Waves in strongly coupled dust-plasma systems
Large ARC project 1999-2001

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Aims, significance and expected outcomes

Dusty plasmas are plasmas which contain small particles ranging in size from nanometres to micrometers. Usually the particles achieve electrostatic equilibrium with respect to the plasma by acquiring negative charge. With a sufficient density of particles it is possible that these negatively-charged particles, rather than free electrons, account for most of the negative charge of the plasma.

Dusty plasmas are common in space, occurring in such diverse environments as interstellar clouds, interplanetary dust, comets, planetary rings, and the earth’s magnetosphere. In the laboratory dusty plasmas can occur naturally in processing plasmas, such as those used for etching semiconductors. Particles form and grow over hours of operation reaching sizes of \( \sim 100 \) nm. They accumulate in sheath regions where electrostatic forces are able to balance those due to gravity, ion drag and gas flow. The accumulation of dust in a processing plasma is undesirable as it creates a risk of contamination of the workpiece. The circumstances which encourage dust formation, the growth kinetics of the particles, and possible means for their removal from the discharge are active areas of investigation.

The recent interest in laboratory dusty plasmas arose from observations of dust in devices developed for plasma etching of silicon [1]. More recently dust has been produced intentionally in, for example, low pressure silane containing plasmas in order to study the growth kinetics of the particles [2, 3]. The use of ultraviolet radiation to remove charge from particles photoelectrically, thereby destroying the force equilibrium of the trapped particles, has been proposed as a possible way of removing trapped dust where the workpiece is at the top of the reactor and the particles are sufficiently large that the gravity force is significant [4].

Dusty plasmas can also be created by adding small particles (typically \( > 1 \mu m \) in diameter) to an otherwise dust-free plasma. These particles also accumulate in sheath regions where the electrostatic force balances the force of gravity with forces due to gas and ion flow usually unimportant for these larger particles.

A dusty plasma is characterised by the value of the coupling parameter \( \Gamma \) which is the ratio of the average Coulomb potential energy between dust particles to the average kinetic energy of a particle,

\[
\Gamma = \frac{Q^2}{4\pi \varepsilon_0 a T} \exp(-a/\lambda_D)
\]  

(1)

where \( Q \) is the charge on the dust particle, \( T \) is the temperature of the dust particles, \( \lambda_D \) is the Debye length, and \( a \) is the distance between the particles which is related
to the particle density $N$ by

$$a \sim \left( \frac{1}{N} \right)^{1/3} \quad (2)$$

Although space plasmas are usually weakly coupled ($\Gamma << 1$), laboratory dusty plasmas are usually strongly coupled ($\Gamma >> 1$). In the latter case, as first suggested by Ikezi [5], dust particles can form a crystal structure known as a Coulomb solid. Such structures have been observed directly for the case of dust particles added to the plasma [6]. At present, there is no satisfactory theory of the dust crystallization process in a plasma.

An enhanced level of plasma oscillations has been reported in some experiments on dust-plasma crystals [7, 8], so that the collective properties of the strongly coupled dust-plasma system can be assumed to play a significant role in the system. The presence of chaotically moving charged dust grains has been shown to lead to a considerable modification of the collective properties. The dispersion relations and damping of the usual plasma waves are affected [9, 10], but there are also new modes associated with the dust motion [11, 12, 13]. The mutual interaction of the dust particles, and thus the crystallization process, is also affected by the plasma environment and its collective effects.

A novel feature of dust grain attraction in plasmas is the interaction of a static test dust particle with the low-frequency collective perturbations of plasma ions flowing toward the negatively charged electrodes [14]. Physically, the mechanism is similar to that which is responsible for the Cooper pairing of electrons in metals (when the attractive interaction is strong enough to overcome the repulsive screened Coulomb interaction, an effective attraction between two electrons can be realized, and superconductivity results). For the dust grains, the result may be their alignment around certain positions in a wake downstream of the test dust particulate, with the moving ions of the flow creating the polarization necessary for the resulting attraction. Independent numerical calculations have demonstrated similar effects [15]. It has also been demonstrated [16] that collective effects can provide the oscillating potential not only along the line of flow but also in the plane perpendicular to the direction of the ion flow downstream of the dust particle.

Two of the chief investigators have recently carried out theoretical investigations of the modes of vibration of a dust-plasma crystal. In particular, the transverse modes of a horizontal line of grains (where the ions flow vertically downward to a plane horizontal cathode) [11], the modes of two such lines of grains [12], and the modes of a vertical string of grains [13] have been investigated. The last two arrangements have the unique feature that the effect of the background plasma on the mutual grain interaction is asymmetric because of the wake downstream of the grains studied in [14, 15, 16]. The characteristic frequencies of the vibrations dust grains, such as the the frequencies could

There have been few experimental investigations of the wave modes supported by Coulomb solids. Low frequency ($\sim 10$ Hz) longitudinal dust acoustic waves have been observed in Coulomb solids several layers deep suspended in the sheath region adjacent to the powered electrode of parallel plate rf discharges [17]. Coulomb solids have also provided opportunities for studying phase transitions on a macroscopic scale, self-organisation, and coherent and incoherent dynamical structures [18].
One of the aims of this project is to study experimentally the forces between the dust grains. These forces are strongly connected with the fluxes of plasma particles onto the grain surfaces, and therefore depend on the plasma environment of the grains. Thus the forces between “isolated” dust grains (when the intergrain distance exceeds the plasma Debye length) are not totally screened out, and are strongly influenced by collective effects in the plasma. One way of investigating the intergrain force is to measure the characteristics of vibrations and waves in the dust crystal. The measurements can be analysed in terms of established and new models of the vibrations, such as those of [11, 12, 13] discussed above, and the models can be subsequently refined to reveal greater understanding of the basic processes involved. We therefore propose to investigate by a number of experimental means the vibrations and waves in the dust crystal, and the properties of the background plasma. More refined theoretical models will be simultaneously developed.

Although the current boom in dusty plasma research is driven mainly by such industrial applications as plasma etching, sputtering and deposition, the physical outcomes of investigations in this rapidly expanding field cover many important topics in space physics and astrophysics as well. Examples are the interaction of dust with spacecraft, the structure of planetary rings, star formation, supernova explosions and shock waves. In addition, the study of the influence of dust in environmental research, such as in the Earth’s ionosphere and atmosphere, is important. The unique binding of dust particles in a plasma opens possibilities for so-called super-chemistry, where the interacting bound elements are not atoms but dust grains.

The important point in understanding dust–plasma systems is their open character: there are fluxes of plasma particles onto dust surfaces, even in the steady state. Thus dusty plasmas are well suited to serve as model systems in studies of self-organisation and phase transitions in nonequilibrium, open, dissipative systems, a topic of much interest recently.

The plasma group at Flinders University pioneered the experimental study of Coulomb crystals in Australia with an investigation of crystals formed from diamond particles in the sheath above an rf powered electrode in an inductively coupled discharge [19]. The program proposed here complements the Flinders work by using waves in the Coulomb crystals to investigate particle interactions, with the aid of models developed by chief investigators Cramer and Vladimirov.

Research plan, methods, techniques and proposed timing

A parallel plate rf plasma reactor will be constructed for the experimental component of the project. It will be based upon a stainless steel cylinder of ~20 cm diameter, with side ports for pumping, gas connections and diagnostic access. The powered electrode will be at the bottom of the vessel, electrically isolated from the walls and adjustable in vertical position. It will be operated with argon at pressures ~10–100 mtorr (~1 – 10 Pa). Coulomb structures in the sheath of the powered (lower) electrode will be created by adding small particles of diameters ~1 – 10μm to the discharge using the well established technique of releasing particles from a shaker near
the upper surface of the reactor. The particles acquire charge as they fall through the discharge and become trapped in the rf sheath above the lower electrode. Similar arrangements have been used to produce Coulomb crystals several layers thick over most of the area of the powered electrode [20, 21, 22, 23].

Longitudinal wave modes have been generated in dust crystals in parallel plate reactors using a long wire parallel to the powered plate, at the height of the dust layer [22]. The wire was driven by a sinusoidal waveform and biased negatively with respect to the plasma in order to avoid large electron currents during the positive part of the waveform. For the proposed experiments a different antenna arrangement will be required as it is intended to excite transverse waves rather than longitudinal waves. A single wire antenna of the kind described above but displaced vertically to a position above or below one edge of the crystal planes, or two such antennas, one above and one below driven in antiphase would appear to be suitable. Empirical refinement will undoubtedly be required to achieve a suitable antenna arrangement.

Optical techniques will be used to detect motion of the charged particles. A mechanically scanned HeNe laser beam will be used to illuminate the particles and a CCD camera to view the crystal structures, to detect wave structures [17], and to detect the motion of individual charged particles [24].

An rf compensated Langmuir probe, already available to the project, will be used to measure electron density and temperature of the plasma prior to addition of particles.

Proposed timing
1999
During the first year of the project, the chamber will be constructed, discharge achieved and techniques for introducing particles, exciting transverse waves and detecting particle motions will be developed.

2000
During the second year the transverse wave modes will be explored in detail. Theoretical models will be used to interpret the characteristics of the waves in terms of particle interactions with each other and with the background plasma and ion flux.

2001
The plan for this year is of necessity more speculative as it will depend upon the outcomes of the previous two years which would themselves be expected to lead to fruitful but unforeseen opportunities. However one area which would be pursued at this stage is the relevance of dust crystals as models systems for phase transitions.

References


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