EQUILIBRIA AND DYNAMICS OF DUST GRAINS IN STREAMING PLASMA

Lampe Martin, Glenn Joyce, Gurudas Ganguli

Plasma Physics Division, Naval Research Laboratory, Code 6709
Washington DC USA 20375-5346

ABSTRACT

Experiments involving a small number of dust grains suspended in a discharge show an amazing range of static and dynamic phenomena, including bound assemblies of dust grains, symmetry-breaking equilibria, hysteresis, and self-excited large-amplitude oscillations [1–7]. We shall briefly review the experimental data, and provide a general theoretical/computational framework for interpreting these observed phenomena. Preliminary results have recently been published in [8].

In discharges, dust normally resides at the edge of the sheath, where it is subject to ion streaming at velocity of order c_s. The dust grains therefore interact via a dynamically shielded potential $\varphi(\mathbf{r})$ that takes the form of a wakefield downstream. The dust grains may be strongly coupled to each other, but ions and electrons are only weakly coupled to the grains. Therefore, $\varphi(\mathbf{r})$ is given by linear response theory, and can be calculated analytically (no need for simulations). Once this is done, the plasma is eliminated from the problem, and the dust cloud can be treated simply as a set of N grains interacting via $\varphi(\mathbf{r})$. However, this system differs from ordinary strongly coupled systems in that the potential $\varphi(\mathbf{r})$ is not symmetric upstream and downstream. Consequently, Newton's third law does not hold and neither energy nor momentum is conserved. We use both analytic theory and simulation in a systematic exploration of this N-body system, beginning with N=2.

We show first that (even with no external confining potential) the dust self-organizes into stable "molecules" that can have two, three or four grains, vertically aligned. The molecules propel themselves upstream against the ion flow, due to the non-reciprocal repulsive/attractive forces between grains. Longer strings can exist only if there is a vertical confining force. By increasing the strength of the vertical confining force, the grains can be squeezed together as close as $\Delta z \sim 0.4\ \lambda_{De}$. If the spacing is closer, the equilibrium is lost and the string breaks up. Even if $\Delta z > 0.4\lambda_{De}$, a string of more than two grains is subject to a hose instability, driven by the ion streaming [which is imbedded within $\varphi(\mathbf{r})$]. This instability is stabilized (due to friction) for neutral pressure P above some critical value P_2. For P less than a smaller critical value P_1, the instability breaks up the string. In an intermediate range $P_1 < P < P_2$, the string survives but goes to a limit cycle of large-amplitude hose oscillations, which are self-excited and persist in spite of frictional dissipation.

If there is also a horizontal confining potential, for any given set of parameters (horizontal and vertical confinement strength) there are usually multiple 3-D equilibria. As the parameters are varied, the equilibrium cycles through a hysteresis loop, which exhibits sharp jumps that resemble phase transitions. For the particular case where the potential well is bi-harmonic, the two-grain problem can be reduced to the mathematical form of a one-particle problem with an effective potential. This permits solution for the ground and excited states. For this case, it is found that all equilibria exhibit the cylindrical symmetry of the potential well, i.e. the two grains are either aligned vertically on axis, or symmetrically in the mid-plane. However, for two grains in an anharmonic well, there are no constants of the motion, and the situation is more complicated. In general, when there are multiple equilibria it is not possible to distinguish a ground state. Equilibria are found that are not symmetric with respect to the axis or the midplane, and in certain parameter ranges the grains do not come to a static equilibrium but rather go into self-excited oscillations of both grains about the mid-plane, which persist in spite of friction. We find analytic solutions for the case of two grains in a quadratic/quartic well, and we show simulation results for a variety of cases. The theoretical/computational results appear to provide at least qualitative explanation for many of the

experimental results. (Quantitative comparisons are difficult, because of gaps in measurement of experimental parameters, and also because of simplifications in the theoretical framework.)

[1] A. Melzer, V. Schweigert, and A. Piel, Phys. Rev. Lett. **83**, 3194 (1999).
[2] V. Steinberg, R. Sutterlin, A. Ivlev, and G. Morfill, Phys. Rev. Lett. **86**, 4540 (2001).
[3] C. Ticos, P. Smith, and P. Shukla, Phys. Scripta **T107**, 117 (2004).
[4] S. Vladimirov and N. Cramer, Phys. Scripta **38**, 80 (1998).
[5] A. Samarian, B. James, S. Vladimirov, and N. Cramer, Phys. Rev. E**65**, 046416 (2002).
[6] S. Vladimirov and A. Samarian, Phys. Rev. E**65**, 046416 (2002).
[7] S. Takamura, et al, Phys. Plasmas **8**, 1886 (2001).
[8] M. Lampe, G. Joyce, and G. Ganguli, IEEE Trans. Plasma Sci. (2000, in press).