FINAL TECHNICAL REPORT

PI: Robert. L. Merlino
Institution: University of Iowa
Project Title: Experimental Investigations of Fundamental Processes in Dusty Plasmas
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ABSTRACT

This is the final technical report for DOE Grant #DE-FG02-04ER54795-Experimental Investigations of Fundamental Processes in Dusty Plasmas. A plasma is an ionized gas, and a dusty plasmas is a plasma that contains, in addition to electrons and ions, micron-sized dust particles. The dust particles acquire and electric charge in the plasma by collecting electrons and ions. The electrons move more rapidly than the ions, so the dust charge is negative. A 1 micron dust particle in a typical low temperature plasma has a charge corresponding to approximately 2000 electrons. Dusty plasmas are naturally found in astrophysical plasmas, planetary rings, technological plasmas, and magnetic fusion plasmas. The goal of this project was to study in the laboratory, the basic physical processes that occur in dusty plasmas. This report provides a summary of the major scientific products and activities of this award.

MAJOR SCIENTIFIC RESULTS

- Developed theory and preformed first experiments on the charging of dust in a plasma with negative ions
- Measurement of the ion drag force on dust particles in the strong ion-grain coupling limit. The ion drag force is one of the most important forces on dust particles in a plasma and the main cause of dust transport
- Development of a new source of heavy negative ions
- First laboratory observation of dust acoustic (DA) shock waves and verification of the theory of DA shocks of Shukla and Eliasson. DA shocks considered to be important as a potential mechanism for coalescence of charged dust in proto-planetary systems.
- Theory and experiments on non-linear DA waves
- First laboratory observation of a structure-forming instability in a dusty plasma
- Development of a source of drifting dusty plasma
- First experimental observation of Taylor instability in a dusty plasma.
- Experiments on the interaction of obstacles with flowing dusty plasmas
- First observations of the formation of a transient bow shock in front of an obstacle in a supersonically flowing dusty plasma
- Experiments on explosion and expansion of charged dust clouds in afterglow plasmas
- First observation of the fission of a charged dust cloud in an afterglow plasma.

SYNERGISTIC AND OUTREACH ACTIVITIES

- PI developed MAPLE based programs to model Langmuir probe I-V characteristics. This was provided as a teaching tool to help students learn how to interpret probe data. The programs were posted for general use on the PI's webpage. The PI also advocated inclusion of plasma experiments as part of the typical undergraduate advanced physics laboratory course. These were presented in a paper in the American Journal of Physics (vol. 85, pp. 1078-1085, 2007).

- PI has participated in the Adopt-a-Physicist program (http://www.adoptaphysicist.org/) sponsored by the AIP/SPS, APS, and AAPT, provided through ComPADRE and the NSF/NSDL.

PERSONNEL SUPPORTED ON THIS PROJECT

- **Graduate Students**

1. Jonathon R. Heinrich, PhD. December 2011
   Thesis Title: Structure Formation and Wave Phenomena in Moderately Coupled Dusty Plasmas. Presently employed at Lockheed Martin: Compact Fusion Research & Development.

2. John K. Meyer, PhD. May 2015
   Thesis Title: Experiments in Flowing and Freely Expanding Dusty Plasmas

- **Research Scientist**

  Su-Hyun Kim (Presently at Mathematics & Science Division, Columbia Basin College, Pasco, WA)

- **Technical Support**

  Michael J. Miller (Engineer)

- **Undergraduate Students**

1. Ross Fisher (Received PhD. in Plasma Physics from Auburn University)
2. Katherine A. Pacha
3. Michael McKinlay (Graduate student in plasma physics at Auburn University)
4. Sean Harding

INVITED TALKS ON PROJECT WORK

1. Linear and Nonlinear Dust Acoustic Waves, Shocks and Stationary Structures in DC-Glow-Discharge Dusty Plasma Experiments, R. L. Merlino, APS DPP 2011.

2. Nonlinear Dust Acoustic Waves, Shocks, and Stationary Structures in a DC Glow Discharge Dusty Plasma, R. L. Merlino, Sixth International Conference on the Physics of Dusty Plasmas, Garmisch-Partenkirchen, Germany, May 2011.

3. Observations of Linear and Nonlinear Dust Acoustic Waves, R. L. Merlino, 13th Workshop on the physics of dusty plasmas, Waco, TX, May 21, 2012.

4. Experiments on Shocks and Dust Structures in Dusty Plasmas, R. L. Merlino, Invited Plenary Talk, EPS/ICPP Stockholm, Sweden, July 2012.

AWARDS

Robert L. Merlino—Star Dust Award, Highest Award of the International Dusty Plasma Community, International Dusty Plasma Organization, presented at the Sixth International Conference on the Physics of Dusty Plasmas, Garmisch-Partenkirchen, Germany, May 2011.

MAJOR COLLABORATORS

1. Edward J. Thomas Jr. (Auburn University)
2. Marlene Rosenberg (University of California, San Diego)
3. K. Avinash (University of New Delhi)
4. V. Nosenko (Deutsches Zentrum für Luft- und Raumfahrt Forschungsgruppe Komplexe Plasmen Münchener Straße 20 82234 Weßling, Germany)

PUBLICATIONS ON THIS PROJECT

1. Dissipative processes and dust ion-acoustic shocks in a Q machine device, S. I. Popel, T. V. Losseva, R. L. Merlino, S. N. Andreev, and A. P. Golub, *Phys. Plasmas* **12**, 054501 (2005).

2. Electron and ion inertia effects on current driven collisional dust acoustic, dust ion acoustic and ion acoustic instabilities, R. L. Merlino and N. D'Angelo, *Phys. Plasmas* **12**, 054504 (2005).

3. Dust ion acoustic shocks in a Q machine device, S. I. Popel, T. V. Losseva, A. P. Golub, R. L. Merlino and S. N. Andreev, *Contrib. Plasmas Phys*. **45**, 461-475 (2005).

4. Experimental investigations of dusty plasmas, R. L, Merlino, *New Vistas in Dusty Plasmas*, edited by L. Buofendi, M. Mikikian and P. K.Shukla AIP Conference Proceedings Vol.799, Melville, New York, 2005, America Institute of Physics, pp. 3-11.

5. Charging of dust grains in a plasma with negative ions, Su-Hyun Kim and Robert L. Merlino, *Phys. Plasmas* **13**, 052118 (2006).

6. Charge neutralization of dust particles in a plasma with negative ions, Robert L. Merlino and Su-Hyun Kim, *Appl. Phys. Lett.* **89**, 091501 (2006).

7. Electron attachment to C_7F_{14} and SF_6 in a thermally ionized potassium plasma, Su-Hyun Kim and Robert L. Merlino, *Phys. Rev. E* **76**, 035401(R) (2007).

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

9. Measurement of the ion drag force in a collisionless plasma with strong ion-grain coupling, V. Nosenko, R. Fisher, R. L. Merlino, S. Khrapak, G. Morfill, K. Avinash, *Phys. Plasmas* **14**, 103702 (2007).

10. Understanding Langmuir probe current-voltage characteristics, R. L. Merlino, *Am. J. Phys.* **75**, 1078 (2007).

11. Observations of dust acoustic waves driven at high frequencies: Finite dust temperature effects and wave interference, E. Thomas, R. Fisher, and R. L. Merlino, *Phys. Plasmas* **14**, 123701 (2007).

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

13. Bayard-Alpert gauge sensitivity for C7F14, S.-H. Kim, J. R. Heinrich, M. Miller and R. L. Merlino, *J. Vac. Sci. Technol. A* **26**, 1355-1356 (2008).

14. Electrostatic ion-cyclotron waves in a plasma with heavy negative ions, Su-Hyun Kim, J. R. Heinrich, and R. L. Merlino, *Planet. Space Sci. 56*, 1552-1559 (2008).

15. Diffraction of dust acoustic waves by a circular cylinder, Su-Hyun Kim, J. R. Heinrich, and R. L. Merlino, *Phys. Plasmas* **15**, 090701 (2008).

16. R. L. Merlino and S.-H. Kim, Measurement of the electron attachment rates for SF_6 and C_7F_{14} at T_e = 0.2 eV in magnetized Q machine plasma, *J. Chem. Phys.* **129**, 224310 (2008).

17. Improved theoretical approximation for the ion drag force in a collisionless plasma with strong ion-grain coupling, S. Khrapak, V. Nosenko, G. Morfill, and R. L. Merlino, *Phys. Plasmas* **16**, 044507 (2009).

18. Laboratory observations of self-excited dust acoustic shocks, J. R. Heinrich, S.-H. Kim and R. L. Merlino, *Phys. Rev. Lett*. **103**, 115002 (2009).

19. Measurements of the power spectrum and dispersion relation for self-excited dust acoustic waves, V. Nosenko, S. K. Zhdanov, S.-H. Kim, J. Heinrich, R. L. Merlino, and G. E. Morfill *Europhys. Letters (EPL)* **88**, 65001 (2009).

20. Dust acoustic waves driven by an ion-dust streaming instability in laboratory discharge dusty plasma experiments, R. L. Merlino, *Phys. Plasmas* **16**, 124501 (2009).

21. Book Review, *Elementary Physics of Complex Plasmas*, Lecture Notes on Physics, Vol. 731, by V. N.Tsytovich, G. E. Morfill, S. V. Vladimirov, and H. M. Thomas, Springer, Berlin Heidelberg, 2008, R. L. Merlino, *J. Plasmas Phys*. **75**, 709-711 (2009).

22. Dust-Acoustic Waves: Visible Sound Waves, R. L. Merlino, *Developments in Nonlinear Plasma Physics*, Edited by Bengt Eliasson and Padma K. Shukla, AIP Conference Proceedings 1188, American Institute of Physics, Melville, NY, 2009, pages 141-152.

23. Supersonic dust jets produced by a dust-discharge instability, J. Heinrich, S-H. Kim, and R. L Merlino, *Phys. Plasmas* **17**, 083702 (2010).

24. On the possibility of refraction of dust acoustic waves, M. Rosenberg, R. L. Merlino, and P. K. Shukla, *J. Plasma Phys*. **77**, 231-236 (2011).

25. Nonlinear dust acoustic waves, shocks, and stationary structures in a DC glow discharge dusty plasma, R. L. Merlino, J. R. Heinrich, and S. H. Kim, AIP Conf. Proc. 1397, 24 (2011).

26. Anomalous dust temperature in dusty plasma experiments, K. Avinash, R. L. Merlino, and P. K. Shukla, *Phys. Lett. A* **375**, 2854-2857 (2011).

27. Observations of a structure-forming instability in a dc-glow-discharge dusty plasma, J. Heinrich, S.-H. Kim, and R. L. Merlino, *Phys. Rev. E* **84**, 026403 (2011).

28. Experimental quiescent drifting dusty plasmas and temporal dust acoustic wave growth, J. Heinrich, S.-H. Kim, J. Meyer, and R. L. Merlino, *Phys. Plasmas* **18**, 113706, (2011).

29. Observation of the Taylor instability in a dusty plasma, K. A. Pacha, J. Heinrich, S.-H. Kim, and R. L. Merlino, *Phys. Plasmas* **19**, 014501 (2012).

30. Second order dust acoustic wave theory, R. L. Merlino, *Phys. Scr*. **85**, 035506 (2012).

31. Nonlinear dust acoustic waves and shocks, R. L. Merlino, J. Heinrich, S.-H. Kim, J. K. Meyer, *Phys. Plasmas* **19**, 057301 (2012).

32. The effect of an external magnetic field on a critical point for the phase separation in a dusty plasma, K. Avinash, P. K. Shukla and R. L. Merlino, *Phys. Scr*. **86**, 035504 (2012).

33. Dusty Plasmas: Experiments on nonlinear dust acoustic waves, shocks, and structures, R. L. Merlino, J. R. Heinrich, S-H. Kim, and J. K. Meyer, *Plasma Phys. Control. Fusion* **54**, 124014 (2012).

34. Secondary dust density waves excited by nonlinear dust acoustic waves, J. R. Heinrich, S.-H. Kim, J. K. Meyer, R. L. Merlino, M. Rosenberg, *Phys. Plasmas* **19**, 083702-1-5 (2012).

35. Interaction of a biased wire with a flowing dusty plasma, John K. Meyer, Jonathon R. Heinrich, Su-Hyun Kim, and Robert L. Merlino, *J. Plasma Phys*. **79**, 677-682 (2013).
36. Transient bow shock around a cylinder in a supersonic dusty plasma, John K. Meyer and Robert L. Merlino, *Phys. Plasmas* **20**, 074501 (2013).

37. Drift instability in a positive ion-negative ion plasma, M. Rosenberg and R. L. Merlino, *J. Plasma Phys*. **79**, 949-952 (2013).

38. Low-frequency electrostatic waves in a magnetized, current-free heavy negative ion plasma S-H. Kim, R. L. Merlino, J. K. Meyer, and M. Rosenberg, *J. Plasma Phys*. ***79***, 1107-1111 (2013).

39. Flow of dusty plasma around an obstacle, John K. Meyer, Robert L. Merlino, Jonathon R. Heinrich, and S. H. Kim, *IEEE Trans. Plasma Sci*. **42**, 2690-2691 (2014).

40. 25 Years of Dust Acoustic Waves, R. L. Merlino, *J. Plasma Phys*. **80**, 773 (2014).

Manuscripts Submitted or in Preparation

1. Evolution of dust clouds in afterglow plasmas, J. K. Meyer and R. L. Merlino, Submitted to *IEEE Trans. Plasma Sci*. July 2015.

2. Coulomb explosion and fission in dusty plasmas, J. K. Meyer, R. L. Merlino, V. Saxena, K. Avinash, and A. Sen, To be submitted to *Physics of Plasmas*, 2015.