Charged Dust Structures in Plasmas

N. F. Cramer and S. V. Vladimirov,
Theoretical Physics Dept., School of Physics, University of Sydney,
NSW 2006, Australia

Dusty plasmas are plasmas containing small particles ranging in size from nanometres to micrometres. The particles acquire negative charge by attachment of the fast plasma electrons, in order to achieve electrostatic equilibrium with respect to the plasma. 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, occuring 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 $\sim$ 100nm, and accumulate in sheath regions where electrostatic forces 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 recent active areas of investigation.

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

$$\Gamma = \frac{Q^2}{4\pi\epsilon_0 aT} \qquad (1)$$

where Q is the charge on the dust particle, T is the temperature of the dust particles, and a is the distance between the particles. Although space plasmas are usually weakly coupled ($\Gamma << 1$), laboratory dusty plasmas are usually strongly coupled ($\Gamma >> 1$). In the latter case, as first shown theoretically by Ikezi [1], 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 [2]. The crystal spacing can be large (of the order of millimetres), so the dust crystal provides a macroscopic, classical model of a solid state crystal. The crystallization process can be studied, and possible diffraction and localization effects on microwaves can be investigated. At present, there is no satisfactory theory of the dust crystallization process in a plasma. The collective properties of the strongly coupled dust-plasma system can be assumed to play a significant role in the system. The dispersion relations and damping of the usual electrostatic and electromagnetic waves in the plasma are affected [3, 4], but there are also new mechanical–electrostatic modes associated with the dust motion [5, 6, 7]. The mutual interaction of the dust particles, and thus the crystallization process, is affected by the plasma environment and its collective effects. An important point in understanding dust–plasm 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 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 [8]. Physically, the mechanism is similar to that which is responsible for the Cooper pairing of electrons in metals. 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. It has also been demonstrated [9] 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.

We report here on theoretical investigations of the mechanical–electrostatic modes of vibration of a dust-plasma crystal, extending earlier work on the transverse modes of a horizontal line of grains (where the ions flow vertically downward to a plane horizontal cathode) [5], the modes of two such lines of grains [6], and the modes of a vertical string of grains [7]. 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 [8, 9]. The characteristic frequencies of the vibrations are dependent on the parameters of the plasma and the dust grains, such as the Debye length and the grain charge, and so measurement of the frequencies could provide diagnostics of these quantities.

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.

References

[1] H. Ikezi, *Phys. Fluids* **29** 1764 (1986)

[2] J.H. Chu and L. I, *Phys. Rev. Lett.* **72** 4009 (1994)

[3] S. V. Vladimirov, *Phys. Plasmas* **1** 2762 (1994)

[4] N. F. Cramer and S. V. Vladimirov, *Physica Scripta* **53** 586 (1996)

[5] S.V. Vladimirov, P.V. Shevchenko and N.F. Cramer, *Phys. Rev. E* 56 R74 (1997)

[6] S.V. Vladimirov, P.V. Shevchenko and N.F. Cramer, *Phys. Plasmas* 5, 4 (1998)

[7] S.V. Vladimirov and N.F. Cramer, *Physica Scripta*, in press (1998).

[8] S. V. Vladimirov and M. Nambu, *Phys. Rev. E* 52 R2172 (1995)

[9] S. V. Vladimirov and O. Ishihara, *Phys. Plasmas* 3 444 (1996)