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Bow Shock Formation in Complex Plasmas
コンプレックスプラズマにおけるバウショック形成

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A bow shock is observed in a wide area two-dimensional complex plasma. The bow shock is formed due to an interaction of a supersonic flow of charged micro-particles with an obstacle placed in the flow. The flow velocity is controllable by the gravitational force through tilting the entire experimental device. The structure of the bow shock is well explained by a polytropic hydrodynamic theory as well as molecular dynamic simulation. It is observed that the wake-like structure is formed when the flow is subsonic and some micro-particles are trapped in the tail of the void.

1. Introduction

Charged micro-particles of organic or inorganic materials on the order of a micrometer or a fraction of a micrometer in diameter are often found in plasmas in the interstellar medium, in the cometary environment, etc. [1]. It is possible for the micro-particles to be charged either positively or negatively. Photoelectric emission makes the charge positive and the presence of plasma particles makes it negative.

Coulomb crystals were discovered in laboratory experiments in 1994 and the discovery activated studies on the lattice formation, the phase transition, the waves, and other phenomena in plasmas, which was often called “complex plasmas”, including the charged micro-particles.

In this paper, we report the experimental observation of a two-dimensional bow shock formation in a large area two-dimensional complex plasma system with a stationary object. The observed bow shock structure is compared with polytropic theory and a molecular-dynamic simulation. In addition, behavior of the micro-particles in subsonic flow is investigated as well.

It is known that the bow shock is observed in various media. Existence of the bow shock indicates that the complex plasma system including the charged micro-particles has physical universality. The complex plasma system has a great advantage in visualizing processes such as the self-organization or waves. It is expected that progress of research work~~s~~ in the complex plasma contributes to the various fields of physics.

2. Experimental Setup

The experiments were performed using the modified YCOPEX (**Y**okohama **Co**mplex **P**lasma **Ex**periment) device [2], which was a glass tube with an inserted flat metal plate of 800 mm × 120 mm and a conducting thin wire of 0.2 mm in diameter and 25 mm in length as a floating obstacle. The entire device was possible to be tilted toward the obstacle by a jack equipped at one end of the device. The charged micro-particles were prevented from flowing by a raised up-and-down gate, which was electrically grounded, even when the device was tilted. By lowering the gate after tilting, the micro-particles began to flow. The flow was almost to be two-dimensional.

To make the micro-particles visible in the naked eye, two thin fan green laser lights and a camera were placed outside the device. The micro-particles were irradiated by the laser lights from the radial directions. Scattered laser light from the particles was observed and recorded by a camera.

The reached vacuum pressure was less than 0.4 Pa. Argon gas was used at a pressure of 3.6 Pa. To avoid the drag forces due to the neutral gas particles and the ions [2-5], the gas flow was stopped by turning off the vacuum pump and by cutting off the gas feeding. Plasma was generated with applying an rf signal of 5 W (13.56 MHz). The measured plasma parameters were $n_e \sim 10^{14}$ - 10^{15} [m^{-3}], $T_e \sim 4$ - 5 [eV], and the plasma potential was ~30 V.

The Au coated silica spheres with 5 μm in diameter and m_d = 1.68×10^{-13} [kg] in mass were used as the micro-particles. The charge of the particles were estimated to $Q = Z_d\, e \approx -4.4\times10^4\, e$, where e is the elementary electric charge [5]. The levitation height of the particles was ~8 mm above the grounded metal plate, where was known as the sheath-plasma boundary called the transient sheath.

3. Experimental Results

A wake-like structure is observed around the tail of the void as shown in Fig. 1, although there is not a clear structure around the leading edge of the void when the flow is subsonic. In addition, it is observed that a small amount of micro-particles are frequently trapped in the tail part of the void.

An arcuate structure appears in front of the leading edge of the void when the flow is supersonic. In the present case, $M = 1$ when $v_f = 71$ [mm/s]. Furthermore, there are particles flown with a subsonic speed between the arcuate structure and the stagnation point. It is known that existence of such a local subsonic region in front of the stagnation point is one of the features of the bow shock [6]. The structure is confirmed as a bow shock.

A dependence of the density ratio n_{dp}/n_{d0}, where n_{d0} and n_{dp} are the densities of the upstream area far from the stagnation point and of the subsonic area just in front of the stagnation point, on the Mach number is studied to clarify one of the hydrodynamic properties of the bow shock observed in the micro-particle flow. The result shows that the micro-particle flow behaves as a polytropic fluid.

4. Molecular Dynamic Simulation

A molecular dynamic simulation is useful to confirm the hydrodynamic properties of the bow shock observed in the present experiment. It is assumed that a micro-particle has the screened Coulomb potential. A point-like charge is used instead of the thin conducting obstacle and the wall of the device in the experiment. The equation of motion for each micro-particle including the electrostatic interactions with other charges, the gravitational force, and the neutral drag force is numerically solved. A periodic boundary condition is applied to the flow direction.

It is found that the void is formed around the point-like charge and the bow shock is observed at the leading edge of the void when the flow of the charged particles is supersonic. These shapes agree with those observed in the experiment. The behavior as the polytropic fluid is also confirmed by investigating the dependence of the density ratio on the Mach number. The polytropic index is found to be 2.2.

5. Conclusion

The two-dimensional bow shock was observed at the leading edge of the void in the complex plasma experiment. The theoretical study and the molecular dynamic simulation confirm that the bow shock behaves as the polytropic fluid.

The wake-like structure was also observed in the tail of the void when the flow velocity was subsonic. It was observed that a small amount of micro-particles were trapped around the void tail.

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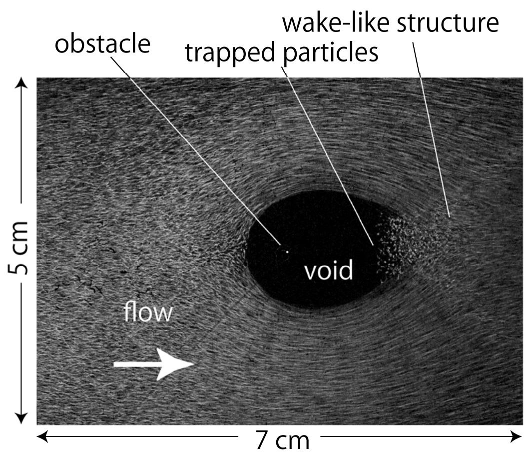

Fig. 1 The wake-like structure and the trapped particles when the flow is subsonic.