Title: DIRECTIONAL ORDERING AND DYNAMICS IN
DUSTY PLASMAS

Author(s): J. E. Hammerberg, XNH
B. L. Holian, T-12
M. S. Murillo, XPA
D. Winske, XPA

Submitted to: To be published in the Proceedings of
the Second International Conference on
the Physics of Dusty Plasmas
Hakone, Japan
May 24-28, 1999

RECEIVED
SEP 07 1999
OSTI

Los Alamos

NATIONAL LABORATORY

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the University of California for the U.S. Department of Energy under contract W-7405-ENG-36. By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy. The Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Directional Ordering and Dynamics in Dusty Plasmas

J. E. Hammerberg, B. L. Holian, M. S. Murillo and D. Winske

*Los Alamos National Laboratory
Los Alamos, NM 87545 USA*

Abstract. We use molecular dynamics (MD) simulation methods to investigate dusty plasma crystal structure, with the grains subject to a spherically symmetric Debye-Hückel potential, a uni-directional external potential and an asymmetric wake potential. The structure is studied as a function of Mach number and magnitude of the wake as well as with the strength of the rf input power, using parameters from a self-consistent dust-sheath model.

INTRODUCTION

Molecular dynamics (MD) methods have been shown to be very useful to understand dust grain dynamics and crystal formation. Such calculations include not only the Coulomb repulsion of the grains screened by the background plasma (1), but also the important contributions of gravity and the sheath electric field (2,3). Other simulations have shown the need to also include the effect of ion flow in the sheath. Such flow effects can be included through a modification of the fluid equations describing the background plasma response (4), through an inherent asymmetric potential around each grain (5) or through a dipole-dipole force in the interaction between grains (2,6). All three methods demonstrate that including even a small asymmetry in the interaction between grains can significantly change the type of crystalline structure that is formed.

Experiments are consistent with the simulations in that the dust grains tend to align into vertical chains as they form crystals (7,8). Recent experiments (9) use a laser to perturb the grains in a crystal and suggest that wake effects which occur on the downstream side of grains immersed in an ion flow contribute to give the proper grain spacing. A similar conclusion has been reached by Murillo and Snyder (10), who use experimental data for the spacing between two vertically aligned grains to develop a self-consistent model for the charge and forces on the grains. The wake structure has been studied in a number of theoretical papers (11,12) as well as with simulations (13).

In this paper we include a spatially asymmetric wake potential in MD simulations of grain dynamics. We show that the wake potential more accurately models the experiments, and is more physically justifiable, than using a dipole interaction.

SIMULATION MODEL AND RESULTS

We consider a system of 1000 dust grains of identical charge Q , mass m , interacting via a screened Coulomb interaction and an anisotropic wake potential. The screening length is taken to be the electron Debye length, λ_{De} . Taking the unit of length to be λ_{De} and the energy unit to be Q^2/λ_{De} , the normalized potential of interaction between two particles situated at r_i and r_j is

$$\phi(r_i, r_j) = \phi_o(r_{ij}) + \phi_w(\rho_{ij}, z_{ij}) \quad (1)$$

where

$$\phi_o(r_{ij}) = \frac{\exp(-r_{ij})}{r_{ij}}, \quad (2)$$

$$\phi_w(r_{ij}, z_{ij}) = \alpha M \sin(z_{ij}/M) \exp(-v z_{ij}/M) \exp(-\rho_{ij}/M). \quad (3)$$

In the expression for ϕ_w , M is the Mach number, ρ_{ij} and z_{ij} are the cylindrical coordinates of the relative particle positions, α is a scale factor, and v is a measure of the ion-neutral collision frequency (13), which we take as 0.1. The wake potential acts only on the "downstream particle (i.e., the one with the smaller z value).

We have considered a range of Mach numbers about $M = 1.2$, a value consistent with the recent experiments (10). Other parameters are taken from the table of values given in that paper. In addition, we use their model for external potential for the electric field in the sheath and gravity. In what follows, we take the origin in z to be the point of zero external force for grains with radius of $10.4 \mu\text{m}$.

The simulations were begun with the grains on a simple cubic lattice with unit nearest neighbor distance. This was equilibrated at a temperature of 0.1 for $10 t_0$. (The time unit $T_0 = (m\lambda_{De}^3/Q^2)^{1/2}$.) During this time, point periodic boundary conditions were imposed in all directions for the $10 \times 10 \times 10$ cube and no external or wake potential was applied. Under these conditions, the lattice of Yukawa grains melted. At this point, the periodic boundary conditions along z are removed and the external potential and wake potential are introduced. The equations of motion are then integrated with a Nose-Hoover thermostat incorporated so that the temperature is quenched to a much lower value. This temperature is taken to be the "effective" electron temperature in

(10). We have used the simulations to study the effects of (a) rf power, (b) Mach number and (c) strength of the wake potential on the resulting crystal structure.

The input power dependence is investigated using the measured and derived plasma conditions of Murillo and Snyder (10), at $M = 1.2$. The system configuration at $t = 100 t_0$ is shown in Fig. 1. for the lowest (75 W) and highest (150 W) power levels. The higher power results in a stronger external potential that confines the system to a smaller region in z . Combined with the smaller λ_{De} for these plasma conditions leads to a decreased spacing ($\sim 20\%$) along z , consistent with experimental measurements (10). The configuration of the strings is well-defined, as Fig. 2(c) and 2(f) show, but the transverse order is more fluid-like, at least at this temperature.

FIGURE 1. Dust configuration at two powers (left panels, 75W; right panels, 150W). Top panels give view along x -axis, middle panels along z -axis, and bottom panels show y - z plane over a narrow slice around $x=0$.

The Mach number dependence of the effect of the wake is shown in Fig. 2, which assumes the parameters of the 125 W experiment. The figure shows results for $M = 1.0, 1.2$, and 1.4 . The effect of the larger Mach numbers is to have a more repulsive near field force along z . Thus, the higher Mach numbers gives rise to a more extended structure along z as well as a different overall equilibrium location. The structure in the transverse direction is highly disordered at these times.

FIGURE 2. Mach number dependence: Dependence on M : (left panels) $M = 1.0$, (center panels) $M = 1.2$, (right panels) $M = 1.4$. Upper panels are views along x ; bottom panels are views along z .

Finally, we consider the effect of the strength of the wake potential at fixed rf power (125W) and Mach number (1.2). Figure 3 shows results with $\alpha = 0.$, 0.01, and 0.1, at somewhat later times, $t = 300 t_0$. The lower two strengths have the same ground state as observed previously, with a slightly different external potential (2). The main ordering is first in planes, followed by fully three-dimensional structure at later times. However, for strengths beyond about $\alpha = 0.1$, the ordering is first along the z -axis, and the resulting structure is dominated by strings (Fig. 4f). The linear features predominate, with more disorder in the transverse directions. Thus, the overall structure is more akin to nematic liquid crystals than to 3-D crystalline order, as is commonly seen in experiments.

FIGURE 3. Dependence on α : (left panels) $\alpha = 0.0$, (center panels) $\alpha = 0.01$, (right panels) $\alpha = 0.1$. Upper panels are views along x ; bottom panels are views along z .

SUMMARY

We have investigated the dynamics of charged dust grains trapped in a plasma sheath and gravitational potential. We have extended our previous calculations (2) to include an asymmetric wake potential to model the flow of ions in the sheath. The addition of this potential changes both the structure of the crystal that results and how it is formed. In the absence of a wake potential (or if the coupling constant is set to a small value), the crystal first forms into planes and then into an entire crystal. With the wake, the grains first form vertical strings and then a more liquid-like crystal is produced. Increasing the flow speed of the ions (i.e., the Mach number) increases the vertical spacing. Using parameters based on experiments (10), we also find that the vertical spacing increases with rf power, in agreement with the measurements.

ACKNOWLEDGMENTS

This work was supported by the Laboratory Directed Research and Development Program.

REFERENCES

1. Hamaguchi, S., Farouki, R. T., and Dubin, D. H. E., *Phys. Rev. E*, **56**, 4671-4682 (1997).
2. Hammerberg, J. E., Holian, B. L., Murillo, M. S., and Winske, D., "Molecular dynamics simulations of dipolar dusty plasmas," *Physics of Dusty Plasmas*, AIP, CP 446, 1998, pp. 257-264.
3. Totsuji, H., Kishimoto, T., and Totsuji, C., *Phys. Rev. Lett.*, **78**, 3113-3116 (1997).
4. Melandso, F., and Goree, J., *J. Vac. Sci. Technol. A*, **14**, 511-517, (1996).
5. Melandso, F., *Phys. Rev. E*, **55**, 7495-7506 (1997).
6. Belotserkovskii, O. M., Nefedov, A. P., Filinov, V. S., Fortov, V. E., and Sinkevich, O. A., *JETP*, **88**, 449-459 (1999).
7. Pieper, J. B., Goree, J., and Quinn, R. A., *Phys. Rev. E*, **54**, 5636-5640 (1996).
8. Nunomura, S., Ohno, N., and Takamura, S., *Phys. Plasmas*, **5**, 3517-3523 (1998).
9. Takahashi, K., Oishi, T., Shimomai, K., Hayashi, Y., and Nishino, S., *Phys. Rev. E*, **58**, 7805-7811 (1998).
10. Murillo, M. S., and Snyder, H. R., "...", this conference, 1999.
11. Ishihara, O., and Vladimirov, S. V., *Phys. Plasmas*, **4**, 69-74 (1997).
12. Xie, B., He, K., and Huang, Z., *Phys. Lett. A*, **253**, 83-87 (1999).
13. Winske, D., Daughton, M. S., Murillo, M. S., and Shanahan, W. R., "Dust wake in a collisional plasma," this conference, 1999.