*35th EPS Conference on Plasma Phys. Hersonissos, 9 - 13 June 2008 ECA Vol.**32D**, P-2.157 (2008)*

Two-Stage Transition in Dust Particle Alignment in a Plasma Sheath

J. D. E. Stokes, A. A. Samarian, S. V. Vladimirov, B.W. James

School of Physics, The University of Sydney, NSW 2006, Australia

Abstract

The alignments and transitions of two dust particles in a plasma sheath have been investigated. It is shown that the Hamiltonian description of a non-Hamiltonian system can be used to predict qualitative features of possible equilibriums in a variety of confinement potentials and can provide useful plasma diagnostics. The results compare favourably with simulation and are used to create new experimental hypotheses. In particular, the symmetry breaking transition of the particles as they leave the horizontal plane admits a Hamiltonian description which is used to elucidate the wake parameter.

Complex plasmas [1] provide an ideal medium for studying structural transitions in non-extensive systems, when even the system of two particles displays rich physics. For example, the binding energy resulting from the attractive wake potential created by two particles in streaming plasma causes them to behave as a molecule [2]. The study of this dust molecule has revealed useful insights into larger plasma crystals including the vertically aligned crystal structure and the driving force behind crystal-liquid phase transitions. The nature of particle arrangements in systems containing large numbers of particles can be understood by considering simplified systems of just a few (e.g. two particles).

It is well known that even an interaction between two dust particles in the plasma sheath environment involves both a symmetrical Debye-type interaction as well as an asymmetric attractive interaction (wake). In addition to the vertical sheath field in which the dust particles levitate against the force of gravity, a radial electric field is typically imposed to trap the particles within the discharge. Under varying discharge parameters, the particles have been found to align either parallel or perpendicular to the direction of ion flow [3]. The stability of the particle arrangements is determined by a combination of confinement strengths, interparticle forces and wake effects [4].

Here, analyses of transitions in a two-particle dust structure in a plasma sheath under various discharge conditions are presented. Two dust particles suspended in the sheath engage in a symmetrical Debye-type interaction as well as an asymmetric attractive interaction due to ion focusing of the vertically streaming plasma. Furthermore, in addition to the linear vertical sheath electric field, which stabilises the particles against the force of gravity, a linear radial electric field is typically applied to trap the particles within the centre of the discharge. The combination of perpendicular electric fields breaks the spherical symmetry of the plasma potential to cylindrical symmetry about the vertical axis with a perpendicular plane of reflection.

A new model was developed and tested for dust particle interactions in a plasma sheath. The model has revealed new features on the static behaviour of the vertical dust particles in terms of existence of previously unknown equilibriums and also on the dynamics of the vertical to horizontal transition. The analysis suggests that the parabolic potential well admits only horizontal and vertical stable dust alignments which are in agreement with experiments and a recent theoretical prediction [5]. It is also suggested that continuous symmetry breaking of the dust particle alignments are possible not just with a quadratic potential well, but also with a cubic anharmonicity due to particle asymmetry and spatial variation of grain charge with elevation in the sheath. If we consider symmetrical confinement with non-zero quadratic coefficients see Fig.1, there are four equilibriums which lie on an X in the (Δx; Δz) plane and when $\omega_p \neq \omega_z$ they lie on the hyperbola. Note that the direction of the transverse axis of this hyperbola depends on the sign of a_2, b_2 [6].

The presence of multiple equilibriums suggests that jumping is theoretically possible. If system remains in one of the equilibriums, however, its position should change continuously with the confinement strength. This also provides a useful diagnostic tool for determining the non-parabolicity of the confinement. When the radial and vertical confinements are equal, the dust particles should make an angle with the horizontal. We suggest that continuous changes in particle alignment are possible not just with a quadratic potential well, but also cubic due to particle asymmetry and variation of grain charge with elevation in the sheath.

In addition to the horizontal alignment instability, the vertically aligned particles can destabilize resulting in a vertical to horizontal transition (VHT). In vertical alignment, the system cannot be assumed to behave as Hamiltonian due to the strongly asymmetric particle-wake interaction which is only communicated downwards. The currently understood theory of how the particles make their way from vertical to horizontal alignment involves continuous upward motion of the lower particle due to the shifting position of the confinement well, followed by a symmetry breaking transition where the lower particle jumps directly to the horizontal plane. The existence of this discontinuous vertical particle motion prior to the vertical to horizontal transition has not been explained. A qualitative explanation of this phenomenon can be based on an analogy with superposition of energy wells. In general, the vertical alignment can be classified into two sub-regimes.

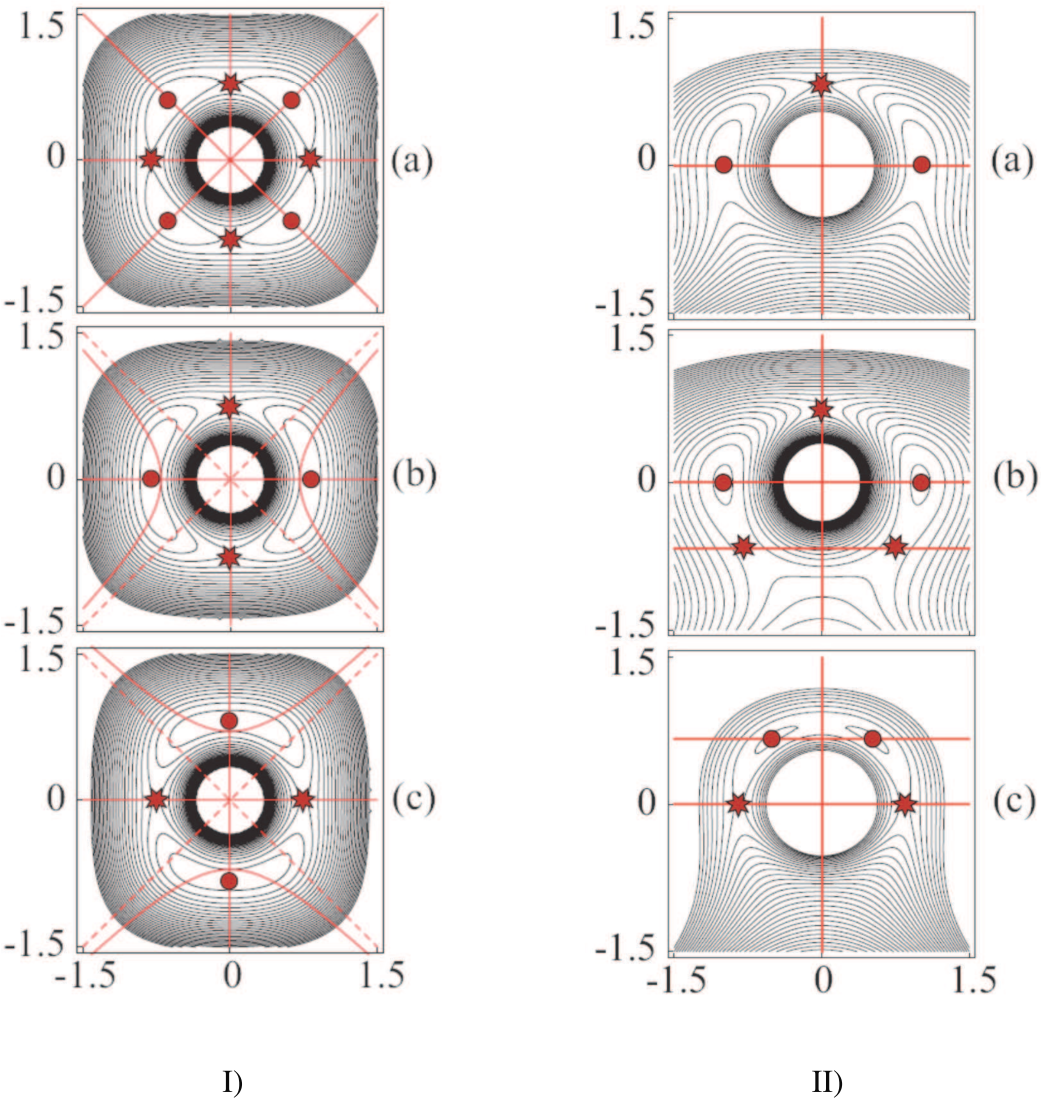

FIG. 1. (I) Potential energy contours for two particles trapped in a well with a cubic anharmonicity in the vertical direction ($a_3 = 0$) and (a) $a_2 = b_2$ (b) $a_2 < b_2$, (c) $a_2 > b_2$. Circles represent stable equilibriums and stars indicate saddle points. (II) Potential energy contours for two particles trapped in a well with quadratic an harmonicity ($a_4 = b_4$) with (a) $a_2 = b_2$, (b) $a_2 > b_2$ (c) $a_2 < b_2$. Circles represent stable equilibriums and stars indicate saddle points.

At low confinement strengths, the wake dominates and there is just one fixed point corresponding to the situation when the lower particle sits directly inside the ion focus. At the other extreme of strong confinement, the wake-induced equilibrium disappears and the particle lies in the minimum of the confinement potential well. At moderate confinement strengths, two stable fixed points exist necessarily separated by a third, unstable fixed point.

Sweeping the control parameter z in the reverse direction can cause the stable wake and unstable attractor to collide and annihilate each other in a global saddle node bifurcation thus leading to jump in the vertical position of the lower particle. Discontinuities in the interparticle separation order parameter have also been observed prior to the second stage, suggesting that the vertical-to-horizontal transition involves an additional critical phenomenon in which two vertically aligned equilibriums {one due to the confinement well and another due to perturbation of positive ions owing in the sheath by the upper particle {merge to from a single equilibrium (see Fig. 6). Although the system is strictly speaking non-Hamiltonian, consideration on the basis of an effective potential energy $V_{eff} = V_D + V_w + V_{conf}$ can be used to explain the regimes as a superposition of two energy wells. Under some conditions the wells overlap creating a single potential minimum. Under another set of conditions the wells are spatially distinct resulting in two energy minima separated by an unstable maximum.

Finally, we note that dynamics of larger ensembles of dust particles is more complicated and can differ from the studied simplest case of a two-particle dust molecule (in particular, larger N-particle dust clusters can demonstrate a variety of stable and metastable configurations, with transitions between them. Moreover, plasma absorption on dust can affect interaction of dust particles leading to long-range attractive and/or repulsive forces which can be of collective character (such as collective attraction) [1]. Applicability of the Hamiltonian approach for these larger systems in the sheath region should be considered by taking into account not only external confining potential but the effects of plasma fluxes on dust as well as inhomogeneities of plasma and dust distributions for a particular system.

Acknowledgements

This work has been supported by the Australian Research Council and the University of Sydney.

References

1.S. V. Vladimirov, K. Ostrikov, and A. A. Samarian, Physics and Applications of Complex Plasmas (Imperial College, London, 2005).

2. A. Melzer, V. A. Schweigert, and A. Piel, Phys. Rev. Lett. 83, 3194 (1999).

3. V. Steinberg, R. Sautterlin, A. V. Ivlev, and G. Morfill, Phys. Rev. Lett. 86, 4540 (2001).

4. A. A. Samarian, S. V. Vladimirov, and B. W. James, Phys. Plasmas 12, 022103 (2005).

5. M. Lampe, G. Joyce, and G. Ganguli, IEEE T. Plasma Sci. 33, 57 (2005).

6. J. D. E. Stokes, A. A. Samarian, and S. V. Vladimirov, Phys.Rev (in press).