

## **Final Progress Report**

**Principal Investigator:** John A Goree  
**Sponsor:** US Department of Energy  
**Title:** Strongly-Coupled Dusty Plasmas  
**Grantor/Contract #:** DE-FG02-00ER54607 Amend 8-9  
**Project Period:** 08/15/2000 - 08/14/2010

This project will continue under funding from the National Science Foundation, with a grant having the same project title, “Strongly-Coupled Dusty Plasmas.” The subject DOE grant and the new NSF grant are both the result of sponsorship by the NSF-DOE Partnership in Basic Plasma Science and Engineering. In 2009, the partnership elected to renew this grant using funding from the NSF rather than by DOE. As a result, the DOE portion of the project is completed, but the project is actually continuing. Thus, this Final Progress Report is final only in the sense that it relates to the period of funding from the DOE.

This report covers the most recent funding period of 08/15/2006 – 08/14/2009, with a no-cost extension to 08/14/2010.

The subject of the project is the basic-plasma physics topic of strongly-coupled plasmas, as studied experimentally using dusty plasmas. This topic is highly interdisciplinary, with significant overlap with astrophysics, space physics, and condensed matter physics.

Among the successes of this project during the most recent four-year period are the 23 papers were produced for peer-reviewed scientific journals. These papers mostly report experiments, as well as some numerical simulations. Coauthors of the papers include collaborators in Germany, Hungary, and Russia, as well as the U.S. Research topics included traditional plasma physics themes such as transport, waves, instabilities, and experimental diagnostics. They also included interdisciplinary topics of melting (condensed matter physics) and rarefied gas dynamics (fluid mechanics).

All of the research topics were chosen to have a high impact. Our success in achieving a high impact is demonstrated by the seven papers published in Physical Review Letters over a four-year period, and a significant number of invited talks.

The project included a broader-impact element that included not only training of graduate students and public dissemination of research results, but also an outreach program. The outreach included presentations motivated by the sound-wave experiments in this project for the “Family Science Adventures” (for children and parents of Iowa City area) and hands-on experiments at a K12 school (3rd and 4th grades in 2007, and 5th and 6th grades in 2008).

## Invited Talks at International Conferences

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- “Diffusion and super-diffusion in strongly-coupled dusty plasmas”  
*48th Annual Meeting of the APS Division of Plasma Physics*  
*Philadelphia, PA* Oct 2006
- “Diffusive Transport of Microparticles in an Rf Glow Discharge Plasma”  
*2007 IEEE Conference on Plasma Sciences*  
*Albuquerque, NM* Jun 2007
- “Comparison of Dusty Plasma and Colloidal Suspension”  
*2008 International Conference on Strongly Coupled Coulomb Systems.*  
*Camerino, Italy,* July 29 - August 2, 2008
- “The electrical charge and motion of objects inserted into a plasma”  
*2009 American Association of Physics Teachers Summer Meeting*  
*Ann Arbor, Michigan* 28 July 2009
- “Imaging Charged Dust in Laboratory Plasmas  
*American Astronomical Society Summer Meeting*  
*Miami, Florida* 23 – 27 May 2010

## Invited Talks at Regional Conferences

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- “The electrical charge and motion of objects inserted into a plasma produced by ionizing gas”  
*Ohio Section of the American Physical Society*  
*Ada, Ohio* 24 April 2009

## Degrees Awarded

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|-------------------------|---------------|------|
| <i>Timothy Flanagan</i> | M.S. Physics  | 2006 |
| <i>Yan Feng</i>         | Ph.D. Physics | 2010 |

## Additional Graduate Students Trained

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|---------------------------|-----------------------------|---------------|
| <i>Suranga Ruhunusiri</i> | Thesis research in progress | 2009- present |
| <i>Amit Mukhopadhyay</i>  | Thesis research in progress | 2009- present |

## Contributed Talks

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- Thermal conductivity measurements in a 2D Yukawa system  
V. Nosenko, A. Ivlev, S. Zhdanov, G. Morfill, J. Goree, A. Piel  
*March Meeting of the APS, Denver, CO* Mar 2007
- Zelluläre Zweiphasenstroemung in komplexen Plasmen  
Oliver Arp and John Goree  
*German Physical Society Section Plasma Physics Meeting, Düsseldorf, Germany* May 2007
- Heating and cooling in dusty plasmas  
Y. Feng, J. Goree, Bin Liu  
*49th Annual Meeting of the APS Division of Plasma Physics, Orlando, FL* Nov 2007
- Self-diffusion and random motion in a strongly-coupled dusty-plasma: experiment  
Bin Liu, J. Goree  
*49th Annual Meeting of the APS Division of Plasma Physics, Orlando, FL* Nov 2007
- Laser manipulation of dust particles in Coulomb balls – to be announced  
T.M. Flanagan, J. Goree  
*49th Annual Meeting of the APS Division of Plasma Physics, Orlando, FL* Nov 2007
- Self-diffusion and random motion in a strongly-coupled dusty-plasma: MD simulation  
J. Goree, Bin Liu, Z. Donkó, P. Hartmann  
*49th Annual Meeting of the APS Division of Plasma Physics, Orlando, FL* Nov 2007
- Superheating of a dusty plasma crystal  
J. Goree, Yan Feng, and Bin Liu  
*50th Annual Meeting of the APS Division of Plasma Physics, Dallas, TX* Nov 2008
- Detection of solid superheating in 2D dusty plasmas  
J. Goree, Yan Feng, and Bin Liu  
*12<sup>th</sup> Workshop on the Physics of Dusty Plasmas, Boulder, CO* May 2009
- Experimental Investigation of Dust Density Waves and Plasma Glow  
O. Arp, D. Caliebe, K. Menzel, A. Piel, John A. Goree  
*12<sup>th</sup> Workshop on the Physics of Dusty Plasmas, Boulder, CO* May 2009
- Time dependence of shear-induced melting and subsequent solidification in a 2D dusty plasma  
Yan Feng, J. Goree, and Bin Liu  
*12<sup>th</sup> Workshop on the Physics of Dusty Plasmas, Boulder, CO* May 2009
- Using dusty plasma to detect thermal creep gas flow  
Tim Flanagan and John Goree  
*12<sup>th</sup> Workshop on the Physics of Dusty Plasmas, Boulder, CO* May 2009

- Improving the accuracy of the moment method for measuring particle positions  
W. D. Suranga Ruhunusiri, Y. Feng, J. Goree, and Bin Liu  
*12<sup>th</sup> Workshop on the Physics of Dusty Plasmas, Boulder, CO* May 2009
- Oscillatory Particle Motion Observed in Dusty Plasma under Microgravity Conditions  
John Goree, Bin Liu, V.E. Fortov, A.M. Lipaev, V.I. Molotkov, O. Petrov,  
G. E. Morfill, H.M. Thomas, H. Rothermel, A. Ivlev  
*2009 IEEE Conference on Plasma Science, San Diego, CA* June 2009
- Oscillatory Particle Motion in Dusty Plasma under Microgravity Conditions  
John Goree, Bin Liu, V.E. Fortov, A.M. Lipaev, V.I. Molotkov, O.F. Petrov, G.E. Morfill,  
H.M. Thomas, H. Rothermel, and A.V. Ivlev  
*51st Annual Meeting of the APS Division of Plasma Physics, Atlanta, GA* Nov 2009
- “Laboratory Observation of Naturally Occurring Dust Density Waves”  
Tim Flanagan and John Goree  
*IEEE Conference on Plasma Science,  
Norfolk, Virginia* Jun 2010
- “Viscoelasticity of 2D Dusty Plasmas”  
Yan Feng, John Goree, and Bin Liu  
*IEEE Conference on Plasma Science,  
Norfolk, Virginia* Jun 2010
- “Viscoelasticity of 2D Dusty Plasmas”  
Yan Feng, John Goree, and Bin Liu  
*Gordon Research Conference on Plasma Processing Science, New London, NH* Jul 2010

## Colloquia and Seminars

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- Physics Colloquium, *University of Greifswald, Germany*  
“Two-dimensional liquids at an atomistic scale: dusty plasma experiments and numerical simulations.” 20 Oct 2006
- Physics Colloquium, *University of Colorado*  
“Two-dimensional liquids at an atomistic scale: dusty plasma experiments and numerical simulations.” 26 Nov 2006
- Colloquium, P/T divisions, *Los Alamos National Laboratory*  
“Dusty plasmas: an overview including topics from condensed matter, fluids, and astronomy.” 2 Aug 2007
- Physics Colloquium, *Boston College*  
“Low-dimensionality condensed matter experiments performed at an atomistic scale using strongly-coupled dusty plasmas” 9 Apr 2008
- Physics Seminar, *Boston College*  
“Non-Gaussian statistics & anomalous transport, with tests using dusty plasmas” 10 Apr 2008
- Physics Seminar, *Grinnell College*  
“Experiments with dusty plasmas performed on the International Space Station and in the laboratory” 28 Apr 2009
- Physics Seminar, *St. Olaf College*  
“The electrical charge and motion of objects inserted into a plasma” 21 Oct 2009
- Mechanical Engineering Seminar, *University of Minnesota*  
“Superheated solids and shear-induced melting experiments using dusty plasma as an analog system” 18 Nov 2009
- Experimental Physics Seminar, *University of Kiel, Germany*,  
“Superheated solids and shear-induced melting experiments using dusty plasma as an analog system” 9 Dec 2009

## Publications in Refereed Journals

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1. A. Piel, V. Nosenko, and J. Goree  
**Laser-Excited Shear Waves in Solid and Liquid 2D Dusty Plasmas**  
*Physics of Plasmas*, Vol. 13, article no. 042104 2006
2. O. S. Vaulina, S. V. Vladimirov, A. Yu. Repin, and J. Goree  
**Effect of electrostatic Plasma Oscillations on the Kinetic Energy of a Charged Macroparticle**  
*Physics of Plasmas*, Vol. 13, article no. 012111 2006
3. V. Nosenko, J. Goree, and A. Piel  
**Cutoff Wave Number for Shear Waves in a Two-Dimensional Yukawa System (Dusty Plasma)**  
*Physical Review Letters*, Vol. 97, article no. 115001 2006
4. A. Piel and J. Goree  
**Relationship between Dust Acoustic Waves in Two and Three Dimensions**  
*Phys. Plasmas*, Vol. 13, article no. 104510 2006
5. T. Flanagan and J. Goree  
**Dust Release from Surfaces Exposed to Plasma**  
*Physics of Plasmas*, Vol.13, article no. 123504, pp. 1-11, 2006
6. Bin Liu and J. Goree  
**Superdiffusion in Two-Dimensional Yukawa Liquids**  
*Physical Review E*, Vol. 75, article no. 016405, pp. 1-5 2007
7. Yan Feng, J. Goree, and Bin Liu  
**Accurate Measurement of Particle Positions from Images**  
*Review of Scientific Instruments*, Vol. 78, article no. 053704, pp. 1-10, 2007
8. Z. Donkó, P. Hartmann, and J. Goree  
**Shear Viscosity of Strongly-Coupled Two-Dimensional Yukawa Liquids: Experiment and Modeling**  
*Modern Physics Letters B*, Vol. 21, pp. 1357 – 1376, 2007
9. V. Nosenko, S. Zhdanov, A. Ivlev, G. Morfill, J. Goree and A. Piel  
**Heat transport in a two-dimensional complex (dusty) plasma at melting conditions**  
*Physical Review Letters*, Vol. 100, article no. 025003, pp. 1-4 2008
10. Bin Liu and J. Goree  
**Superdiffusion and non-Gaussian statistics in a driven-dissipative 2D dusty plasma**  
*Physical Review Letters*, Vol. 100, article no. 055003, pp. 1-4 2008
11. Yan Feng, J. Goree, and Bin Liu  
**Solid Superheating Observed in Two-Dimensional Strongly Coupled Dusty Plasma**  
*Physical Review Letters*, Vol. 100, article no. 205007, pp. 1-4 2008
12. T. E. Sheridan, V. Nosenko and J. Goree  
**Experimental Study of Nonlinear Solitary Waves in Two-Dimensional Dusty Plasma**  
*Physics of Plasmas*, Vol. 15, article no. 073703, pp. 1-6 2008

13. Yan Feng, Bin Liu, and J. Goree  
**Rapid Heating and Cooling in Two-Dimensional Yukawa Systems**  
*Physical Review E*, Vol. 78, article no. 026415 2008
14. Bin Liu, J. Goree, and Yan Feng  
**Non-Gaussian Statistics and Superdiffusion in a Driven-Dissipative Dusty Plasma**  
*Physical Review E*, Vol. 78, article no. 046403 2008
15. Z. Donkó, J. Goree, P. Hartmann, and Bin Liu  
**Time Correlation Functions and Transport Coefficients of Two-Dimensional Yukawa Liquids**  
*Physical Review E*, Vol. 79, article no. 026401 pp. 1-12 2009
16. T.M. Flanagan and J. Goree  
**Gas flow driven by thermal creep in dusty plasma**  
*Physical Review E*, Vol. 80, article no. 046402 pp. 1-7 2009
17. Oliver Arp, David Caliebe, Kristoffer O. Menzel, Alexander Piel, and John A. Goree  
**Experimental Investigation of Dust Density Waves and Plasma Glow**  
*IEEE Transactions on Plasma Science*, Vol. 38, pp. 842-846 2010
18. Yan Feng, J. Goree, and Bin Liu  
**Evolution of shear-induced melting in dusty plasma**  
*Physical Review Letters*, Vol. 104, article no. 155003 2010
19. Bin Liu, J. Goree, V. E. Fortov, A. M. Lipaev, V. I. Molotkov, O. F. Petrov, G. E. Morfill, H. M. Thomas, and A. V. Ivlev  
**Dusty plasma diagnostics methods for charge, electron temperature and ion density**  
*Physics of Plasmas* Vol. 17, article no. 053701 2010.
20. Z. Donkó, J. Goree, and P. Hartmann  
**Viscoelastic response of Yukawa liquids**  
*Physical Review E*, Vol. 81, article no. 056404 2010
21. Yan Feng, J. Goree, and Bin Liu  
**Viscoelasticity of 2D liquids quantified in a dusty plasma experiment**  
*Physical Review Letters*, Vol 105, article no. 025002 2010
22. Bin Liu, J. Goree and Yan Feng  
**Mode coupling for phonons in a single-layer dusty plasma crystal**  
*Physical Review Letters*, Accepted 22 July 2010
23. Yan Feng, J. Goree, and Bin Liu  
**Simulations of relaxation to study anomalous diffusion and melting in dusty plasmas**  
*Physical Review E*, submitted 2010