Recent Advances in the Research of Complex Plasma

コンプレックスプラズマ研究の展開

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A complex plasma is rich in the physical phenomena with a strongly cloupled dust system and a weakly coupled background plasma. Experimental observation of Coulomb crystals prompted the study of basic minimum energy configuration of dust particles. Some of the theoretical/computational studies on the minimum energy state like a double helical structure are reviewed. Dynamic motions of dust particles in the presence of magnetic field are reviewed from a particle viewpoint as well as a fluid viewpoint. It is pointed out that magnetized rotating spherical dust particles placed in a plasma could produce potential structure around each dust particle, resulting in a new form of interaction between dust particles.

1. Introduction

In a conventional plasma, we have dealt with a plasma in which charged particles move freely with thermal energy much larger than Coulomb energy. Such a weak coupling among particles is the basis for the variety of collective behavior manifested in a plasma. On the other hand, the presence of dust particles in a plasma changed the concept of the plasma of weak coupling.

Dust particles of micron size are negatively charged in a plasma, and are confined in a plasma to remain charge neutral as a system. Such a plasma was originally studied in a context of plasma in universe and was often called as a dusty plasma in the field of astrophysics.[1,2] Even in a recent study of accelerating expansion of the universe, the presence of dust particles must be considered to evaluate the red-shift properly. As industrial applications grow in our everyday life, the plasma processing became a popular tool to meet a modern electronics technology.[3] Dust particles often born in a plasma by coagulation became the topic to eliminate from the processing itself. On the other hand massive charged dust particles in a plasma gathered attention by plasma community largely because of the nature of strongly coupled state.

2. Structure formation in a complex plasma

Dust particles are negatively charged in a plasma and are subject to gravitational force because of the heavy mass. Dust particles are found to be suspended in the sheath because of the balance between the downward gravitational force and the upward sheath electric force. Because of the presence of the ion flow in the sheath, a dust particle is found to make a vertical pair supported by a wake potential.[4,5,6] Dust particles, if they exist as a group in a plasma like a dust cloud, are characterized by the Coulomb energy much larger than the thermal energy, indicating the possibility of strongly coupled system in a plasma. The presence of strongly coupled system of dust particles is coexisting with a weakly coupled system of plasma particles. This system is now known as a complex plasma,[7-12] which is characterized by the coexistence of collective behavior of extremely low frequency and collective behavior of very high frequency. Because of the nature of strongly coupled system, dust Coulomb crystals have been observed and the crystals are observable by naked eyes through the scattering of laser light on dust particles. In a complex plasma, dust particles could behave like individual particles making the physical phenomena observable on a kinetic level by naked eyes,[13,14] while the dust cloud

behave like fluid making the motion observable on a level of fluid elements also by naked eyes.[15,16] The research on a complex plasma gives an opportunity to study fundamental structures of matter by observing the transition of structures through the interaction of dust particles and background plasmas.

3. Complex plasma in a magnetic field

Recent efforts have been focused on the study of the nature of complex plasma in the presence of magnetic field. The earlier experiments revealed the revolution of plasma crystals and dust cloud controlled by the strength of magnetic field.[17,18] Theoretical and computational studies revealed the unique nature of a single spinning dust motion[19,20,21] and detailed dynamics of rotating dust rings.[22] Recent experimental study showed the dynamic circulation of dust cloud accompanied by mass ejection of dust particles prompted by the application of magnetic field.[16] Recent experimental efforts are reported to investigate the behavior of dusty plasma in a stronger magnetic field up to 2.5T in MDPX (Magnetized Dusty Plasma Experiment).[23]

We consider dust particles with magnetic dipole and investigate interaction of dust particles placed in a plasma. A spherical dust particle of radius a is assumed to have a magnetization $\mathbf{M} = \mathbf{m}\delta(\mathbf{x})$, which produces a magnetic field around the sphere $\mathbf{B} = \mu_0 (a/r)^3 \mathbf{M} \cdot \left[\mathbf{xx}/r^2 - \mathbf{1}/3\right]$, where μ_0 is a permeability of free space. When a dust sphere placed in a plasma rotates in a spinning motion with angular frequency Ω, the electric field is produced as the plasma corotates with the dust sphere: $\mathbf{E} = \left(\Omega\mu_0 |\mathbf{m}| / 4\pi r^2\right) \sin\theta \left(\mathbf{e}_r \sin\theta - 2\mathbf{e}_\theta \cos\theta\right)$, where θ is the angle from the spinning axis and $\mathbf{e}_r$, $\mathbf{e}_\theta$ are the unit vectors in radial direction and angular direction, respectively. It should be emphasized that the electric potential is produced around the magnetized sphere when the dust sphere rotates and is responsible for the interaction between dust particles.

We note that a complex plasma in the presence of magnetic field is characterized by the permeability different from that of free space, which may open a new area to be explored.

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