. The clusters show a variety of configurations depending on the number of dust particles and also on the strength of the confinement potential. Structures of the Coulomb cluster are reviewed.

1. Structures by like charges

Like charges have been known to form variety of structures since the beginning of the twenty century. Thomson explained the atomic structure from the stability conditions of the charges in rings[1], while Madelung discussed the structure of ionic compound from the viewpoint of electrostatic energy of a nearly infinite crystal [2].

But it is only recently that the detailed structures formed by the interaction of like charges of finite numbers become the subject of intensive research. On the surface of liquid helium electrons are found to form a Wigner crystal in 1979[3]. In 1980s, the research of quantum dots revealed that the confined electrons take the discrete energy as the energy level of electrons around the nucleus. Such an analogy introduced the name of artificial atoms for quantum dots. Research on artificial atoms is directed to find the behavior of a classical system with finite number of electrons in a confined potential. The computer simulation showed the Wigner crystallization and melting of electrons in the two-dimensional quantum dots [4]. On the other hand, advanced technology of laser cooling succeeded to trap ions in the confined region by the electromagnetic field. The trapped ions are observed to form certain structures [5]. Ions trapped in a Paul trap by the electric field and ions trapped in a Penning trap by the magnetic field are known to form various structures [6]. Dubin and O'Neil discussed the shell structure of a nonneutral plasma confined by the Penning trap [7].

Computer simulation was used to study the laser-cooled ion structure confined in a harmonic potential. And the stable configurations were identified as states of minimum energy [8]. The stable configuration was found to include concentric shell structures [9].

2. Structures by dust particles

In 1994 Coulomb crystal was discovered in a plasma where fine particles are negatively charged and the Coulomb energy overcomes the thermal energy [10]. The Coulomb cluster in a plasma could be observed by naked eyes through the CCD camera. The structure of the cluster becomes observable by a very fundamental method, i.e., by human vision and the dust plasma becomes the topic of the research among many plasma scientists [11]. Formation of the Coulomb crystals and melting process of the Coulomb crystals have been observed and studied in detail. The phase transition is now observable by kinetic level through detecting trajectories of dust particles [12]. Computer simulations by the method of molecular dynamics and Monte Carlo contributed to the understanding of the Coulomb cluster. Two and three dimensional structures of the clusters in which repulsive negative charges are confined in an electrostatic potential have been studied. The ring structure in the two dimensional confinement and the shell structure/BCC structure in the three dimensional confinement were clarified, where the confinement of dusts was established by the harmonic potential [13, 14]. The inharmonic potential was used to produce the transition from the two-dimensional to three-dimensional structures [15].

Our system in consideration may be expressed by the Hamiltonian:

$$H=\sum_{i=1}^{N}\left(\frac{\left|\mathbf{p}_i-Ze\mathbf{A}\right|^2}{2m}+\frac{m\omega^2}{2}\left(r_i^2+\frac{z_i^{\,2}}{\kappa}\right)\right.$$
$$\left.+\sum_{j<i}\frac{(Ze)^2}{4\pi\varepsilon_0\left|\mathbf{x}_i-\mathbf{x}_j\right|}e^{-\left|\mathbf{x}_i-\mathbf{x}_j\right|/\lambda_D}+V_1(\mathbf{x}_i)\right), \qquad (1)$$

where N is the number of dust particles, m, $\mathbf{p}$, Ze are mass, momentum and charge of a dust particle, respectively, $\mathbf{A}$ is the vector potential, ω is the frequency of the harmonic potential, κ is a confinement parameter, $r^2=x^2+y^2$, λ_D is a screening length, and $V_1(\mathbf{x}_i)$ is a potential related to all other forces like a gravitational force, a drag force and a sheath electric field. If we introduce characteristic scales [$\ell=\left(2Z^2e^2/4\pi\varepsilon_0 m\omega^2\right)^{1/2}$ for the length, $m\omega^2\ell^2/2$ for the energy, $m\omega\ell$ for the momentum, $m\omega\ell/Ze$ for the vector potential], the Hamiltonian can be written as

$$H=\sum_{i=1}^{N}\left(\left|\mathbf{p}_i-\mathbf{A}\right|^2+r_i^2+\frac{z_i^{\,2}}{\kappa}\right.$$
$$\left.+\sum_{j<i}e^{-\left|\mathbf{x}_i-\mathbf{x}_j\right|/\lambda_D}/\left|\mathbf{x}_i-\mathbf{x}_j\right|+V_1(\mathbf{x}_i)\right). \qquad (2)$$

The ring configuration of dust particles in the absence of magnetic field ($\mathbf{A}$=0) was studied for possible stable structures in the presence of ion drag force. The stable formation was found for dust particles up to 6, while the dust particles more than 6 in a ring become unstable (see Fig. 1). The particle dynamics in the presence of magnetic field was also studied. The rotation of the ring configuration was observed by the experiment and recovered by the simulation [17]. The three dimensional dust structures for **p**=**A**= V_1=0, $\lambda_D\to\infty$ depend only on N and κ. Figure 3 shows the spindle-shape structure for N=70 and 134 with $\kappa=5$ [18].

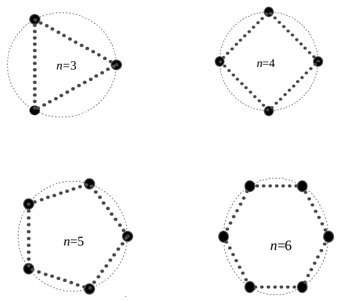

Fig. 1 Stable ring configurations in the absence of magnetic field. [Ref.16].

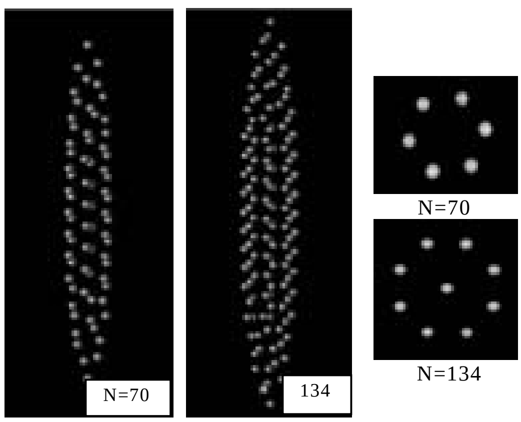

Fig. 2 Stable Coulomb cluster. κ =5, N=70 and 134. Side and top views[Ref. 18].

This research was supported by Japan Society for the Promotion of Science Grant-in-Aid for Scientific Research (B)(2) 16340179.

References

[1] J.J. Thomson, Phil. Mag. S. 6, **7** (1904) 237.
[2] E. Madelung, Phys. Z. **19** (1918) 524.
[3] C. C. Grimes and G. Adams, Phys. Rev. Lett. **42** (1979) 795.
[4] A.V. Filinov, M. Bonitz, and Y.E. Lozovik, Phys. Rev. Lett. **86** (2001) 3851.
[5] D.J. Wineland and W.M. Itano, Physics Today **40**, (1987) 34.
[6] B. G. Levi, Physics Today **40** (1988) 17.
[7] H.E. Dubin and T.M. O'Neil, Rev. Mod. Physics **71** (1999) 87.
[8] R. Rafac, J.P. Schiffer, J. s. Hangst, D. H.E.Dubin, and D.J. Wales, Proc. Natl. Acad. Sci. USA **88** (1991) 483.
[9] R. Hasse and V.V. Avlov, Phys. Rev. A **44** (1991) 4506.
[10] H. Chu and L. I: Phys. Rev. Lett. **72** (1994)4009; H. Thomas, G.E. Morfill, V. Demmel, J. Goree, B. Feuerbacher, and D. Mohlmann: Phys. Rev. Lett.,**73** (1994) 652; Y. Hayashi and K. Tachibana: Jpn. J. Appl. Phys.**33** (1994) L804.
[11] O. Ishihara, Butsuri **57** (2002) 476 (in Japanese).
[12] Y. Watanabe et al., JSPF **73** (1997); 1220-1261; O. Ishihara et al., J. Plasma Fusion Res. **78** (2002) 293-334. (in Japanese)
[13]V.M. Bedanov and F.M. Peeters, Phys. Rev. B **49B** (1994) 2667.
[14] H. Totsuji, T. Kishimoto, C. Totsuji, and K. Tsuruta, Phys. Rev. Lett. **88** (2002) 125002.
[15] Y.G. Cornelissens, B. Partoens, and F.M. Peeters, Physica E **8** (2000) 314.
[16] O. Ishihara, Phys. plasmas **5** (1998) 357.
[17] O. Ishihara, T. Kamimura, K. Hirose, and N. Sato, Phys. Rev. E **66** (2002) 046406.
[18] T. Kamimura, O. Ishihara, and K. Hirose, Res. Reports Faculty of Science and Technology, Meijo University, Nagoya Japan No.45 (2005).