Final Technical Report

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Dust-Plasma Interactions

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1 Introduction

This is the final technical report for DOE grant no. **DE-FG02-04ER54804, "Dust-Plasma Interactions,"** with period of performance from August 15, 2006 to October 14, 2009.

The objective of our theoretical research under this grant over the past three years was to develop new understanding in a range of topics in the physics of dust-plasma interactions, with application to space and the laboratory. This included studies related to the physical properties of dust, waves and instabilities in both weakly coupled and strongly coupled dusty plasmas, and innovative possible applications. A major consideration in our choice of topics was to compare theory with experiments or observations, and to motivate new experiments, which we believe is important for developing this relatively new field. We have made significant progress in our research. Section 2 gives a brief summary of our research accomplishments, with reference to our publications listed in Section 3. Section 4 lists our invited and contributed conference presentations, and Section 5 summarizes our conference organization activities. Cited references are listed at the end.

2 Summary of research

We summarize our research, with reference to our list of publications in Section 3.

2.1 Physical properties and applications

We theoretically explored the possible use of noble metal nanoparticles that have surface plasmon resonances (SPR). At the SPR frequency (basically the plasma frequency of the conduction electrons in the metal grain) the absorption and scattering of electromagnetic waves can be greatly enhanced. We considered the use of larger noble metal nanoparticles, whose scattering cross section at the SPR is larger than the absorption cross-section, to generate a dense dusty plasma liquid [6].

Dust grains in hot plasmas like tokamak plasmas can get heated. We studied the temperature dependence of thermal radiation from metallic dust, taking into account the temperature dependence of the optical constants of the dust [7, 11]. This has application to diagnosing heated metallic dust in hot environments like fusion plasmas, thermal plasmas, and perhaps combustion environments.

2.2 Waves and instabilities in space dusty plasmas

We investigated a possible lower-hybrid instability driven by fast ions sputtered from a fast meteoroid at high altitude in the Earth's ionosphere, and considered conditions for radar scattering from the excited waves [9]. Motivated by the recent detection of heavy negative ions or aerosols in the satellite Titan's ionosphere, we studied an ion-acoustic instability whose observation would indicate the presence of electric fields that may levitate the aerosols [14].

2.3 Wave and instabilities in weakly coupled laboratory dusty plasmas

We compared the kinetic theory of dust acoustic waves with recent experimental results, and found that theory compared well if the dust thermal energy was taken into account [10]. Motivated by current and upcoming laboratory dusty plasma experiments with large magnetic fields, we began to investigate instabilities in dusty plasmas where both electrons and ions are magnetized. We considered the instability of obliquely propagating dust waves driven by ion cross-field drift [2]. Motivated by recent experiments by Kim and Merlino [2006] on dusty plasmas containing negative ions, we considered a "fast wave" ion acoustic instability and found that the behavior of the wave frequency might be useful diagnostic for the presence of positively charged dust in this type of plasma [5]. We also investigated the excitation of higher harmonic electrostatic cyclotron waves in a negative ion plasma, in order to compare with recent experiments of Kim and Merlino [2008]. We found that the presence of the negative ions enhances excitation of these high harmonics, which appears to be consistent with experimental trends [12]. In addition, we studied the excitation of dust acoustic waves in a dusty negative ion plasma, and found that the waves could propagate in the direction of the negative and/or positive ion drifts; suggestions for new experiments were given [13]. We extended the latter study to consider the a cross-field dust acoustic instability in a negative ion plasma in a large magnetic field, in which the positive ions (and electrons) are magnetized while the negative ions are marginally unmagnetized [19]. We found conditions for the excitation of dust acoustic waves due to $\mathbf{E} \times \mathbf{B}$ drifts of ions; suggestions for new experiments were given. We also considered the excitation of drift waves in a dusty collisional negative ion plasma [17].

2.4 Waves and instabilities in strongly coupled dusty plasmas

Using the quasi-localized charge approximation (QLCA) approach of Kalman and Golden [1990], we derived the dispersion relation for waves in the liquid phase of a two dimensional

(2D) strongly coupled dusty plasma, where the grains interact via a screened Coulomb (Yukawa) interaction [see 4]. Experiments show agreement with our predictions [Nosenko et al., 2006; Piel et al., 2006]. We computed the full anisotropic phonon dispersion relation for a Yukawa solid (i.e., a 2D hexagonal lattice), and found that there is a similarity between the angle averaged dispersion and the QLCA derived dispersion for waves in the liquid phase [4]. We studied a 2D beam-plasma instability in both the liquid and solid phases of a Yukawa plasma, in the case that the beam is weakly coupled [3, 15]. When the Yukawa plasma is in the solid phase, we found that the mixing of polarizations in the phonon spectrum can lead to a novel transverse beam-plasma instability that competes with the usual longitudinal instability; experimental parameters for observing the beam-plasma instabilities were suggested [15]. The introduction of dust grains with magnetic moments is expected to lead to new areas of research, and we began studies in this area. We theoretically analyzed the ground state configuration of a layer of charged magnetic dipoles, finding a structural transition from a ferromagnetic to anti-ferromagnetic phase as the relative strength of the magnetic to electrostatic coupling increases [8]. In addition, we reported observations of wave excitations in a dusty plasma bilayer, and provided analytical and numerical simulation results that compared reasonably well with experiment and helped to identify the waves [20].

2.5 Innovative applications

We proposed and discussed a novel type of 2D dusty plasma formed by positioning charged dust grains on the surface of a cryogenic fluid like liquid helium [1]. In addition, we suggested a possible dusty microplasma source of mid infrared source [18]. The radiation arises from thermal emission of heated grains made of material that are selective emitters in the mid infrared.

3 Journal publications

1. M. Rosenberg and G. J. Kalman, Suggestion for a two-dimensional cryogenic complex plasma, *Europhys. Lett.* **75**, 894 (2006).

2. M. Rosenberg and P. K. Shukla, Instability of obliquely propagating dust waves in a collisional highly magnetized plasma, *J. Plasma Phys.* **73**, 189 (2007).

3. S. Kyrkos, G. J. Kalman, and M. Rosenberg, Beam-plasma interaction in two-dimensional Yukawa lattices, *IEEE Trans. Plasma Sci.* **35**, 342 (2007).

4. P. Hartmann, Z. Donko, G.J. Kalman, S. Kyrkos, M. Rosenberg and P. M. Bakshi, Collective modes in 2-D Yukawa solids and liquids, *IEEE Trans. Plasma Sci.* **35**, 337 (2007).

5. M. Rosenberg and R. L. Merlino, Ion-acoustic instability in a dusty negative ion plasma, *Planet. Space Sci.* **55**, 1464 (2007).

6. M. Rosenberg, A note on the possibility of generating a dense dusty plasma liquid, *IEEE Trans. Plasma Sci.* **35**, 1805 (2007).

7. M. Rosenberg, R. D. Smirnov, and A. Y. Pigarov, On thermal radiation from heated metallic dust grains, *J. Phys. D: Appl. Phys.* **41**, 015202 (2008).

8. J. D. Feldmann, G. J. Kalman, P. Hartmann, and M. Rosenberg, Ground state of magnetic dipoles on a two-dimensional lattice: Structural phases in complex plasmas, *Phys. Rev. Lett.* **100**, 085001 (2008).

9. M. Rosenberg, On the possibility of a lower-hybrid instability driven by fast ions sputtered from a meteoroid, *Planet. Space Sci.* **56**, 1191 (2008).

10. M. Rosenberg, E. Thomas, Jr., and R. L. Merlino, A note on dust wave excitation in a plasma with warm dust: Comparison with experiment, *Phys. Plasmas* **15**, 073701 (2008).

11. M. Rosenberg, R. D. Smirnov, and A. Y. Pigarov, On thermal radiation from fusion related metals, *Fus. Eng. Design* **84**, 38 (2009).

12. M. Rosenberg and R. L. Merlino, Instability of higher harmonic electrostatic cyclotron waves in a negative ion plasma, *J. Plasma Phys.* **75**, 495 (2009).

13. M. Rosenberg, On dust acoustic instability in a negative ion plasma, *Phys. Scripta* **79**, 015008 (2009).

14. M. Rosenberg and P. K. Shukla, On the possibility of ion-acoustic instability in Titan's atmosphere, *Planet. Space Sci.* **57**, 2030 (2009).

15. S. Kyrkos, G. J. Kalman and M. Rosenberg, Beam-plasma instabilities in a 2-D Yukawa lattice, *Phys. Rev. Lett.* **102**, 225006 (2009).

16. W. Sekine, O. Ishihara and M. Rosenberg, Dust dynamics in a cryogenic environment, *J. Plasma Fusion Res. SERIES* **8**, 290 (2009).

17. P. K. Shukla and M. Rosenberg, Drift wave excitation in a collisional dusty magnetoplasma with multi-ion species, *J. Plasma Phys.* **75**, 153 (2009).

18. M. Rosenberg and R. D. Smirnov, A possible dusty microplasma source of mid infrared radiation, *IEEE Trans. Plasma Sci.*, to appear, 2009.

19. M. Rosenberg, Cross-field dust acoustic instability in a dusty negative ion plasma, *Phys. Scripta*, to appear, 2009.

20. P. Hartmann, Z. Donko, G. J. Kalman, S. Kyrkos, K. I. Golden, and M. Rosenberg, Collective dynamics of complex plasma bilayers, *Phys. Rev. Lett.* **103**, 245002 (2009).

4 Conference presentations

1. M. Rosenberg and G. J. Kalman, "'Suggestion for a two-dimensional cryogenic complex plasma," poster GP1.00052 at 48th APS-DPP Meeting, Oct. 30-Nov.3, 2006, Philadelphia, PA.

2. J. Feldman, G. Kalman, P. Hartmann and M. Rosenberg, "Ground state and collective modes of magnetic dipoles fixed on two-dimensional lattice sites," poster GP1.00054 at 48th APS-DPP Meeting, Oct. 30-Nov.3, 2006, Philadelphia, PA.

3. P. Hartmann, Z. Donko, G. Kalman, P. Bakshi, S. Kyrkos and M. Rosenberg, "Collective modes in 2D Yukawa solids and liquids," poster GP1.00064 at 48th APS-DPP Meeting, Oct. 30-Nov.3, 2006, Philadelphia, PA.

4. S. Kyrkos, G. J. Kalman and M. Rosenberg, "Beam-plasma interaction in a 2D complex plasma," poster GP1.00065 at 48th APS-DPP Meeting, Oct. 30-Nov.3, 2006, Philadelphia, PA.

5. R. D. Smirnov, A. Yu. Pigarov, S. I. Krasheninnikov, M. Rosenberg and D. A. Mendis, "Modeling of dust dynamics in tokamaks," poster JP1.00051 at 48th APS-DPP Meeting, Oct. 30-Nov.3, 2006, Philadelphia, PA.

6. M. Rosenberg and P. K. Shukla, "Instability of obliquely propagating dust waves in a collisional highly magnetized dusty plasma," poster ZP1.00024 at 48th APS-DPP Meeting, Oct. 30-Nov.3, 2006, Philadelphia, PA.

7. M. Rosenberg and G. J. Kalman, "2D Cryogenic dusty plasmas: A suggestion, poster at Pulsed Power Plasma Science Conference 2007, PPPS 2007, June 17-22, 2007, Albuquerque, NM (abstract in Conference Record, p. 925).

8. R. D. Smirnov, A. Yu. Pigarov, M. Rosenberg, S. I. Krasheninnikov and D. A. Mendis, "Transport of carbon dust particles in Tokamaks," poster at Pulsed Power Plasma Science Conference 2007, PPPS 2007, June 17-22, 2007, Albuquerque, NM (abstract in Conference Record, p. 921).

9. C. Fichtl, G. Lapenta and M. Rosenberg, "PIC Simulations of dust charging in the presence of a magnetic field," poster at Pulsed Power Plasma Science Conference 2007, PPPS 2007, June 17-22, 2007, Albuquerque, NM (abstract in Conference Record, p. 917).

10. S. Kyrkos, G. J. Kalman and M. Rosenberg, "Beam-plasma interaction and instability in a 2D Yukawa plasma," poster at Strongly Coupled Coulomb Systems SCCS2008, July29-August2, 2008, Camerino, Italy.

11. M. Rosenberg and G. J. Kalman, "A two-dimensional cryogenic complex plasma?, " poster at Strongly Coupled Coulomb Systems SCCS2008, July29-August2, 2008, Camerino, Italy.

12. M. Rosenberg, "Instabilities in ionospheric dusty plasmas," talk at XXIX General Assembly of the International Union of Radio Science, August 7-16, 2008, Chicago, Il. (page 153 of book of abstracts)

13. R. L. Merlino, R. Fisher, E. Thomas, S. H. Kim, J. R. Heinrich and M. Rosenberg, "Dust acoustic wave (DAW) experiments at the University of Iowa, Invited talk at XXIX General Assembly of the International Union of Radio Science, August 7-16, 2008, Chicago, Il. (page 153 of book of abstracts)

14. M. Rosenberg, E. Thomas, L. Marcus, R. Fisher, J. D. Williams and R. L. Merlino, "Dust acoustic wave excitation in a plasma with warm dust," poster NP6.00005 at 50th APS-DPP Meeting, Nov. 17-21, 2008, Dallas, TX.

15. R. D. Smirnov, K. I. Krasheninnikov, A. Y. Pigarov, M. Rosenberg and D. A. Mendis, "Dust radiation and imaging in tokamak plasmas," talk NO3.00007 at 50th APS-DPP Meeting, Nov. 17-21, 2008, Dallas, TX.

16. R. L. Merlino, S.-H. Kim, J. Heinrich and M. Rosenberg, "Electrostatic ion cyclotron waves in a plasma with heavy negative ions," poster UP6.00094 at 50th APS-DPP Meeting, Nov. 17-21, 2008, Dallas, TX.

17. Z. Donko, G. J. Kalman, P. Hartmann, S. Kyrkos and M. Rosenberg, "Studies of binary layers in complex plasmas," poster at the 12th Workshop on the Physics of Dusty Plasmas, May 17-20, 2009, Boulder, CO.

18. P. Hartmann, M. Rosenberg, G. J. Kalman and Z. Donko, "Ground state structures of superparamagnetic dusty plasma crystals," poster at the 12th Workshop on the Physics of Dusty Plasmas, May 17-20, 2009, Boulder, CO.

19. M. Rosenberg, "Dust acoustic instabilities in multi-ion species plasmas," poster at the 12th Workshop on the Physics of Dusty Plasmas, May 17-20, 2009, Boulder, CO.

20. R. D. Smirnov, M. Rosenberg, A. Y. Pigarov, J. H. Yu, A. L. Roquemore, J. L. Terry, S. I. Krasheninnikov, D. A. Mendis and W. P. West, "Dust dynamics and radiation in fusion plasmas," poster at IEEE International Conference on Plasma Science 2009, June 1-5, 2009, San Diego, CA.

21. M. Rosenberg, "Instabilities in dusty negative ion plasmas," poster at IEEE International Conference on Plasma Science 2009, June 1-5, 2009, San Diego, CA.

22. M. J. Nicolls, M. Rosenberg and M. C. Kelley, "On the charging of mesospheric dust," poster at IEEE International Conference on Plasma Science 2009, June 1-5, 2009, San Diego, CA.

23. E. Thomas, R. L. Merlino and M. Rosenberg, "A proposed magnetized dusty plasma user facility," poster at 51st APS-DPP Meeting, Nov. 2-6, 2009, Atlanta, GA.

5 Related professional activities

1. The PI organized the Dusty Plasma session at the IEEE Pulsed Power and Plasma Science 2007 Conference, PPPS 2007, June 17-22, 2007, Albuquerque, N. M.
2. The PI organized the Dusty Plasma session at the XXIX URSI General Assembly 2008, Aug. 7-16, 2008, Chicago, Ill.
3. The PI organized the Dusty Plasma session at the IEEE International Conference on Plasma Science 2009, June 1-5, 2009, San Diego, CA.

References

[1] Kalman, G. and Golden, K.I. 1990 *Phys. Rev. A* **41**, 5516.

[2] Kim, S.-H. and Merlino, R. L. 2006 *Phys. Plasmas* **13**, 052118.

[3] Kim, S.-H., Heinrich, J. R. and Merlino, R. L. 2008 *Planet. Space Sci.* **56**, 1552.

[4] Nosenko, V., Goree, J. and Piel, A. 2006 *Phys. Rev. Lett.* **97**, 115001.

[5] Piel, A., Nosenko, V. and Goree, J. 2006 *Phys. Plasmas* **13**, 142104.