Measuring the Charge of a Particle in an RF Dusty Plasma

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Abstract

A dusty plasma is an ionized gas that contains micron-sized solid particles. The particles in a dusty plasma gain a large negative charge by collecting electrons and ions from the surrounding plasma. Consequently, the particles can be levitated by an electric field in the plasma. They can also interact with each other via Coulomb repulsion to form stable, ordered structures resembling crystal lattices called dusty plasma crystals. Because electrostatic forces are responsible for these and other phenomena, most experimental and theoretical studies of dusty plasmas require a knowledge of the particle charge. One technique to measure the charge, called the vertical resonance method, uses a video camera to measure the height of vertical particle vibrations caused by modulating the RF voltage. The resonance frequency of the oscillations, along with Langmuir probe measurements of the plasma ion density, then determines the particle charge. We formed 2-D dusty plasma crystals in an argon RF discharge and evaluated several methods of measuring the particle charge. We tested the original vertical resonance method against a new variation of the method that relies on more accurate measurements of plasma potential and particle height instead of ion density. In addition, we measured the phonon spectrum of the plasma crystal and studied the propagation of laser-induced longitudinal and transverse waves, all of which allowed an independent means of determining the charge. We are continuing to compare the charge measurements from all these methods.

Summary

Dusty plasmas are ionized gases that contain macroscopic particles of solid matter. Research on dusty plasmas spans many disciplines. In astrophysics, dusty plasmas are found in the rings of Saturn and the tails of comets. The plasma etching processes used in the manufacture of semiconductors also form dusty plasmas. Dust particles at the edge of a fusion plasma must also be factored into the eventual design of commercial fusion reactors. Moreover, dusty plasmas are also fascinating from the standpoint of fundamental physics. They can support novel wave modes, as well as exhibit solid-like behavior. In particular, because the dust particles acquire a large negative charge, they can arrange themselves into a stable ordered configuration called a dusty plasma crystal. Like the atoms in a crystalline solid, the particles in a dusty plasma crystal are locked into a relatively rigid, regular lattice structure. Charged dust particles can also be levitated by the sheath electric field near a horizontal lower electrode in an RF gas discharge.

Because many of the interactions of particles in a dusty plasma are electrostatic, most studies of dusty plasmas require a knowledge of the charge of the dust particles. Consequently, several methods have been developed in the literature to measure the charge. One of the earliest methods, called the vertical resonance method, involves modulating the levitating RF electric field, causing the dust particles to undergo vertical oscillations, the amplitude of which can be measured with a video camera. In this method, the dust particles are modeled as damped driven oscillators that have a particular resonant frequency. The resonant frequency depends on several parameters, including the plasma ion density and the particle charge. Thus, the particle charge can be determined from the resonant frequency, Langmuir probe measurements of the ion density, and other known parameters such as the mass of the particles. This method is fairly simple, but has the serious disadvantage that the ion density measured in the bulk plasma may differ from the ion density in the plasma sheath, where the particles are levitated, leading to large uncertainties of up to 50% in the particle charge.

At the University of Iowa, we formed 2-D dusty plasma crystals in a 13.56 MHz argon gas discharge. Our particles were plastic microspheres 8.09 ± 0.18 μm in diameter. Typical plasma parameters were electron temperature $T_e \approx 2$ eV, plasma potential $V_p \approx 21$ V, and ion density $n_i \approx 3 \times 10^{15}$ m^{-3}. We measured the particle charge using the original vertical resonance method, as well as a new variation on the original method that uses more accurate measurements of particle height and plasma potential instead of ion density. Instead of assuming that the ion density is uniform between the bulk plasma and the sheath, as does the original vertical resonance method, the modified resonance method instead makes the more realistic assumption that the electric field in the sheath varies linearly with height. We also induced longitudinal and transverse mechanical waves in the 2-D crystal using an argon laser. The sound speed measured in the plasma crystal from these pulses provided another charge measurement. Finally, we also measured the phonon spectrum of the plasma crystal, providing yet another determination of the charge. Work to compare charge measurements from all these methods is ongoing.