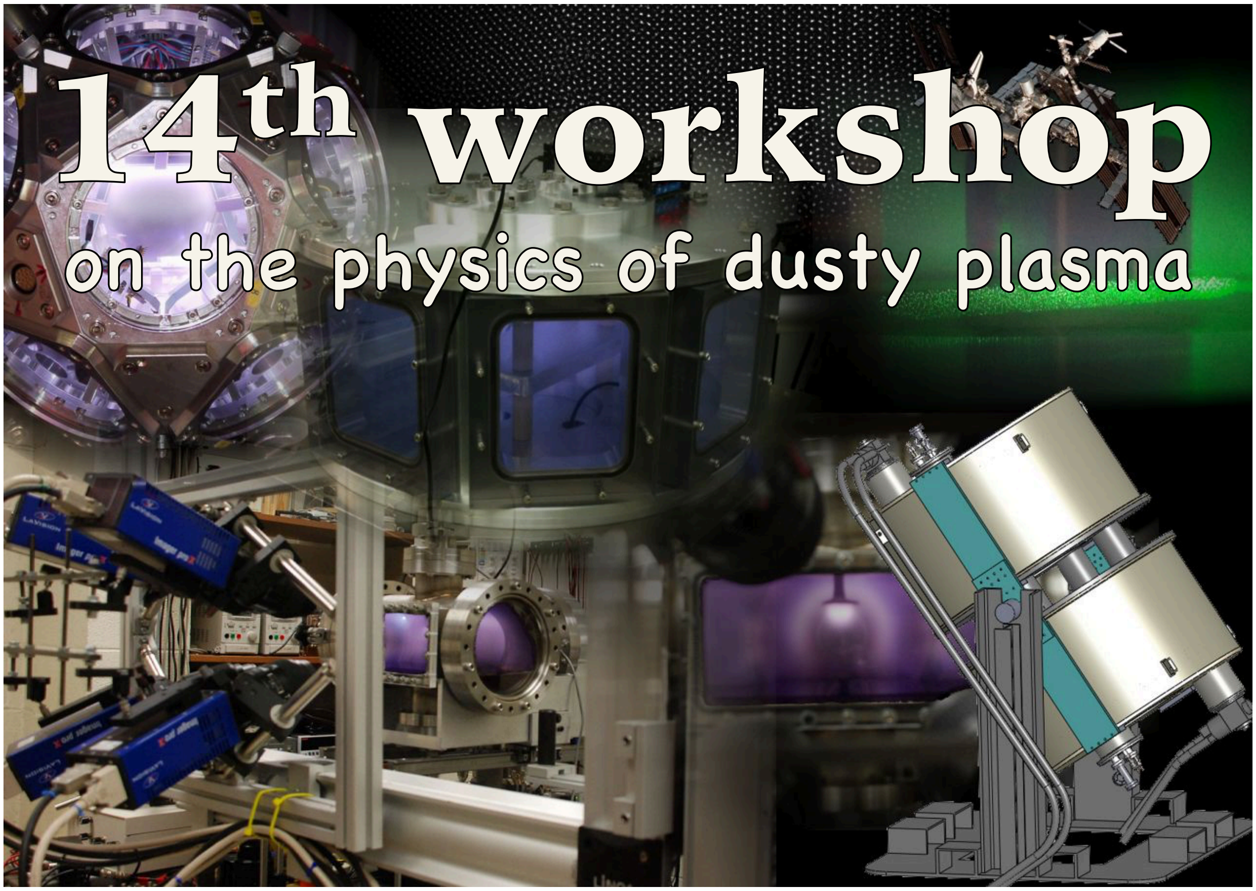

May 26 – 29, 2015
Auburn, Alabama

NSF

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Announcing a Special Issue of the *IEEE Transactions on Plasma Science* on the Physics of Dusty Plasmas

(Scheduled for publication in April 2016)

The IEEE Transactions on Plasma Science will offer a special issue titled the "Physics of Dusty Plasmas" to be published in April 2016 covering the most recent developments in the field of dusty and complex plasmas. This issue will include papers presented at the 14th Workshop on the Physics of Dusty Plasmas, which will be hosted by Wittenberg University and Auburn University and will be held 26-29 May 2015, in Auburn, AL. The workshop website is: http://www.wpdp2015.org. Topics will include laboratory, industrial, applied, theoretical and computational studies of dusty and complex plasmas. A wide range of topics are suitable for this issue including: astrophysical and solar system dust, microgravity study of complex plasmas, lunar dust levitation and transport, dust in the ionosphere, dust in industrial plasmas, dust charging processes, plasma crystals, strong coupling and phase transitions, dusty plasma waves and instabilities, magnetic field effects, particle growth and coagulation, electrical discharges in dust storms and volcanic plumes, dusty plasma diagnostic tools, and dust in fusion devices. This continues the tradition of publication of such special issues with past issues published in April of 1994, 2001, 2004, 2007, 2010, and 2013.

The deadline for submission is 30 June 2015.

Please direct questions to the Guest Editors:

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Acknowledgements

The organizers would like to acknowledge and thank the following for their assistance with the 14th Workshop on the Physics of Dusty Plasmas:

The National Science Foundation

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College of Science and Mathematics, Auburn University

Local Organizing Committee

Uwe Konopka, Auburn University

Edward Thomas, Jr., Auburn University

Jeremiah Williams, Wittenberg University

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Markus Thoma, Universitat Giessen

Edward Thomas, Jr., Auburn University

Jeremiah Williams, Wittenberg University

Special thanks to Priscella Goodson for her help with the initial organization of this workshop, to Myra Girad and John Freeze of the Auburn University Outreach Office for invaluable assistance, to COSAM Outreach for help with posters and the Auburn-Opelika Convention Bureau for providing information about the local area.

About the host universities

Wittenberg University

Chartered in 1845, Wittenberg University is a Lutheran-affiliated, selective residential liberal arts college in the heart of Southwest Ohio. Wittenberg provides a liberal arts education dedicated to intellectual inquiry and wholeness of person within a diverse residential community that challenges students to become responsible global citizens, to discover their callings, and to lead personal, professional, and civic lives of creativity, service, compassion, and integrity.

Located in Springfield, OH, Wittenberg is a primarily undergraduate institution that is known for its strong academic program and widely known for its friendly and welcoming atmosphere. It offers more than 80 majors and minors and special programs to approximately 1900 students. Of these, approximately 30% of students major in a STEM discipline and Wittenberg ranks in the top 7% of institutions whose baccalaureate graduates went on to earn doctoral degrees in the physical sciences from 2002 to 2011.

(Adapted from: http://www.wittenberg.edu/about)

Auburn University

Auburn University was established in 1856 as the East Alabama Male College, 20 years after the city of Auburn's founding. In 1872, under the Morrill Act, the school became the first land-grant college in the South and was renamed the Agricultural and Mechanical College of Alabama. In 1899 the name again was changed, to the Alabama Polytechnic Institute. Finally, in 1960 the name of the school was changed to Auburn University, a title more in keeping with its location, and expressing the varied academic programs and larger curriculum of a major university.

Today, Auburn is one of the few universities to carry the torch as a land, sea and space grant university. Our students can choose from more than 140 degree options in 13 schools and colleges at the undergraduate, graduate and professional levels.

Auburn University has developed into one of the largest universities in the South, remaining in the educational forefront with its traditional blend of arts and applied science, and changing with the needs of today while living with a respect for the traditions and spirit that are Auburn.

(Adapted from: http://www.auburn.edu/main/welcome)

May 6, 2015

Attendees of the 14th Workshop on the Physics of Dusty Plasmas:

On behalf of Wittenberg University, I am pleased to welcome you to Auburn, AL for the 14th Workshop on the Physics of Dusty Plasmas. Wittenberg is honored to be hosting the latest in this series of workshops with Auburn University.

I know that the organizers of this conference have worked hard to plan a workshop that presents the current state of complex (dusty) plasmas and helps to lay the groundwork for next directions for your community. I am pleased that you have chosen to attend and bring your expertise to this workshop.

Please accept my warm welcome and best wishes for a productive and rewarding workshop on behalf of Wittenberg University. I hope that you will enjoy your visit to Auburn, AL and the scientific discussions that are motivated by this workshop.

Sincerely,

Mary J. Zembar

Mary Jo Zembar, Ph.D.
Interim Provost and Professor

OFFICE OF THE PROVOST

Ward Street at North Wittenberg Avenue | Post Office Box 720 | Springfield, Ohio | 45501-0720
phone 937.327.7915 | fax 937.327.7522 | www.wittenberg.edu

PASS IT ON

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COLLEGE OF
SCIENCES AND MATHEMATICS

May 26, 2015

To Attendees of the 14th Workshop on the Physics of Dusty Plasmas

I would like to extend a warm welcome on behalf of Auburn University and the College of Sciences and Mathematics. Our College is very happy that you have decided to join us here in Auburn, Alabama.

Plasma physics research is an important focus area for the Auburn University Physics Department, with research programs in space plasmas, fusion plasmas, and laboratory plasmas. Our growing effort in dusty plasma research includes both magnetized dusty plasmas and microgravity studies of dusty plasmas.

Over the next few days, I hope that you will enjoy your visits to our research labs, the beauty of the campus, the hospitality of our town, and the scientific discussions motivated by this workshop. I know that the joint Auburn University and Wittenberg University teams have worked hard to plan this Workshop and we are all looking forward to your visit here.

I wish you all the best success for the Workshop.

Sincerely,

Nicholas J. Giordano

Nicholas J. Giordano, Dean
College of Sciences and Mathematics

315 Roosevelt Concourse, Auburn, Alabama 36849-5319; Telephone: 334-844-5737; Fax: 334-844-5824

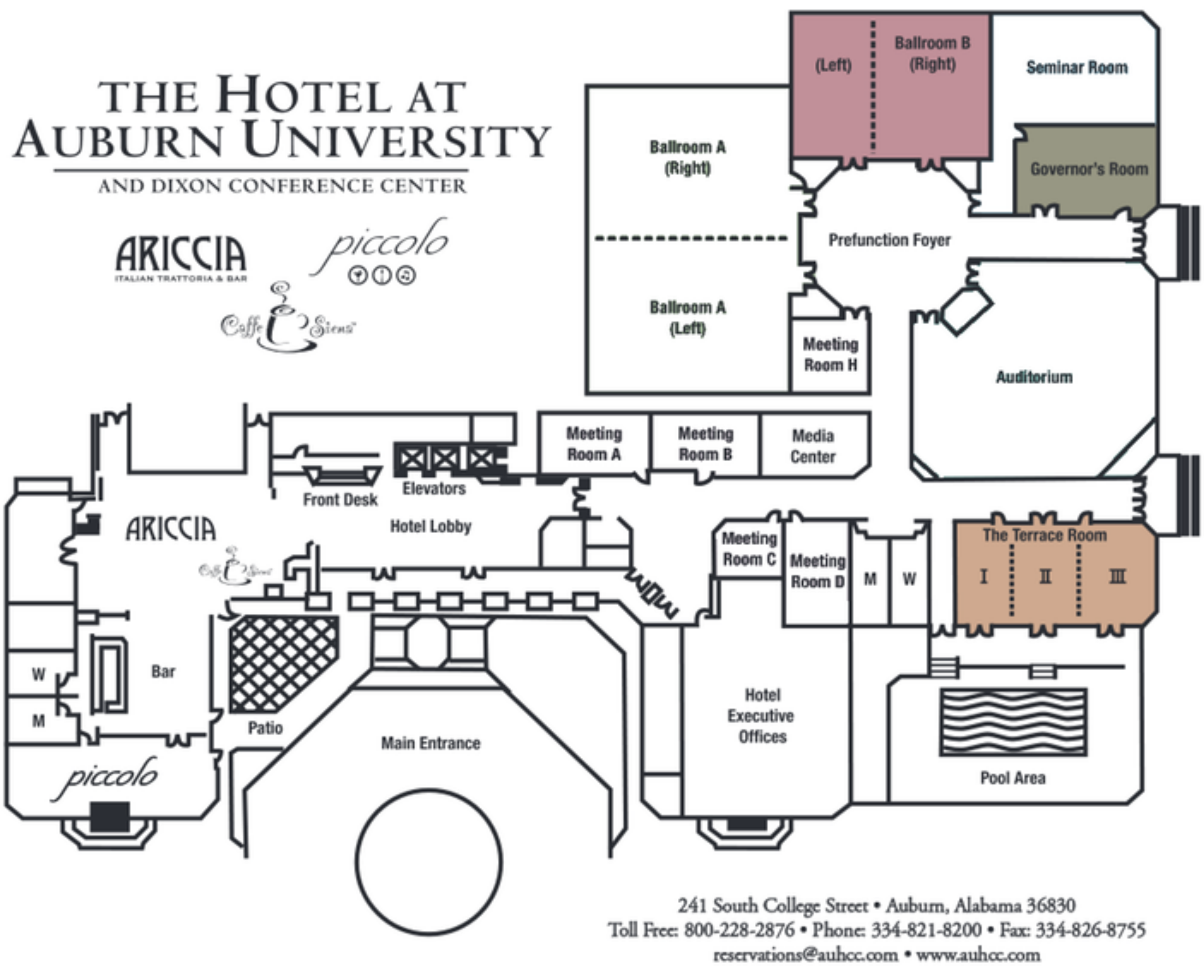
www.auburn.edu/COSAM

Auburn University Hotel and Conference Center

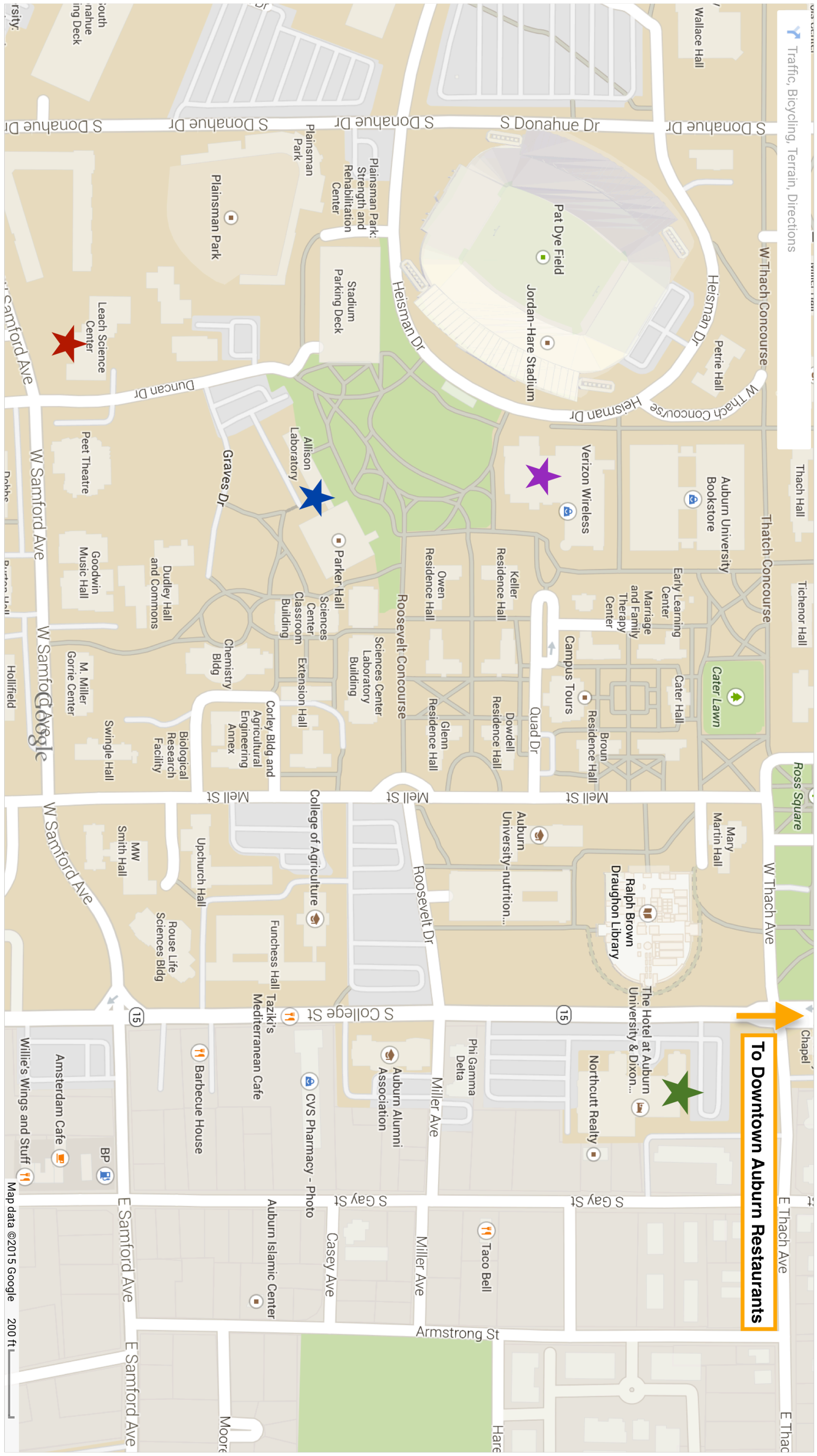
Conference Venue

EVENT	LOCATION
Registration	Terrace Room
Opening Reception	The Terrace Room and Pool area
Oral Presentations	Ballroom B
Coffee Breaks	Governor's Room
Poster Presentation	Governor's Room
Conference Banquet	Auburn University Club

Hotel Layout



Auburn University



- Auburn University Hotel and Conference Center
- Leach Science Center, Physics Lab Tours
- Auburn University Student Center - food services on 1st and 2nd floors
- Physics Department, Allison Laboratory

Workshop Program

14TH WORKSHOP ON THE PHYSICS OF DUSTY PLASMAS - MAY 26-30, 2015 - AUBURN, AL
Workshop Program

	Wednesday 27-May-15
Session 1	Strong coupling and colloidal systems
Session 2	Particle Charging 1
Session 3	Magnetic field effects

	Thursday 28-May-15
Session 4	Particle Charging 2
Session 5	Interactions
Session 6	Waves and collective effects

	Friday 29-May-15
Session 7	Applications
Session 8	Thermal Properties
Session 9	Microgravity

Tuesday 26-May-15
REGISTRATION 4:00 PM - 7:00 PM
WELCOME RECEPTION 6:00 PM - 9:00 PM

	Wednesday 27-May-15
8:15 AM	**Welcome**
8:30 AM	D. Block
9:00 AM	T. Sheridan
9:20 AM	T. Hyde
9:40 AM	P. Yunker
10:10 AM	M. Chaudhuri
10:30 AM	**BREAK**
10:50 AM	L. Matthews
11:10 AM	B. Shortoban
11:30 AM	R. Yousefi
11:50 AM	R. Le Picard
12:10 PM	**LUNCH**
1:30 PM	POSTER SESSION 1
3:30 PM	**BREAK**
3:50 PM	J. Wilms
4:10 PM	M. Dropmann
4:30 PM	M. Puttscher
4:50 PM	B. Tadsen
5:10 PM	E. Thomas, Jr.
	LAB TOURS* 5:45 PM - 7:00 PM

	Thursday 28-May-15
8:30 AM	M. Horanyi
9:00 AM	S. Robertson
9:20 AM	Z. Sternovsky
9:40 AM	P. Bellan
10:00 AM	K.-B. Chai
10:20 AM	**BREAK**
10:40 AM	A. Ivlev
11:10 AM	I. Semenov
11:30 AM	M. Lampe
11:50 AM	I. Lisina
12:10 PM	**LUNCH**
1:30 PM	POSTER SESSION 2
3:30 PM	**BREAK**
3:50 PM	H. Kaehlert
4:10 PM	I. Laut
4:30 PM	J. Williams
4:50 PM	K. Qiao
5:10 PM	S. Jaiswal
	BANQUET** 6:00 PM - 9:00 PM

	Friday 29-May-15
8:30 AM	Z. Wang
9:00 AM	G. L. Delzanno
9:20 AM	Y. Hayashi
9:40 AM	A. Michau
10:00 AM	E. Gillman
10:20 AM	**BREAK**
10:50 AM	C. Killer
11:10 AM	J. Kong
11:30 AM	J. Goree
11:50 AM	O. Petrov
12:10 PM	**LUNCH**
1:30 PM	P. Huber
2:00 PM	M. Thoma
2:30 PM	C. Knapek
2:50 PM	U. Konopka
3:10 PM	NASA: U. Israelsson
3:25 PM	**BREAK**
3:45 PM	Future directions
4:45 PM	Summary and Closing

All oral presentations are in Ballroom B
All poster presentation are in the Governor's Room

Speakers in RED - highlighted talks, 30 minutes
Speakers in BLACK - contributed talks, 20 minutes
Speaker in GREEN - space agency talk, 15 minutes
Each morning from 7:30 am to 8:30 am, a continental breakfast will be offered
(yogurt, fruits, granola, croissants, muffins, danish, coffee, tea, juice, milk)

* LAB TOURS	Leach Science Center
** BANQUET	Auburn University Club

Detailed Workshop Program

Tuesday, May 26

4:00 - 7:00 PM Registration (The Terrace Room)

6:00 - 9:00 PM Welcome Reception (The Terrace Room and Pool area)

Wednesday, May 27

7:30 - 8:30 AM Breakfast at Hotel

8:15 AM Welcome - Jeremiah Williams

Abstract

Session I - Strong coupling & colloidal systems
Chair: Alexei Ivlev
Ballroom B

8:30 AM ***Controlling structure and dynamics of complex plasmas*** 1
Dietmar Block

9:00 AM ***How many equilibria does an elliptical dust cluster have?*** 2
Terrence Sheridan

9:20 AM ***Ordering Processes within Vertically Aligned 3D Dust Clusters*** 3
Truell Hyde

9:40 AM ***Connecting Talk - Colloidal Physics; Title TBD*** 4
Peter Yunker

10:10 AM ***Experiments on classical manuy body strongly correlated systems: from dusty plasmas to colloids*** 5
Manis Chaudhuri

10:30 AM Coffee Break (Governor's Room)

Session II - Particle charging I
Chair: Markus Thoma
Ballroom B

10:50 AM ***Dust Charging and Coagulation Processes in Protoplanetary Environments*** 6
Lorin Matthews

11:10 AM ***Prominent deviation of dust charge distribution from Gaussianity caused by secondary electron emission*** 7
Babak Shotorban

11:30 AM ***Electric charge and dipole of dust aggregates in the presence of ion flow*** 8
Razie Yousefi

11:50 AM ***The effect of single particle charge limits on particle charge distributions in dusty plasmas*** 9
Romain Le Picard

12:10 PM Lunch

1:30 PM Poster Session I (Governor's Room)

3:30 PM Coffee Break (Governor's Room)

Wednesday, May 27

	Session III - Magnetic field effects Chair: Uwe Konopka Ballroom B	Abstract
3:50 PM	***Crystalline Particle Flows in Magnetized Anodic Plasmas*** Jochen Wilms	10
4:10 PM	***Interactions of Plasma with Single and Multiple Dipole Magnets in a GEC RF Reference Cell*** Michael Dropmann	11
4:30 PM	***Dust particles under the influence of crossed electric and magnetic fields in the sheath of an rf discharge*** Marian Puttscher	12
4:50 PM	***The Charge of Single Grains in Dense Nanodust Clouds*** Benjamin Tadsen	13
5:10 PM	***A summary of initial studies of ordered structures and collective modes using the Magnetized Dusty Plasma Experiment (MDPX) device*** Edward Thomas	14
5:45 - 7:30 PM	Lab Tours (Leach Science Center)	

Thursday, May 28

7:30 - 8:30 AM	Breakfast at Hotel	
	Session IV - Particle Charging 2 Chair: Eric Gillman Ballroom B	
8:30 AM	***Charged Dust Measurements by the Lunar Dust Experiment*** Mihaly Horanyi	15
9:00 AM	***Meteoric dust particles are the primary charge carriers in the lower ionosphere*** Scott Robertson	16
9:20 AM	***Experimental investigation of micrometeoroid ablation using a dust accelerator*** Zoltan Sternovsky	17
9:40 AM	***Motivation/Design of the Caltech Water-Ice Dusty Plasma Experiment*** Paul Bellan	18
10:00 AM	***Formation and alignment of elongated, fractal-like water-ice grains in extremely cold, weakly ionized plasma*** Kil-Byoung Chai	19
10:20 AM	Coffee Break (Governor’s Room)	

Thursday, May 28

		Abstract
	Session V - Interactions Chair: Dietmar Block Ballroom B	
10:40 AM	***Statistical mechanics where Newton's third law is broken*** Alexei Ivlev	20
11:10 AM	***Dynamical properties of the chain-like structure of particles interacting nonreciprocal quasi dipole-dipole interaction*** Irina Lisina	21
11:30 AM	***Grain-Grain Interaction in Stationary Dusty Plasma*** Martin Lampe	22
11:50 AM	***Approximate expression for the electric potential around a dust grain in isotropic collisionless plasma*** Igor Semenov	23
12:10 PM	Conference Photograph	
12:20 PM	Lunch	
1:30 PM	Poster Session II (Governor’s Room)	
3:30 PM	Coffee Break (Governor’s Room)	
	Session VI - Waves and collective effects Chair: Marlene Rosenberg Ballroom B	
3:50 PM	***Ion-dust streaming instability and dust wake potential with magnetized ions*** Hanno Kählert	24
4:10 PM	***Experimental study of global synchronization of the dust acoustic wave in a weakly-coupled dusty plasma system*** Jeremiah Williams	25
4:30 PM	***Mode coupling and resonance instabilities in small dust systems*** Ke Qiao	26
4:50 PM	***Synchronized motion in two-dimensional complex plasma crystals*** Ingo Laut	27
5:10 PM	***Flow induced dust acoustic and dust acoustic solitary waves in a complex plasma*** Surabhi Jaiswal	28
6:00 - 9:00 PM	Conference Banquet (Auburn University Club)	

Friday, May 29

		Abstract
7:30 - 8:30 AM	Breakfast at Hotel	
	Session VII - Applications Chair: Hanno Kählert Ballroom B	
8:30 AM	***Dust transport in magnetized fusion plasmas:experimental challenges and opportunities*** Zhehui Wang	29
9:00 AM	***Beyond Orbital-Motion-Limited theory effects for dust transport in tokamaks*** Gian Luca Delzanno	30
9:20 AM	***Mie-Scattering Ellipsometry System for Analysis of Dust Formation Process in Large Plasma Device*** Yasuaki Hayashi	31
9:40 AM	***Aerosol Dynamics in DC discharge*** Armelle Michau	32
10:00 AM	***Competing processes due to microparticle injection and effects on microwave transmission through an overly dense plasma layer*** Eric Gillman	33
10:20 AM	Coffee Break (Governor's Room)	
	Session VIII - Thermal Properties Chair: Angela Douglas Ballroom B	
10:50 AM	***Investigating size and density distribution in large 3D dust clouds using Computer Tomography and Mie Imaging*** Carsten Killer	34
11:10 AM	***Dust particle thermal properties in a glass box*** Jie Kong	35
11:30 AM	***Localized viscous heating observed in a two-dimensional strongly coupled dusty plasma*** John Goree	36
11:50 AM	***Phase Transitions in Small and Large Plasma-Dust Systems*** Oleg Petrov	37
12:10 PM	Coffee Break (Governor's Room)	

Friday, May 29

Abstract

Time	Session IX - Microgravity Chair: Jeremiah Williams Ballroom B	Abstract
1:30 PM	***Complex Plasma Research on the International Space Station*** Peter Huber	38
2:00 PM	***PK-4: Complex Plasmas onboard the ISS - The Present Generation*** Markus Thoma	39
2:30 PM	***PlasmaLab/EKOPlasma - The next laboratory for complex plasma research on the International Space Station*** Christina Knapek	40
2:50 PM	***A Dodecahedron Plasma Chamber for Future Complex Plasma Research in Microgravity Environments*** Uwe Konopka	41
3:10 PM	***NASA: Current and planned ISS research activities on the physics of dusty plasmas*** Ulf Israelsson	42

3:25 PM Coffee Break (Governor's Room)

Session X - Discussion of Future Directions
Chair: Edward Thomas, Jr.
Ballroom B

3:45 PM Prof. Edward Thomas, Jr., ***Moderator***

Prof. Mihaly Horanyi, ***Space and astrophysical studies***

Prof. Peter Hartmann, ***Strongly coupled plasmas***

Dr. Jeff Wang, ***Dusty plasma applications***

Prof. Robert Merlino, ***Magnetized dusty plasmas***

Dr. Christina Knapek, ***Microgravity studies of complex plasmas***

Session XI - Summary and Closing
Chair: Jeremiah Williams
Ballroom B

4:45 PM Business Meeting and Closing Ceremony

Poster Session I
Governor's Room

Poster Session II
Governor's Room

Talk Abstracts

Controlling structure and dynamics of complex plasmas

Jan Schablinski[1], Frank Wieben[1], and Dietmar Block[1]
[1] Institut of Experimental and Applied Physics, University of Kiel, Germany

block@physik.uni-kiel.de

To investigate structural properties and dynamics of a strongly coupled system it is beneficial to manipulate the system. In the past several approaches have been made. First, global or local variations of plasma and discharge parameter have been used. However, it soon turned out that laser manipulation is a more powerful tool, because it leaves the plasma conditions and hence the charge and screening of the particles unaffected and thus enables a direct and quantitative comparison of different states. This contribution presents two novel applications of lasers to complex plasmas. In the first part, the influence of diffuse reflections of laser light on complex plasmas is discussed [1]. Guided by the simple idea that even diffuse reflections will imply a momentum transfer to particles, we present an experimental setup which allows to measure the radiation pressure of diffuse reflections and which can be used as a localized driver in 2D complex plasmas. The second part is devoted to a novel tool for single particle manipulation in complex plasmas [2]. In a set of experiments we show that it is possible to construct a kind of optical tweezer for complex plasmas. It is shown that this optical trap is able to confine and position individual particles in a 2D complex plasma. Beside a brief discussion of the trapping mechanism and its deviations from a conventional optical tweezer, two examples for its application are shown to demonstrate its prospects for complex plasma research. The first one demonstrates the quasi-static manipulation of a plasma crystal, i.e. its structure. The second example is devoted to the excitation of dynamical processes in plasma crystals.

This work has been funded by Deutsche Forschungsgemeinschaft under grant SFB-TR24 project A3b. Valuable discussion with H. Kersten and V. Schneider (project B4) are gratefully acknowledged.

[1] J. Schablinski and D. Block, Physics of Plasmas **22**, 023703 (2015)

[2] J. Schablinski, F. Wieben, and D. Block, submitted to Physics of Plasmas

How many equilibria does an elliptical dust cluster have?

T. E. Sheridan
Ohio Northern University, Ada, OH USA
t-sheridan@onu.edu

Strongly-coupled dust clusters in a two-dimensional biharmonic potential energy well can have one or more equilibrium configurations. For identical particles interacting through a Debye potential these configurations depend on only three non-dimensional parameters: the number of particles n, the potential well anisotropy, and the Debye shielding parameter. For very small values of n (e.g. $n = 3$), there is always a single equilibrium configuration irrespective of the well anisotropy and the Debye shielding parameter. For larger values of n, a stable equilibria and one or more metastable equilibrium configurations may exist.

We generate stable and metastable configurations for $n \leq 20$ using a Monte Carlo simulation. Typically n and the Debye shielding parameter are held constant while the potential well anisotropy is varied. Many combinations of parameters give only a single equilibrium configuration. However, in some cases up to four unique equilibria are observed. Each value of n appears to be a "special case," that is, no obvious patterns are seen as n varies. Properties of the equilibria will be discussed.

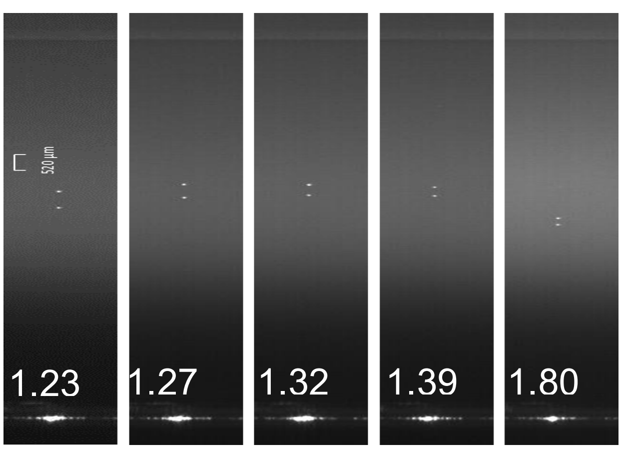
Ordering Processes within Vertically Aligned 3D Dust Clusters

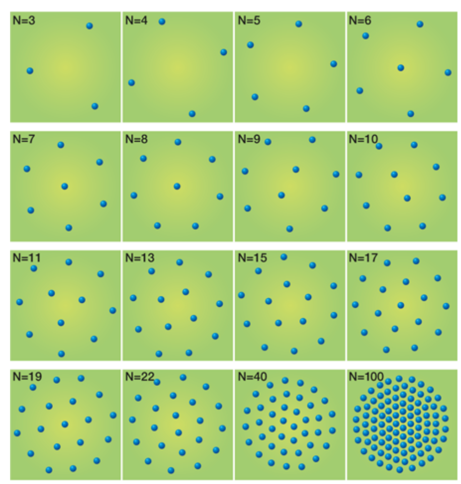
Truell W. Hyde, Lorin S. Matthews, Jie Kong, Ke Qiao, Mudi Chen and Bo Zhang

CASPER, Baylor University, Waco, TX 76798-7310 USA
Truell_Hyde@baylor.edu

The ordered structures observed to develop in systems where the kinetic energy (temperature) is comparable to the average potential energy have long been of interest in physics. In 1934, Wigner [1] predicted that electrons in a metal would react in the same manner as atoms or molecules, 'freezing' into a 'solid' (crystal) phase under appropriate boundary conditions. Although this behavior has not yet been shown in metals, Wigner 'crystals' have been observed elsewhere, for example, the electron structures ('Wigner islands') floating on the surface of superfluid helium shown below [2]. Although it is clear these structures are driven in large part by the correlation between the particles comprising them, establishing the fundamental physics behind such correlation effects has been surprisingly difficult.

Complex plasmas are proving a versatile analog for the study of such systems, particularly those where their global behavior is determined by the combined effect of the particles' low temperature / kinetic energy and interparticle interactions and the system's global and/or local confinement and streaming ion flow. In this talk, the interaction between pairs of two-particle and three–particle vertically aligned strings are examined experimentally. It will be argued that the interaction between the confinement force (partially controlled using an Indium-Tin-Oxide glass box placed on the lower powered electrode within a GEC rf Reference Cell), the interparticle interaction, and the ion flow determines the ordering process within these vertically aligned 3D structures.





Ground state configurations for N=3 to 100

[1] E. Wigner, *Physical Review* **46**, 1002 (1934).
[2] F. Peeters, *Physics* **2**, 4 (2009).
[3] E. Rousseau, et al., *Physical Review B* **79**, 045406 (2009).

Colloidal glasses composed of microgel particles

Peter J. Yunker[1], Tim Still[2], and Zexin Zhang[3], Arjun G. Yodh[2]

[1]Georgia Institute of Technology, School of Physics
[2]University of Pennsylvania, Department of Physics
[3]Soochow University, Department of Physics
peter.yunker@physics.gatech.edu

Colloidal particles are often used as model atoms in order to investigate the physics of phase transitions. Unlike atoms, colloidal particles sit in, and interact with, a solvent. However, this solvent is quite often useful for investigating new physics. I will disucss a number of experiments that made use of solvent-mediated phenomena, from hydrophobic particles that change size [1-3], to particles that can change from sticky to purely repulsive in situ [4], to shape-based interactions on fluid-interfaces [5] I will also discuss cases where the solvent may obscure the underlying physics, for example, by damping vibrational modes [6-8]. Many of these experiments focus on unraveling the mystery of the glass transition, which is considered to be one of the most important open questions in physics. In particular, the exact reasons for why glasses are hard are difficult to ascertain. While there are distinct transitions from liquid to crystal, there is no sharp transition from liquid to glass. In molecular glass-formers, the glass transition occurs when temperature is decreased; in colloidal glasses, the glass transition occurs when packing fraction is increased.

[1] P. Yunker, Z. Zhang, K.A. Aptowicz, and A.G. Yodh, *Physical Review Letters* 103, 115701 (2009).
[2] P. Yunker, Z.X. Zhang, and A.G. Yodh, *Physical Review Letters* 104, 015701 (2010)
[3] P.J. Yunker, K. Chen, T. Still, M.A. Lohr, M. Gratale, and A.G. Yodh, *Reports on Progress in Physics*, 77 (5), 056601 *(2014)*.
[4] Z. Zhang, P. J. Yunker, P. Habdas, and A.G. Yodh, *Physical Review Letters* 107, 208303 (2011).
[5] P.J. Yunker, T. Still, M.A. Lohr, and A.G. Yodh, *Nature* 476, 308-311 (2011).
[6] K. Chen, W.G. Ellenbroek, Z.X. Zhang, D.T.N. Chen, P.J. Yunker, S. Henkes, C. Brito, O. Dauchot, W. van Saarloos, A.J. Liu, and A.G. Yodh, *Physical Review Letters* 105, 025501 (2010).
[7] K. Chen, M. L. Manning, P.J. Yunker, W.G. Ellenbroek, Z. Zhang, A.J. Liu, A.G. Yodh, *Physical Review Letters*107, 108301 (2011).
[8] M.D. Gratale, P.J. Yunker, K. Chen, T. Still, K.B. Aptowicz, A.G. Yodh, *Physical Review E* 87, 052301 (2013).

Experiments on classical many body strongly correlated systems: from dusty plasma to colloids

Manis Chaudhuri[1] and David Weitz[1,2]
[1] School of Engineering and Applied Sciences, Harvard University, Cambridge, MA 02138, USA
[2] Department of Physics, Harvard University, Cambridge, MA 02138, USA
chaudhuri@seas.harvard.edu

Soft matter is a growing interdisciplinary research area which provides a fascinating testing ground to investigate fundamental questions in condensed matter physics, as for example, many-body statistical physics, phase transition, jamming transition, topological defects, rhe- ology, hydrodynamics, and many more. In recent times, dusty plasma (complex plasma) is being considered as the plasma state of soft matter which shares unique complementary features with very popular soft matter system "colloids". Both these systems can be used to explore statistical physics of classical many body strongly correlated systems due to exper- imental simplicities. Hard sphere colloids have been used extensively for a long time where volume fraction is the only controlling parameter to explore phase space. However, more interesting features are associated with soft colloids where the softness of inter-particle in- teractions can be tuned by adding surfactants in the solvents or polymers grafted on surface. In this presentation an experimental study will be reported to explore melting transition using density matched, charge stabilized PMMA particles. The particles with Yukawa in- teractions form stable, homogeneous three dimensional crystal structures at higher volume fractions. The melting point is approached by lowering volume fractions and a crystal-liquid co-existence region develops at certain volume fractions. A comparative studies will be made with plasma crystals and liquids.
.

Dust Charging and Coagulation Processes in Protoplanetary Environments

Lorin Matthews and Truell Hyde
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The earliest stages of protoplanetary development are characterized by the coagulation of micron-sized dust grains. Aggregate growth due to collisions between grains is highly dependent on the local environment, including the dust and gas densities, turbulence, and grain charging mechanisms, as well as the physical characteristics of the aggregates themselves. Over large regions of a protoplanetary disk, the gas is weakly ionized, leading to primary charging currents to dust grains, or the dust grains are exposed to ionizing radiation. The resulting charge is distributed over the aggregate's irregular surface which complicates modeling the charge and dynamics of coagulating grains.

Objects which are immersed in plasma generally acquire a negative potential. Collisional grain growth is thus slowed by the repulsion of the like-charged grains, although the charge-dipole interactions lead to rotations of the grains which alter the geometry of aggregates grown through collisions and increase the growth rate. The charging and dynamics are further complicated by other effects: secondary electron emission can lead to differential charging of grains, with grains becoming positively or negatively charged depending on the grain size or porosity; very weakly charged grains are strongly affected by stochastic charge fluctuations; and closely interacting aggregates are subject to "shadowing" which can reduce the grain charge and strongly affect the collision outcome. Each of these processes will be important in different regions of the protoplanetary disk at different times, shaping the evolution of the disk and the emerging planetesimals.

Prominent deviation of dust charge distribution from Gaussianity caused by secondary electron emission

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Primary energetic plasma particles can cause the emission of secondary electrons from the surface of a dust grain upon impact with the grain. Both ion and electron impacts can cause the secondary electron emission. The current study investigates the influence of the secondary electron emission on the intrinsic charge fluctuations of grain charge. This type of fluctuations is intrinsic noise present in systems with discrete particles, e.g., ions and electrons in the dust charging system. These fluctuations have been extensively studied for cases where grains are charged only by electron and ion impingent mechanisms, and it has been found that the dust charge distributions are Gaussian with a very good approximation.

In this work, a master equation based on Markovian description of charging process was employed to obtain the charge distribution of dust. In addition to ion and electron attachment rates, the detachment rate of electrons by secondary electron emission was accounted for to calculate the transition probability per unit time in the master equation. The well-know relation of Sternglass (1954) was used to calculate the electron yield. The master equation was solved for grains in a hydrogen plasma. Two different distributions of Maxwellian and non-Maxwellian electrons were considered (Meyer-Vernet, 1981). It was found that the distribution of dust charge could substantially deviate from Gaussianity when secondary emission mechanism is present. Figure 1 shows a bimodal distribution of dust charge for a grain radius of 50 nm. A substantial deviation from Gaussianity was also observed for cases where the plasma was non-Maxwellian.

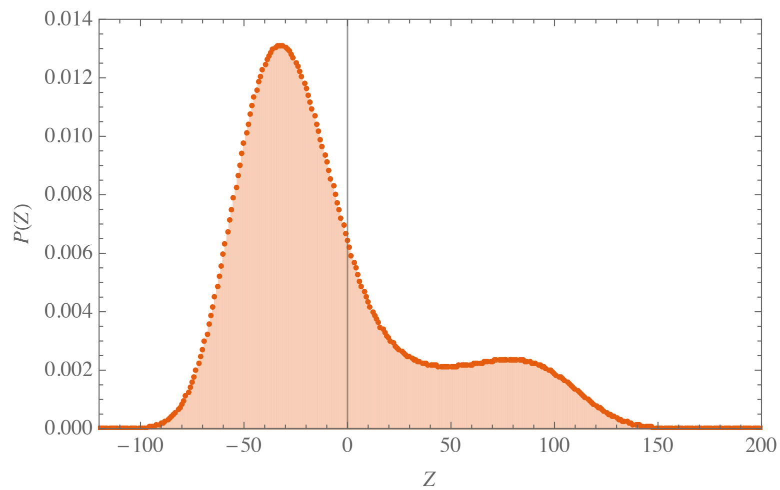

Figure 1 - Probability density function of dust charge in a Maxwellian plasma with $T_i = T_e$; secondary emission parameters are $T_s/T_e = 1.5$, $\delta_M = 15$, and $E_M/4kT_e = 45.6$ (Meyer-Vernet, 1981)

Electric charge and dipole of dust aggregates in the presence of ion flow

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Any proper explanation of the electrostatic behavior of dust particles immersed in dusty plasma requires knowledge of such basic properties as their net electric charge and dipole moment. This is a complicated problem, given the particles are often located within the sheath of an rf plasma where their charge is affected by the presence of an ion flow. Previous work has shown that the charge distribution on an aggregate can be determined using a numerical approach where orbital-motion-limited (OML) theory is modified by a line-of-sight (LOS) approximation: only those electron and ion trajectories which are not blocked by other parts of the aggregate contribute to charging. This approach is modified to include the effects of ion flow on the charging of aggregate grains, demonstrating how the total charge and electric dipole moment are impacted by the presence of an ion flow.

The effect of single particle charge limits on particle charge distributions in dusty plasmas

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A nanoparticle in a plasma acquires charge due to collisions with electrons and ions. Under typical low-pressure plasma conditions, nanoparticles tend to be negatively charged due to the higher mobility of electrons compared to ions. For very small nanoparticles, for which stochastic charging is important, it is of interest to acknowledge a particle charge distribution around an average particle charge. Matsoukas and Russell derived an analytical expression for the steady-state particle charge distribution, and showed that it is well represented by a Gaussian distribution, providing that the average charge is not too small [1].

However, nanoparticles can only carry a limited number of electrons, and this effect was not considered in [1]. Here we study the effect of particle charge limits on particle charge distributions. We derive an analytical expression for the particle charge distribution in the presence of charge limits, and compare it with the results of a Monte-Carlo charging model [2]. Fig. 1 shows results for stationary particle charge distributions (a) without charge limit, (b) q_{lim}=14, and (c) q_{lim}=10, all for the same plasma conditions. We discuss effects of particle charge limits, such as the time required to reach the steady-state charge distribution (charging time). The smaller the charge limit, the faster the charging time.

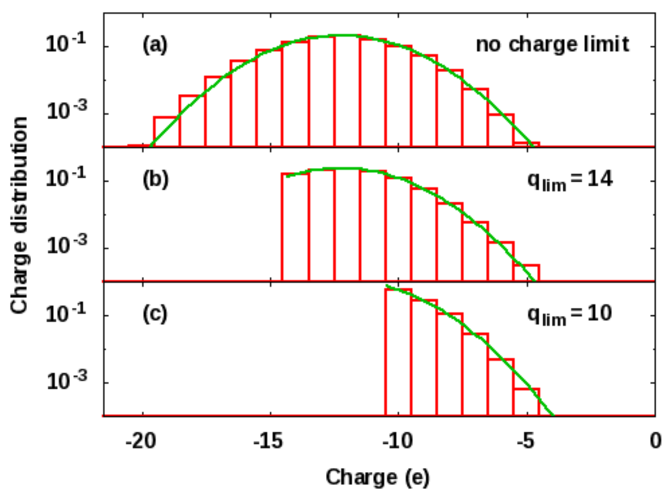

Figure 1 – Particle charge distributions for different charge limit magnitudes, from either analytical solution (solid lines) or Monte Carlo simulation (histograms). (a) Without charge limit; (b) q_{lim} = 14; (c) q_{lim} = 10. Plasma conditions: n_e/n_i=1, T_e=3eV, T_e/T_i=116, m_e/m_i=1.37×10^{-5} (Ar ions).

[1] T. Matsoukas and M. Russell, J. Appl. Phys., **77**, 4285 (1995).
[2] R. Le Picard and S. L. Girshick, in preparation for journal submission.

Crystalline Particle Flows in Magnetized Anodic Plasmas

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Dust trapping in magnetized anodic plasmas is generally well understood. In first order, the equilibrium of electric field force and ion drag leads to an upright, torus-shaped confinement [1]. In second order, the magnetic field results in a Hall component of the ion drag that drives the particles in toroidal direction. Thus, the entire dust cloud performs a rotational motion about a central void. A stationary but inhomogeneous flow pattern develops because of acceleration and deceleration due to gravity. This flow pattern is found to be in good agreement with the velocity fields obtained from detailed 3D molecular-dynamics simulations. In addition, the simulations feature interesting phenomena in the strongly coupled dust flow, which are not yet experimentally confirmed for dynamic systems. One of these is the formation of nested shells in the dust stream, which were found to be a crystallization based on an effective cooling of the dust by neutral friction [2]. The verification of this behavior under real experimental conditions is challenging, since effects like dust density waves and fluctuations of the anodic plasma are neglected in the simulations. These effects act as additional heating mechanisms and prevent crystallization. In recent experiments, we have systematically suppressed these disturbances and obtained a crystalline dust torus. In this contribution we summarize our approach towards crystallization of the dust flow in the MATILDA-II setup. Further, we study the crystalline order with correlation techniques (see Fig. 1) and show the interaction of inhomogeneity of the dust flow and structure.

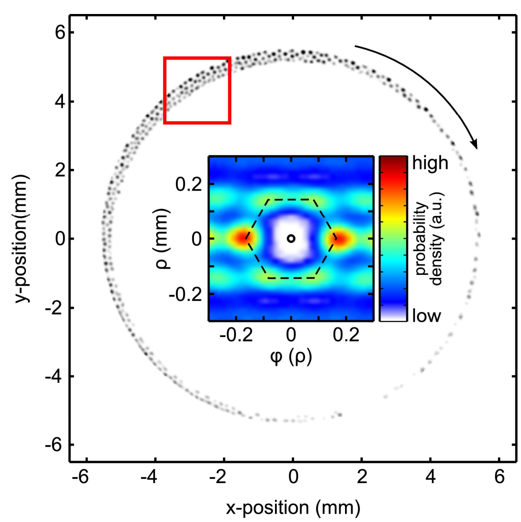

Figure 1 Snapshot of a crystalline dust torus in end-on geometry. The 2D pair correlation function for the marked region is shown in the center of the picture. A hexagonal arrangement of the nearest neighbors is clearly visible.

This work was financially supported by SFB TR24/A2.

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Interactions of Plasma with Single and Multiple Dipole Magnets in a GEC RF Reference Cell

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The interaction of plasma with a magnetic field close to a non-conductive surface has been investigated in a GEC RF reference cell. Such magnetic field-plasma interactions are believed to be responsible for the formation of Lunar Swirls, albedo patterns found on the Moon at local magnetic field anomalies. These magnetic field anomalies may lead to strong horizontal electric fields, which can influence the solar wind flux towards the surface and thus affect space weathering and direct dust transport processes.

In previous experiments, the effects on a plasma of single dipole magnets oriented in both the horizontal [1] and vertical [2] direction have been analyzed. Recently, Hemingway and Garrick-Bethell approximated the magnetic field measured by Lunar Prospector at two magnetic anomalies on the Moon using multiple dipole magnets as sources [3]. In the experiments presented here, scaled models of these magnetic fields have been built using multiple dipole magnets (see figure 1) and the interaction of the plasma with the magnetic field has been investigated in order to better understand ion deflection and dust transport at the lunar surface. In this case, dust particles were introduced into the plasma and used for diagnostic purposes. The dust particles charge negatively due to electron collection and are affected by the electric fields in the plasma. A vertically fanned laser beam was used to illuminate the dust particles and a high-speed camera recorded the particle trajectories. Moving the laser beam between particle drops allowed data collection from two different perspectives, which was then used to generate a three-dimensional vector field of the forces acting in the magnetically perturbed plasma sheath. These results will be examined to determine the electric fields that occur as a result of the interaction of the magnetic field with the plasma.

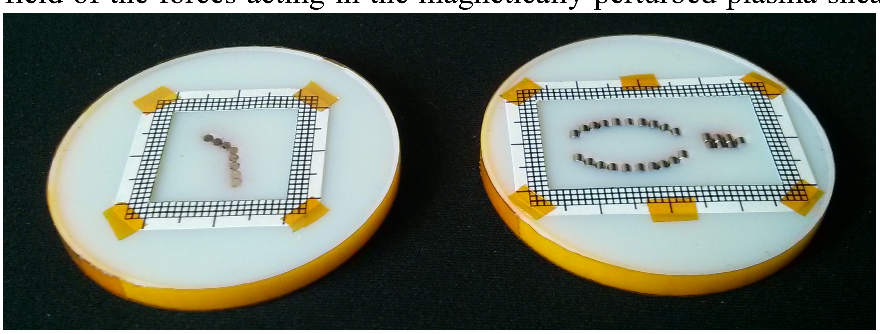

Figure 1 – Magnet configurations representing scaled models of magnetic anomalies on the moon. Left: Scaled model (1:3,000,000) of the magnetic field at Airy formation. Right: Scaled model (1:2,000,000) of the magnetic field at Reiner Gamma formation.

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Dust particles under the influence of crossed electric and magnetic fields in the sheath of an rf discharge

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At present there is a great interest in studies on dusty plasmas in magnetic fields. Direct effects on the dust particles due to Lorentz-forces as well as indirect effects, like in this work, due to the influence of magnetic fields on other plasma species are under investigation.

This contribution describes the behaviour of nonmagnetic plastic particles which are confined in the sheath of an rf discharge. In addition to the sheath electric field an external transverse magnetic field of up to 50mT field strength is applied. Depending on the experimental parameters the dust particles move in the direction of **E**x**B**-drift or opposite to it. This transport of the dust particles is described by means of plasma-based forces in the horizontal plane, namely ambipolar electric field force, ion wind and neutral gas wind.

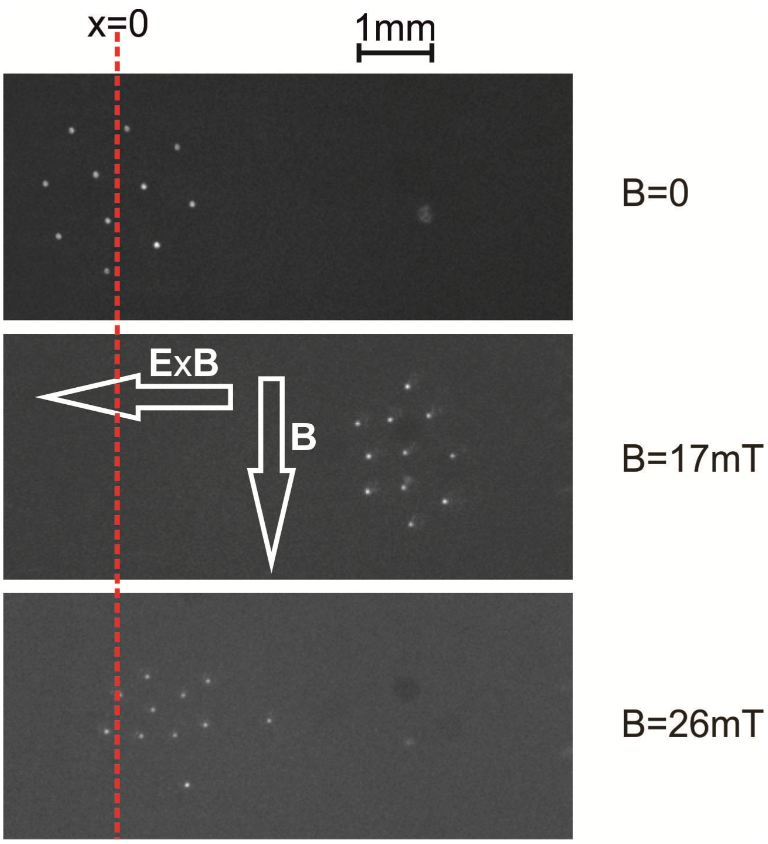

Figure 1 – Top view camera images of a two-dimensional dust cluster under the action of a horizontal magnetic field.

The Charge of Single Grains in Dense Nanodust Clouds

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The combination of dusty plasmas and magnetic fields is undoubtedly challenging since the established electrical probe techniques only work in dust-free plasmas and the confinement of dust in magnetized plasmas has been a difficult issue for many years. Recently, we have shown that dense nanodust clouds can be confined for some minutes in a magnetized rf discharge without a splitting of the plasma into filaments using a special preparation sequence [1]. Dust size and dust density information are made available from polarized light scattering and extinction measurements.

Our final goal is to produce a dusty plasma, in which even the dust particles are magnetized so that the dust cyclotron frequency is larger than the dust-neutral friction frequency:

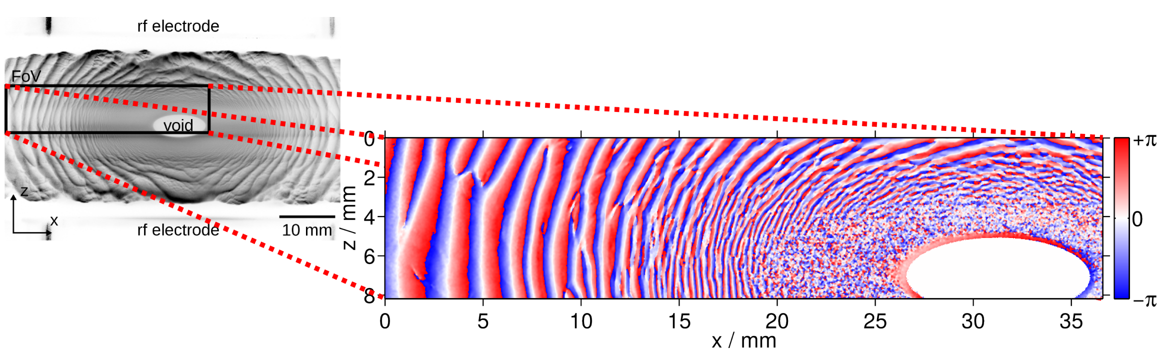
$$\omega_{cd} = \frac{Z_d e B}{m_d} > \nu_{dn} .$$

This could be achieved in the superconducting magnet "Suleiman" with its magnetic induction of B < 4 T when dust particles with a radius smaller than 100 nm and a neutral pressure of p < 1 Pa are used.

The key premise in this calculation is that the dust charge Z_d reaches high values, i.e. there is no Havnes/charge reduction effect in the dust cloud. Therefore, we study dust density waves (DDWs) to verify the dust charge.

We present the appropriate dispersion relation for DDWs and show the existence regime for unstable self-excited waves by numerical calculations. The results of this model are compared with experimental data obtained in unmagnetized dusty plasmas. Good agreement between experiment and theory is found at dust charges much lower than predicted by the standard formula. For magnetizing the dust this will be the most important parameter to tune.

This work was supported by the DFG via SFB-TR24/A2: "Magnetized dusty plasmas".



A dense dust cloud (left) with a field of view analyzed in terms of the so called Hilbert transform (right) providing the local phase of the wave.

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A summary of initial studies of ordered structures and collective modes using the Magnetized Dusty Plasma Experiment (MDPX) device

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After over 5 years of development, the Magnetized Dusty Plasma Experiment (MDPX) located at Auburn University began operations in April, 2014. After several months of evaluation and testing, the MDPX device has been steadily progressing towards a regular operating schedule since early Fall, 2014. At this time, the MDPX device is configured to produce radio frequency (rf) excited argon plasmas at 13.56 MHz using a capacitively-coupled, parallel plate configuration. Experiments have been performed using silica microspheres of 0.5, 2.0, and 8.0 micron particles in uniform magnetic fields up to 2.5 Tesla. The initial operations show that reproducible plasmas and dusty plasmas can be generated in the MDPX device.

This presentation will describe two different phenomena that have been observed in the MDPX device at magnetic fields above 1 T. The first phenomenon is the observation of a new type of imposed ordered structure that forms in the dusty plasma. This ordered structure in unlike the previously reported plasma crystals or Coulomb balls in that it requires the presence of the magnetic field in order to appear in the plasma and the formation of the structure is *degraded* with increasing neutral pressure. The second phenomenon is an investigation of coupled parallel and transverse (relative to the magnetic field) particle transport in self-excited and driven dust acoustic / dust density waves. The observed transverse motion of the particles may lead to a modification of the dispersion relation.

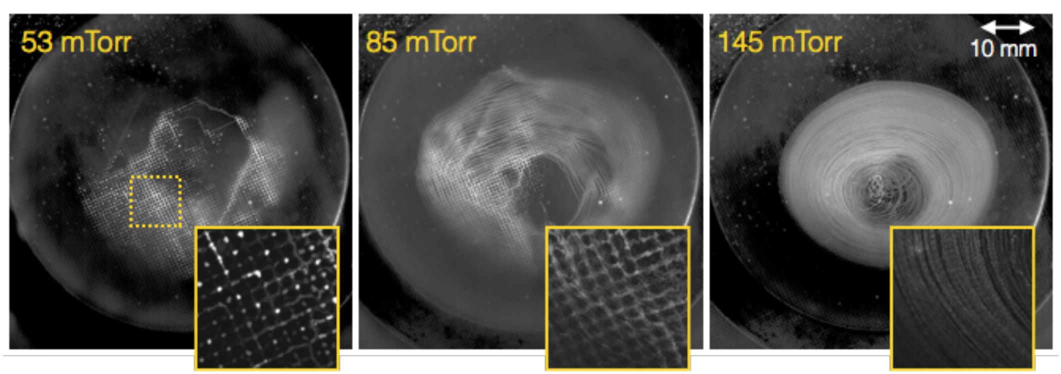

Figure 1 – Comparison of the imposed grid structure formed using 0.5-micron diameter silica microspheres in an rf-generated argon plasma at 4 W and B = 1.5 T viewed from the top and as a function of the neutral gas pressure. The images are 2048 x 2000 pixels (64.5 x 63 mm). The insert is a magnification of a 200 x 200 pixel (6.3 x 6.3 mm) region indicated by the dashed box.

Charged Dust Measurements by the Lunar Dust Experiment

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The Lunar Dust Experiment (LDEX) onboard the Lunar Atmosphere and Dust Environment Explorer (LADEE) mission discovered a permanently present dust cloud engulfing the Moon. The size, velocity, and density distributions of the dust particles are consistent with ejecta clouds generated from the continual bombardment of the lunar surface by sporadic interplanetary dust particles. Intermittent density enhancements were observed during several of the annual meteoroid streams, especially during the Geminids. In addition to the mass and speed of the impacting particles, in a significant fraction of the events, LDEX also recorded the electrostatic charge of the dust grains before their impact (Figure 1). The talk will discuss the workings of LDEX, the status of the analysis and the interpretation of the data.

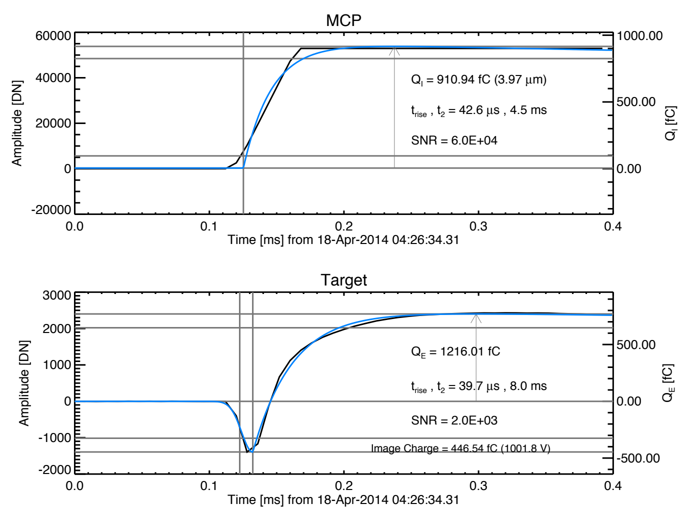

Figure 1. Waveforms from the collection of ions (top) and electrons (bottom) in a dust impact generated plasma cloud recorded just minutes before the end of the LDEE mission at an altitude of h ~2 km. The ion signal saturated, but the electron signal amplitude can still be used to estimate the size of the impacting dust particle a ≈ 4 μm. The dip preceding the sudden rise of the electron signal is due to the charge the particle had before the impact, and its depth indicates a dust charge of Q ≈ 450 fC.

Meteoric dust particles are the primary charge carriers in the lower ionosphere

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The CHAMPS (CHarge And Mass of meteoric smoke ParticleS) rocket campaign consisted of two sounding rockets with one launched at night 11 October and one launched in daytime 13 October 2011 from the Andøya Rocket Range, Norway. These dates are after the noctilucent cloud season to avoid the detection of icy cloud particles. The rockets carried instruments including a mass spectrometer for meteor smoke particles that from 60 – 100 km altitude measured the number density of positively and negatively charged particles in 5 logarithmically spaced mass ranges from about 10 – 10^5 amu. Meteoric smoke particles with number densities of several thousand per cc were detected in mass ranges up to 8,000 amu but not heavier, indicating an upper bound of about 1.2 nm on the radius of meteoric smoke particles. Recent numerical modeling of ionization, recombination of ions with electrons, and recombination on the smoke particles gives a distribution of charge among the species that is consistent with the nighttime observations. The model explains the unusual observation of equal numbers of positive and negative dust particles at 60 – 70 km altitude. In this altitude range, the modeling shows that the positive and negative charges reside primarily on the smoke particles and charge-neutrality requires an equal number of positive and negative particles. In the past, the ionization rate in this region of the ionosphere has been calculated by assuming that the ionization rate is equal to the electron-ion recombination rate; however, our model shows that the recombination is in fact primarily on the dust particles. The daytime data indicate that photodetachment reduces the number of negatively charged particles in the daytime and that photoemission is not an important process, probably as a result of a higher energy threshold for photoemission that for photodetachment.

Kolbjorn Dahle photo/Andøya Rocket Range

Experimental investigation of micrometeoroid ablation using a dust accelerator

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The dust accelerator operating at the University of Colorado of Colorado is expanded with a capability to investigate the ablation of micron-sized dust particle. The particles are accelerated to velocities relevant to micrometeoroids entering the Earth's atmosphere (> 10 km/s) using a 3 MV electrostatic accelerator. The particles then enter a gas cell, where the pressure is maintained around between 0.05-0.5 mTorr. The particles frictionally heat and completely or partially evaporate. The ablated atoms and molecules may ionize in collisions with individual molecules of the background gas. A set of charge sensitive amplifiers is installed along the particles' flight path and the generated plasma is collected with spatial resolution. There is an impact detector installed at the end of the path to detect the mass of the remaining particle, if any. The first few sets of measurements have been performed using iron dust particles and nitrogen and oxygen gases. The measurements yield the evaporation rates and ionization efficiencies of the ablated elements that are critical to the interpretation of meteor radar data. In the Earth's atmosphere, layers of neutral metal atoms (Fe, Mg, Ca, K, Na), which peak between 85 and 95 km and are ~20 km in width, are produced by the daily ablation of billions of Interplanetary Dust Particles (IDPs). Once the meteoric metals are injected into the Earth's upper atmosphere they are responsible for a diverse range of phenomena, including: the formation of layers of metal atoms and ions; nucleation of noctilucent clouds, impacts on stratospheric aerosols and O3 chemistry, for example.

Motivation/Design of the Caltech Water-Ice Dusty Plasma Experiment

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Water-ice particles in astrophysical dusty plasma contexts have traditionally been assumed to be spherical with a power law density distribution $n \sim r^{-p}$. However, one may ask why should particles be spherical? A motivation for the Caltech water-ice dusty plasma experiment was to test the hypothesis that water-ice dust particles should be non-spherical. This hypothesis depends on water molecules being highly dipolar and on electric fields being large at sharp points on charged conductors.

Consider an initially spherical ice particle in a plasma environment. The particle will become negatively charged following the usual dusty plasma mechanisms. Suppose the particle develops a small bump. To the extent the electrons constituting the surface charge have any mobility, the particle surface will be an equipotential and so both the electric field and its gradient will be largest at the bump. Ambient water molecules are neutral and so do not experience an electric force $\sim q\mathbf{E}$. However, because of their large dipole moment, ambient water molecules experience a force $-\ \mathbf{p}\cdot\nabla\mathbf{E}$ with the molecule aligning so the force is always attractive towards the bump. Thus, ambient water molecules are preferentially attracted to the large field gradient at a bump on an ice particle. The resulting preferential accumulation of water molecules at the bump will make the ice particle more non-spherical. If the molecule is collisionless, it will have a curved trajectory governed by orbital motion theory (OML) in the potential $-p|E(\mathbf{r})|$.

Because water molecules are preferentially collected at sharp points, a needle-shaped ice particle will elongate just like a bar magnet attracting ion filings. To the extent that these arguments apply to each ice particle, all particles should have approximately the same shape and size, i.e., not a power law density distribution $n \sim r^{-p}$. The ice particle size and shape will thus depend on ambient conditions [1] so if the ambient conditions change, all the ice particles will change the same way (e.g., all get longer).

The Caltech water-ice dusty plasma experiment [2] investigates this hypothesis using an rf discharge plasma with LN2-cooled electrodes as in Ref.[3], but differs by having direct injection of water vapor and direct imaging of ice particles. Experimental details and results are provided in the companion presentation by Chai and Bellan.

[1] Chai, K.B. and Bellan, P. M., 2015, Formation and alignment of elongated, fractal-like water-ice particles in extremely cold, weakly ionized plasma**,** Astrophysical Journal, in press

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Formation and alignment of elongated, fractal-like water-ice grains in extremely cold, weakly ionized plasma

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We inject water vapor into a weakly-ionized rf discharge plasma formed in a background gas cooled to an astrophysically relevant temperature. Water-ice grains then spontaneously form and levitate between the two discharge electrodes [1]. Our apparatus is similar to what was reported in Ref. [2] but is improved by having an adjustable distance between the electrodes and a controlled amount of water vapor directly injected into the chamber. Our previous studies indicated that water-ice grains grow non-spherically when the mean free path of a water molecule exceeds the screening length for the ice grain in which case water molecules incident on the ice grain can be considered to have collisionless trajectories [3]. In the present study [4], water-ice grains formed in a plasma produced from low mass gas (e.g., hydrogen, helium) are larger, more elongated, and more fractal-like than water-ice grains formed in plasmas produced from high mass gas (e. g., argon, krypton). Aspect ratios (length to width ratio) can be as great as 5 while fractal dimensions are typically about 1.7. Water-ice grain lengths in plasmas formed from low mass gas can be several hundred microns long (see Fig.1). It is also found that water-ice grains levitate with regular spacing and align parallel to the sheath electric field. Infrared absorption spectroscopy reveals that the water-ice grains are crystalline and so are similar in constitution to the water-ice grains in protoplanetary disks, Saturn's rings, and mesospheric clouds. The properties and behavior of these laboratory water-ice grains may provide insights into the morphology and alignment behavior of water-ice grains in astrophysical dusty plasmas.

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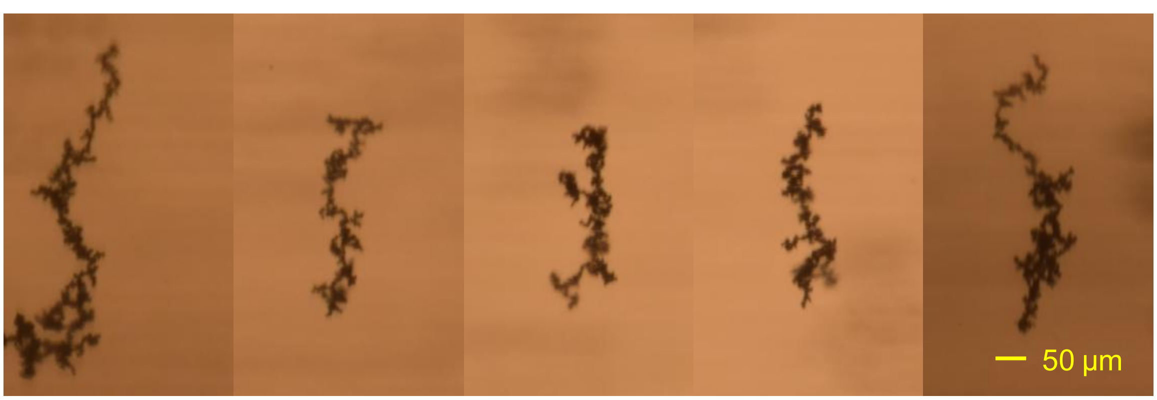

Figure 1 – Elongated, fractal-like water-ice grains spontaneously formed in cryogenic temperature hydrogen plasma.

Statistical mechanics where Newton's third law is broken

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There is a variety of situations in which Newton's third law is violated. Generally, the action-reaction symmetry can be broken for mesoscopic particles, when their effective interactions are mediated by a *non-equilibrium* environment – prominent examples include complex plasmas and colloidal dispersions. We have investigated different classes of non-reciprocal interactions relevant to real experimental situations, and performed their basic statistical mechanics analysis. We rigorously showed that in certain cases systems with non-reciprocal interactions, being intrinsically non-equilibrium, can nevertheless be described in terms of equilibrium statistical mechanics and exhibit detailed balance with distinct temperatures for each species.

To verify the principal theoretical predictions, we have performed experimental tests with quasi-2D binary complex plasmas. By injecting two sorts of monodisperse microparticles it was possible to obtain a mixture where different particles levitated at slightly different heights (but no vertical pairs were formed). In agreement with the theory, we found that (i) the kinetic temperature of the horizontal motion was noticeably higher for the “upper ”particles (see Fig. 1), and (ii) the temperature difference between particles of different sorts increased with the height difference.

The interaction of particles of one sort with wakes generated by particles of the other sort leads to a very general mechanism of the action-reaction symmetry breaking, occurring in the presence of a flow. This makes 2D complex plasmas perfectly suited for studying generic properties of various many-body systems with non-reciprocal interactions.

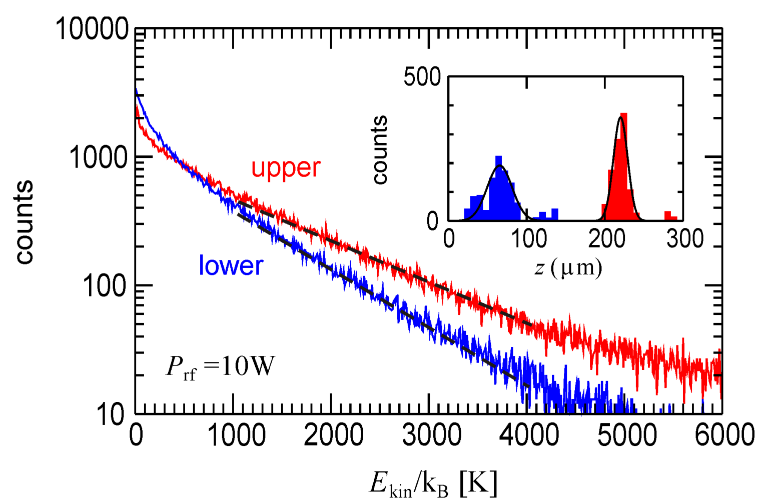

Figure 1 – Kinetic energy distribution for a binary mixture of microparticles.

Dynamical properties of the chain-like structure of particles interacting via nonreciprocal quasi dipole-dipole interaction

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The conditions of dusty plasma systems formation are most commonly investigated using the model of isotropic pair interaction potential. A possible reason for nonreciprocal anisotropic interaction (when the third Newton's low isn't valid) in the dust particle systems can be ion fluxes. Nonreciprocal interaction between dust particles in the plasma also concerns quasi-dipole-dipole interaction, caused by the effects of ion/electron focusing, as well as the effects of the Lesage forces resulted from bombardment of the surface of dust particles by the flow of plasma and neutral gas.

This report presents a model which describes a sources of additional kinetic energy and its redistribution in systems of many particles with nonreciprocal interaction. Numerical studies have been carried out for particles with a quasi-dipole-dipole interaction, similar to the interaction occurring due to the effect of ion focusing under experimental conditions of laboratory dusty plasma. Analytical expressions that allow to describe the mechanism of heating and redistribution of kinetic energy in systems with nonreciprocal interparticle interaction are proposed.

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Grain-Grain Interaction in Stationary Dusty Plasma

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Abstract

We present a PIC simulation study of the steady-state interaction between two stationary dust grains in uniform stationary plasma. Both the electrostatic force and the shadowing force on the grains are calculated explicitly. The electrostatic force is found to be always repulsive. There is no indication whatsoever of electrostatic attraction due to overlapping Debye spheres, as suggested by Resendes et al[1], nor of electrostatic attraction due to nonlinear grain-grain interaction, as suggested by Lampe et al.[2] For two grains of the same size, the electrostatic force is very nearly equal to the shielded electric field due to a single isolated grain, acting on the charge of the other grain. For two grains of unequal size, the electrostatic force on the smaller grain is found to be smaller than the isolated-grain field, and the electrostatic force on the larger grain is found to be larger than the isolated-grain field. In all cases, the attractive shadowing force exceeds the repulsive electrostatic force when the grain separation d is greater than an equilibrium separation d_0, which is found to be between $6\lambda_D$ and $9\lambda_D$ in all cases. The attraction due to the shadowing force is strong enough to bind a pair of dust grains as a two-grain "molecule." We are not able to calculate the binding energy accurately, but it is estimated to be between 19eV and 900eV for various cases. The results appear to be in qualitative agreement with the experimental observation of bound clusters by Usachev et al.[3]

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Approximate expression for the electric potential around a dust grain in isotropic collisionless plasma

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Accurate theoretical predictions of the electric potential distribution around a dust grain immersed in weakly ionized gas are of importance for understanding various properties of complex plasmas. For the case of isotropic collisionless plasma the exact potential distribution can be obtained by solving numerically the nonlinear Poisson equation with charge density derived from the solution of the stationary Vlasov equation [1,2]. The analytical solution of the linearized Poisson equation is given by the sum of the Debye-Hückel (DH) potential and the far-field asymptote $\varphi_{as} \propto r^{-2}$, where r is the distance from the grain center. The linearization is valid only for small values of the nonlinearity parameter $\beta = (a/\lambda_{\rm i})(\varphi_a/kT_{\rm e})(T_{\rm e}/T_{\rm i})$, where a is the grain radius, $\lambda_{\rm i}$ is the ion Debye length, φ_a is the grain potential and $T_{\rm i,e}$ are the temperatures of ions and electrons in plasma, respectively. As it was shown in [3,4], for high values of β the exact solution at small distances from the grain ($r \sim \lambda_{\rm i}$) is well approximated by the DH potential with an effective screening length $\lambda_s > \lambda_{\rm i}$ which depends only on the parameter β. It can be demonstrated, however, that at intermediate distances ($r \lesssim 10\,\lambda_{\rm i}$) the DH potential with the effective length λ_s gives a poor approximation to the exact solution. Behavior of the potential in this range can influence, for example, the properties of 3D dust systems which are usually studied in microgravity experiments. From this point of view, it would be desirable to obtain a more accurate approximation for the potential distribution in the whole range of distances.

In the present work a new approximate expression for the electric potential around a dust grain in isotropic collisionless plasma is proposed. The model potential reads as

$$\varphi(r) = \frac{q_a}{r} e^{-y\,k(y)} + \varphi_{as}(r), \tag{1}$$

where $q_a = a\,(\varphi_a - \varphi_{as}(a))$ and $y = (r-a)/\lambda_{\rm i}$. The first term in (1) is written in a DH form where the inverse screening length depends on the distance as follows

$$k(y) = k_* + (1-k_*)\,f(y\,c_*).$$

Here k_* and c_* are the adjustable parameters and $f(x) = \ln(\cosh(x))/x$. The procedure based on the charge balance considerations is employed to find the parameters k_* and c_* which are shown to depend only on the nonlinearity parameter β. Simple approximations to the functions $k_*(\beta)$ and $c_*(\beta)$ are proposed. It is shown that the model potential (1) is in excellent agreement with the solution of the nonlinear Poisson equation up to $\beta \sim 100$.

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Ion-dust streaming instability and dust wake potential with magnetized ions

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The ion-dust streaming instability [1-3] excited by ions streaming past the heavy dust grains is a ubiquitous phenomenon in many complex plasma experiments. The properties of the ion flow (drift speed, velocity distribution, etc.) are determined by the interplay between electric fields in the plasma and collisions of ions with the ambient neutral gas. We investigate the ion-dust streaming instability using a dielectric function, where this interplay is self-consistently taken into account and gives rise to a non-Maxwellian velocity distribution [4]. Additionally, we include the effect of an external magnetic field parallel to the ion flow to study the instability in the full range from weak to strong ion magnetization. The analysis shows that magnetizing the ions can either facilitate or hinder the growth of the instability-depending on the ion Mach number.
The same dielectric function is then employed to calculate the dust wake potential, where we also find qualitatively different behavior for weak and strong ion flows. A comparison with the case of Maxwellian ions [5] is presented.

This work is supported by the DFG via SFB-TR24, projects A7 and A9.

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Experimental study of global synchronization of the dust acoustic wave in a weakly-coupled dusty plasma system

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The dust acoustic wave (also known as the dust density wave) is low-frequency, longitudinal mode that propagates through the dust component of the dusty plasma system and is self-excited by the free energy from the ion streaming through the dust component. In the laboratory setting, the majority of the self-excited dust acoustic waves that are observed are nonlinear, which allows for detailed studies of the nonlinear properties of waves at the kinetic level. One such nonlinear process is synchronization, which is observed when the self-excited dust acoustic wave mode couples with and adjusts to an externally applied modulation. In this work, the nonlinear process of synchronization is examined in the spatial and temporal domains by applying a time-resolved Hilbert Transform to high-speed video imaging of the wave mode over a wide range of experimental conditions.

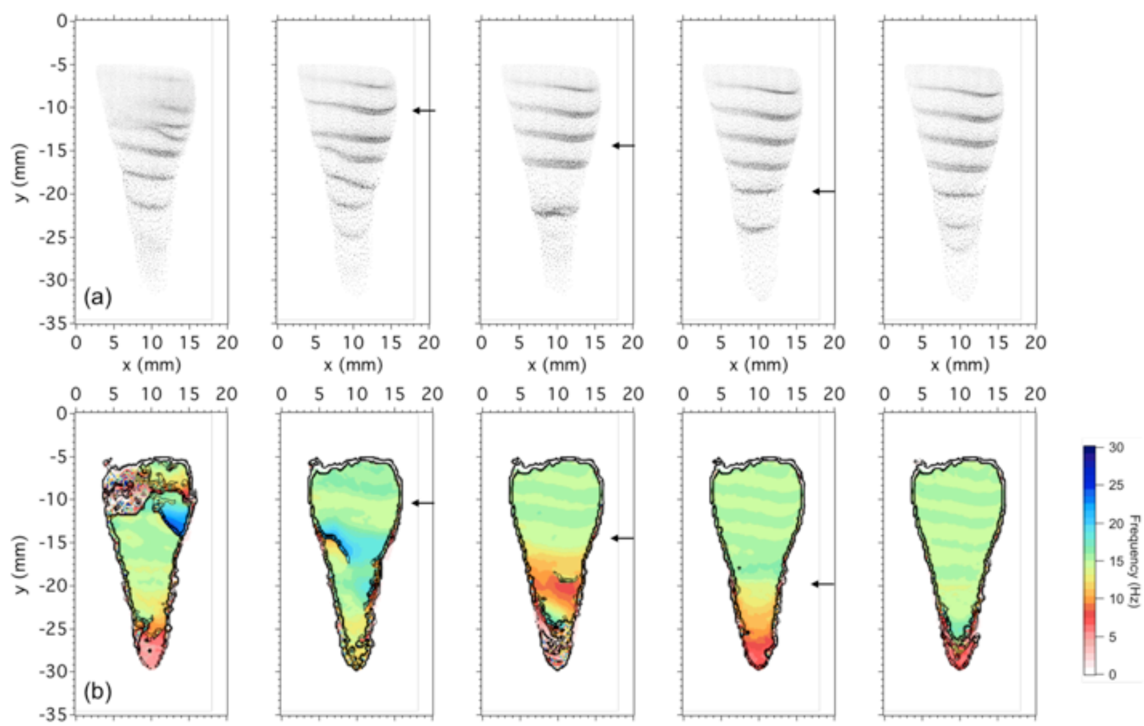

Figure 1 – Image sequence (Δt = 140 ms) showing the temporal evolution of the (a) wave and (b) spatial distribution frequency as the cloud synchronizes with an external modulation. The arrows indicates a separation between the regions of the cloud that have/have not synchronized with the external modulation. The spatial distribution of frequency plots have been filtered to only show regions where wave activity is present and contours depicting where the standard deviation in a 5×5 pixel region exceed 1 Hz have been superimposed to indicate the existence of frequency clusters.

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Mode coupling and resonance instabilities in small dust systems

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Mode couplings and resonance instabilities have recently received tremendous attention in both large plasma crystals [1] and small dust clusters [2, 3] due to their fundamental importance across a variety of research fields [4-6]. In this research, normal modes of a horizontal finite chain consisting of 3-20 dust particles in a complex plasma are investigated using simulation and an analytical method. The resultant mode coupling, resonance instabilities and melting are analyzed and compared with previous research on large crystals and circular dust clusters. Furthermore, transition from the normal mode spectra in finite systems to wave dispersion relations in large systems is studied using the dust chain model with a large number of dust particles.

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Synchronized motion in two-dimensional complex plasma crystals

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Two-dimensional complex plasma crystals are an ideal model system to study dynamic processes [1]. Recently, synchronized motion of alternating in-phase and anti-phase particle lines was observed during mode-coupling instability (MCI), where the out-of-plane mode couples to the longitudinal mode [2]. The coupling allows energy to be transferred from the flowing ions in the plasma sheath to the crystal until the crystal melts. While MCI is equally strong in three directions for an ideal hexagonal lattice [3], it was observed in only two directions in Ref. [2].

Here, we demonstrate with molecular dynamics simulations that an asymmetry in the horizontal confinement of the plasma crystal can cause an anisotropic ignition of MCI. The confinement asymmetry leads to a deformation of the hexagonal lattice that is typically observed in experiments. The instability is accompanied by synchronized particle motion that is characterized by a new order parameter. Depending on the orientation of the confinement asymmetry, MCI and synchronized motion are observed in one or two directions. The good agreement of simulation and experiment suggests that the confinement asymmetry can be used to explain the synchronized motion observed in experiments.

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Flow induced dust acoustic and dust acoustic solitary waves in a complex plasma

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We report an experimental observation of particle flow induced Dust Acoustic (DA) and Dust Acoustic Solitary (DAS) waves in Dusty Plasma Experimental (DPEx) device. The experiments are performed in a U-shaped glass tube and the plasma is formed by applying a DC voltage between a disk type anode and a long grounded cathode in the background of argon gas. The plasma parameters are measured using a Langmuir and emissive probes. The non dispersive micron sized kaolin particles, are sprinkled on the cathode, and are seen to levitate near the cathode sheath region when the plasma is produced. A scanning laser sheet and a couple of cameras are used to capture the dynamics of the dust fluid. The flow of the dust fluid is initiated by adjusting the pumping speed and neutral gas flow. An isolated cupper wire is mounted on the cathode which acts as a potential hill to the flow of dust particles. The DA and DASWs are excited by controlling the neutral gas flow along the axis of dust cloud. Physical interpretation of the experimental results will be discussed with the help of model numerical and analytic solutions.

Dust transport in magnetized fusion plasmas: experimental challenges and opportunities

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Abstract: There is a significant gap between theories and observed dust phenomena in magnetized fusion plasmas. When dust is produced at divertor and other locations inside the vacuum vessel, plasma-material interactions (PMI) generate grains with different shapes, sizes, texture, and composition, which are hardly predictable. Most theories have been developed using idealized assumptions about the dust shape, the amount of charge on the dust and the dust temperature, which are not validated by measurements. Meanwhile, understanding dust transport in a magnetic fusion environment is essential to dust inventory control, due to concerns about dust safety hazards, such as tritium retention, toxicity, and flammability, and about introducing impurities to the fusion plasma core by moving dust. Dust grains are highly mobile because of their small sizes. Dust velocity above 100 m/s has been associated with pellet injection. Two recent developments can be particularly useful to bridge the gap between theory and experiment: A.) dust injection technologies that control dust material properties as well as dust momenta. B.) high-speed imaging sensors, in conjunction with microlens arrays, for light-field imaging of dust dynamics.

Beyond Orbital-Motion-Limited theory effects for dust transport in tokamaks

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Long-pulse tokamaks like ITER or DEMO are characterized by much higher energy fluxes to the wall than present-day short-pulse tokamaks, implying stronger plasma-material interaction and higher quantities of dust produced in the chamber. Indeed, ITER is the first tokamak with dust safety and administrative limits, setting the maximum amount of dust that can be present at any given time in the machine [1]. For this reason, dust transport in tokamaks and dust destruction/survival have received a lot of attention in recent years [2-5].

Studies of dust transport typically involve solving simultaneously the following time-dependent equations: (1) the dust charging equation; (2) the dust equation of motion; (3) the dust heating equation; and (4) an equation for dust mass loss. The dust charging equation yields the dust charge due to collection of background plasma particles and electron emission processes, and is a necessary ingredient to calculate the forces acting on the dust grain and the energy fluxes. The expressions for the dust charging currents, forces and energy fluxes are normally expressed analytically in the framework of the Orbital-Motion-Limited (OML) theory [2-5].

In this work, we explore the regimes of validity of OML. We perform self-consistent Particle-In-Cell simulations of dust charging for conditions relevant to the edge of a tokamak, including thermionic emission from the dust grain. We study micron-sized tungsten dust, in a regime where the plasma Debye length is comparable to the dust radius. We find that OML can become inaccurate when the grain becomes positively charged: it can miss the transition between negatively and positively charged dust, and it can overestimate the dust charge, currents and the energy fluxes (the latter by 30-50% for the energy collected by the background electrons and for the parameters considered). This behavior is associated with the development of a non-monotonic potential (a potential well) near the dust grain due to the trapping of some of the thermionic electrons [6]. The controlling parameters are the dust size relative to the Debye length and the dust temperature relative to the background electron temperature. We also discuss a new charging theory that is much more accurate than OML for positively charged dust.

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Mie-Scattering Ellipsometry System for Analysis of Dust Formation Process in Large Plasma Device

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The generation of dusts in nuclear fusion reactors is becoming a serious problem, because they play as sources of core cooling and tritium pollution. *In-situ* measurements and analyses of dust behaviors are important issues to reduce the generation of dusts in a nuclear fusion reactor. Mie-scattering ellipsometry[1)] is a useful method for the analysis of dust growth and behavior in a plasma devices. We have been developing a Mie-scattering ellipsometry system for the analysis of generation and transport of dusts in a large plasma device like the Large Helical Devise (LHD) in Japan.

The ellipsometer system consists of two modules. One module composed of a laser-light (532 nm) source, a polarizer, and a rotating-compensator, which is attached to a view-window of a port under diverters in LHD. The other module of analyzer, which is composed of a wire-grid polarizer and a mirror plate, is set in the vacuum chamber of LHD. The image of distribution of scattered light through a wire-grid polarizer can be observed out of the chamber by using a CCD camera attached to the view-window. Using this system, Mie-scattering ellipsometry measurement of dusts can be carried out from a long distance, e. g., 2 meters.

The performance of the developed ellipsometer system was examined being attached to an RF plasma equipment under the same arrangement as in LHD. Spherical divinylbenzene fine particles of 2.25 μm in diameter were suspended on an RF electrode. The intensity of light on CCD as a function of rotating-compensator azimuth C, i. e., I(C), was obtained as shown in Figure 1. Fourier coefficients of I(C) were calculated, then ellipsometric parameters were obtained to be Ψ=75.8°, Δ=38.3°, which are valid values for the measurement.

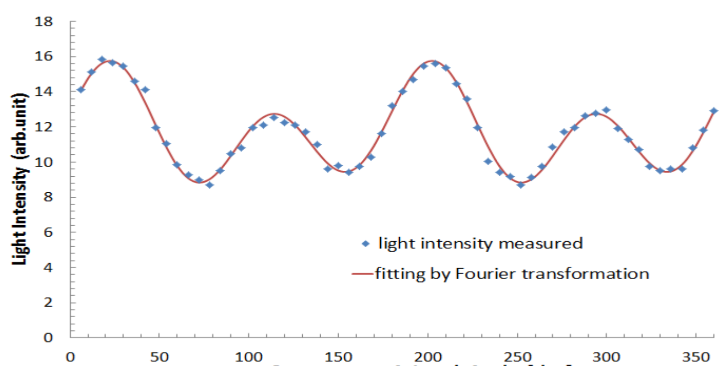

Figure 1 – Variation of light intensity with rotating-compensator azimuth during Mie-scatetring ellipsometry measurement. Dots and curve indicate measured values and calculated function by Fourier transformation, respectively.

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Aerosol Dynamics in DC discharge

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Nucleation and growth of nanostructured dust particles is of particular interest for different fields. As an example, in laboratory and industrial chemically active discharges, dust can affect the performance of produced electronic devices or films [1].

A modeling study of carbon dust particles formation through carbon graphite sputtering in argon DC discharges is presented. The model combines self-consistently the description of plasma discharge kinetics, molecular growth and transport of carbon clusters and aerosol dynamics for dust particles. The aerosol dynamics is solved by a so named sectional model [2] which take into account particle growth through molecular sticking and coagulation, nucleation, transport and particle charge. This model allows a fine resolution of the particle behavior as fonction of time and particle size. The particle size distribution presents for long discharge durations a depletion in the range 2-10 nm which can be explained by the particle charging process.

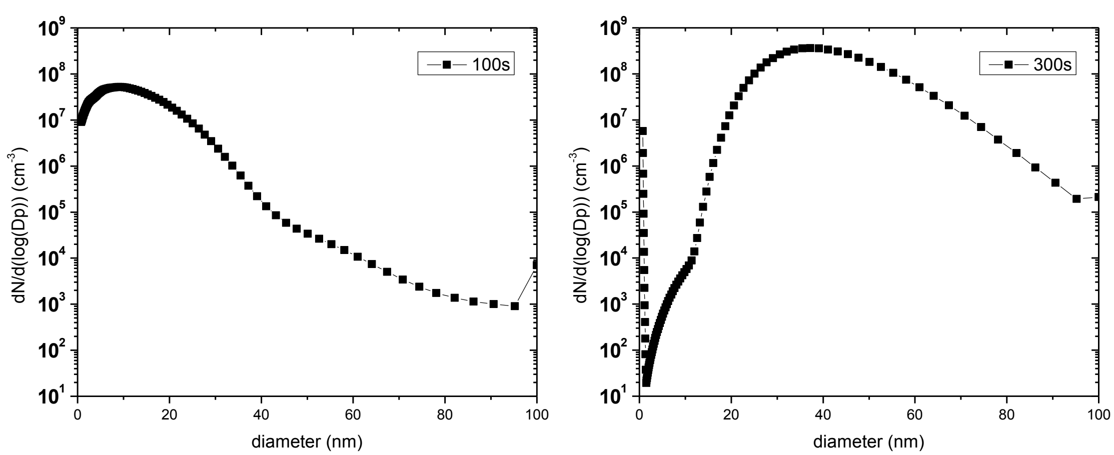

Figure 1 –Particle size distribution at the beginning of the nucleation phase and after 300 s of discharge duration

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Competing processes due to microparticle injection and effects on microwave transmission through an overly dense plasma layer*

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Microparticles injected into a plasma have been shown to significantly reduce the electron density as electrons are captured during the microparticle charging process. This has in turn been shown to increase the transparency and penetration of microwaves into an overly dense plasma layer. However, these charge microparticles can also act to scatter electromagnetic signals.

Here we focus on understanding the physical phenomena associated with the competing processes that affect microwave penetration through an overly dense plasma layer. In particular, we investigate the competing processes that occur due to microparticle injection and charging. Results from these studies focus on understanding the correlation between the rate of microparticle injection and effects on microwave penetration of the plasma layer, as well as microwave scattering off of the charged microparticles. The timescales for which each of these competing processes dominates the interaction of electromagnetic signals in the plasma layer is analyzed in detail.

It was found that while both processes play a significant and dominant role at times, ultimately, transmission through this impenetrable plasma layer can be significantly increased by microparticle injection. These studies are applicable for mitigating the communications radio blackout problem experienced by hypersonic vehicles and may have additional applications for satellite communications.

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Investigating size and density distribution in large 3D dust clouds using Computer Tomography and Mie Imaging

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3D dust clouds consisting of millions of dust particles can be confined in low temperature plasmas, where they exhibit a complex structure (including the characteristic void) and interesting dynamical phenomena such as self-excited waves and vortices.

Most experiments on these dust clouds rely on the illumination of a thin slice of the cloud. Here, in order to retrieve information about the dust system as a whole, a new optical technique based on light extinction has been developed. The light transmission through a trans-illuminated dust cloud gives a measure for the line-of-sight integrated dust density. Now, by performing experiments in a plasma chamber with 360° optical access and by using a rotating stage for the light source and the camera, the extinction measurement is performed from many different angles. Using standard algorithms from common computer tomography, the 3D dust density distribution can be reconstructed.

In addition, a Mie imaging technique has been developed which enables us to monitor the spatio-temporal evolution of the dust size distribution in these clouds. Measuring the scattering intensity of laser-illuminated particles over a wide angular range allows us to determine the dust size with a high precision. Interestingly, dust clouds consisting of seemingly monodisperse MF particles feature a segmentation into homogenous populations of different dust sizes. It has furthermore been observed that even tiny amounts of impurities (oxygen or others) in argon plasmas result in a significant reduction of the dust size over the course of hours.

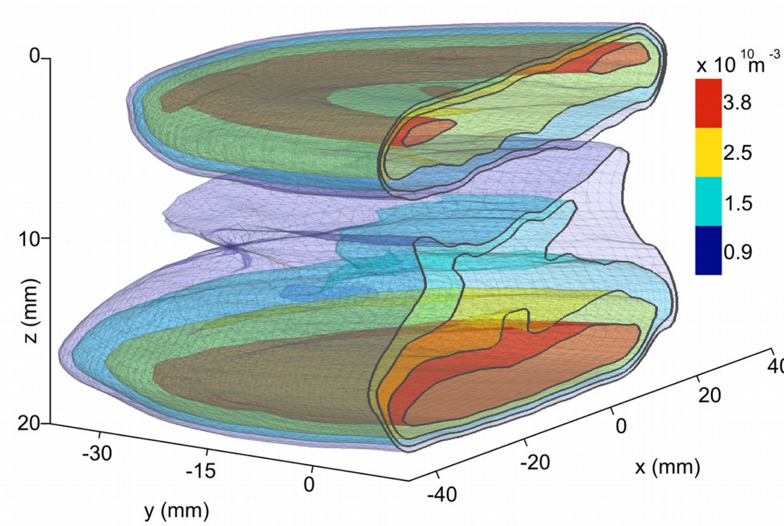

Figure 1 – Dust density distribution in a 3D dust cloud

Dust particle thermal properties in a glass box

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Einstein pointed out that small particle Brownian motion connected the viscous friction to the diffusion constant of the particle through the equation $D = k_B T / m\gamma$, where D is the diffusion constant and $m\gamma$ is the friction constant. Linear response theory states that a small particle's response to a weak, external perturbation is proportional to the perturbation itself. Therefore, the Brownian motion of a particle can also be used to probe the properties of its environment.

In this work, the thermal fluctuation or Brownian motion of dust particles confined in a glass box placed within a GEC rf reference cell and analyzed using the fluctuation–dissipation theorem will be examined. Specifically, recent experiments comparing the velocity distributions and resonance frequencies (as determined from the oscillatory motion) for dust particles comprising small number clusters at different background neutral pressures and rf powers will be discussed.

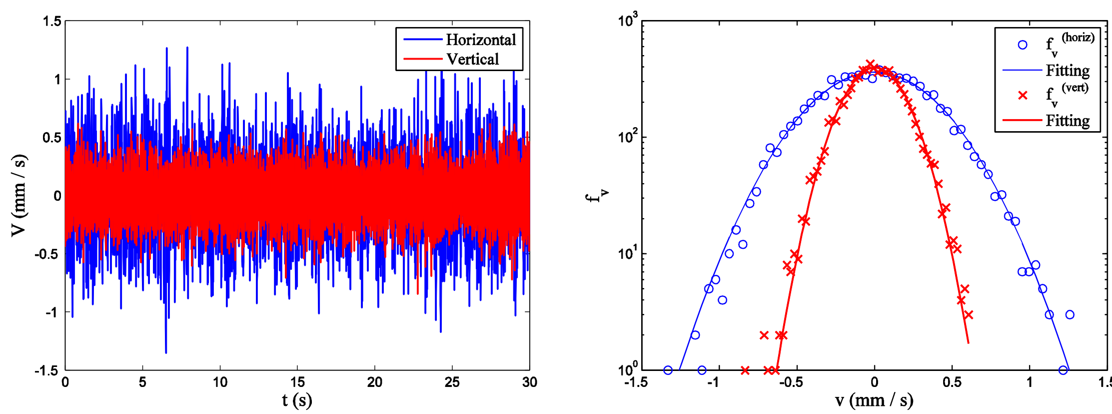

Figure 1 – Dust particle velocity fluctuation of a single particle in a glass box in the GEC cell and the corresponding Gaussian distribution fittings.

Localized viscous heating observed in a two-dimensional strongly coupled dusty plasma

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Viscous heating is the conversion of directed energy to thermal energy in a liquid when there is a shear in the velocity profile. It occurs locally at a rate proportional to the square of the velocity shear. For this reason, one might expect to observe a hot spot in a region of high shear. However, such a hot spot is never seen in an ordinary liquid such as water because thermal conduction carries the generated heat away too rapidly for the temperature profile to change detectably.

We have found that we can observe such a hot spot in a liquid-like strongly coupled dusty plasma. The microspheres were electrically levitated as a single horizontal layer. They were imaged by video microscopy. We drove two counter-propagating flows with a pair of laser beams that were displaced so that the flow had a shear region between them. Using image analysis methods, we measured individual particle velocities. We then calculated the local flow velocity as the first moment of the particle velocities, and the local kinetic temperature as the second moment. The resulting profiles have profound peaks, which we interpret as the signature of localized viscous heating. A calculation of the dimensionless Brinkman, Prandtl and Eckert numbers confirms this interpretation.

Work supported by NSF and NASA.

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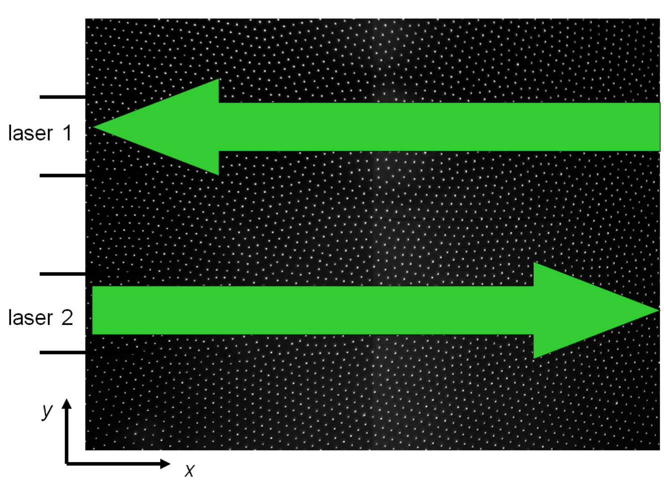

Figure 1 – Experimental configuration.

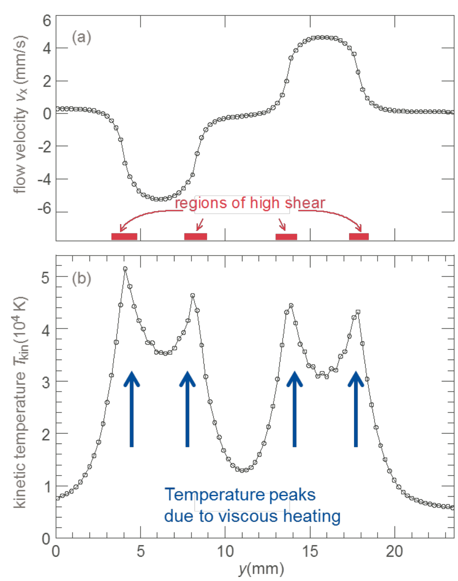

Figure 2 – Profiles of flow velocity (a) and temperature (b).

Phase Transitions in Small and Large Plasma-Dust Systems

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In the presented work we studied a nature of phase transition in quasi-two-dimensional (quasi-2D) dusty plasma clusters and investigated the influence of the quasi-2D cluster size (a number of particles in it) on the features of the phase transition. Experiments and numerical simulation was conducted for the systems consisting of small (~10) and large (~10^3) number of particles. To estimate the phase state of the system with 7, 18 and 100 particles observed in numerical and laboratory experiments, we used the method based on analysis of dynamic entropy. Numerical modeling of small systems was conducted by the Langevin molecular dynamic method with the Langevin force, responsible for the stochastic nature of the motion of particles with a given kinetic temperature. Calculations were performed for two-dimensional systems with the Yukawa potential of interparticle interaction.

Phase state of systems with the number of elements in the order of 10^3, was estimated using the methods of statistical thermodynamics. Here we present new results of an experimental study of the change of translational and orientational order and topological defects, the entropy and the pair interactions at 2D melting of dust cluster in rf discharge plasma. The experimental results have revealed the existence of hexatic phase as well as solid-to-hexatic phase and hexatic-to-liquid transitions. The pair correlation and bond-angular correlation functions, the number of topological defects, the pair potentials and the excess entropy are measured and analyzed. The bond-orientational correlation functions show a clear solid-to-hexatic-to-fluid transition, in perfect agreement with the Berezinskii-Kosterlitz-Thouless (BKT) theory. The spatial distribution of pair interparticle interaction forces was recovered by the original method based on solving the inverse problem using Langevin equations. The measured phase-state points with the theoretical phase diagram of two-dimensional Yukawa system have been obtained.

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Complex Plasma Research on the International Space Station

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Complex (dusty) plasma research under microgravity conditions complements the research in the laboratory. Due to reduction of the main force on microparticles in the lab, gravity, it is possible to form large, homogeneous 3D complex plasma systems in the bulk region of plasmas and to investigate phenomena other than those accessible on earth in detail. Therefore, our team designed and built different setups for microgravity research.
PK-3 Plus, which ended in 2013, already gained a long series of interesting scientific results with about 40 publications. The chambers of this setup has a pair of parallel electrode plates and is therefore able to produce a cylindrical symmetric rf-plasma. Particles of different size and material can be injected into the discharge. The cloud is illuminated by a laser sheet and observed in 2D with cameras with different resolutions and fields of view. Moving this observation system in the direction of sight, tomographic reconstruction of the 3D particle configuration is possible later on.
This configuration is ideal to investigate stable liquid and crystalline systems and give interesting insights into a wide range of phenomena like crystallization, phase separation of binary mixtures, instabilities like heart-beat instability or projectile interaction with a strongly coupled complex plasma cloud.
This contribution will give an overview over a selection of recent results of the very successful project PK-3 Plus.
This work and some of the authors were funded by DLR/BMWi FKZ 50WP0203, 50WM1203 and 50WM1441.

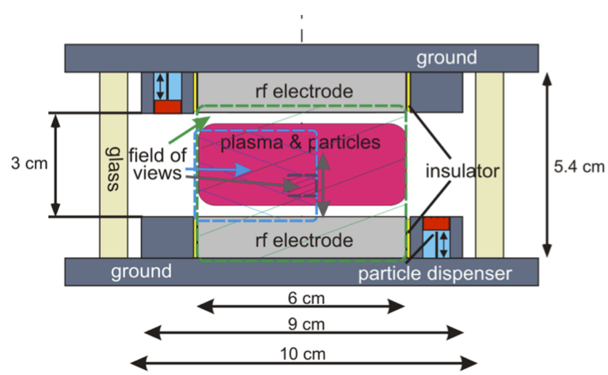

Figure 1: PK-3 Plus is a cylindrical symmetric plasma chamber ideal for stable complex plasma clouds in rf-discharges.

PK-4: Complex Plasmas onboard the ISS – The Next Generation

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PK-4 is an experiment facility for investigating complex (dusty) plasmas in a dc discharge under microgravity conditions onboard the ISS supported by ESA and DLR [1]. It was launched to the ISS in October 2014 by a Progress transporter and installed in the European Columbus laboratory. The commissioning experiments will be conducted in June 2015. The experiments are planned, prepared and analysed by the Research Group Complex Plasmas at DLR, the Joint Institute for High Temperatures (Moscow), the Univ. Giessen and international partner institutes.

In addition, laboratory experiments on ground as well as parabolic flight experiments in reduced gravity have been performed with various PK-4 set-ups since 2002. In the present talk the PK-4 project will be introduced and electrorheological experiments will be discussed as an example [2].

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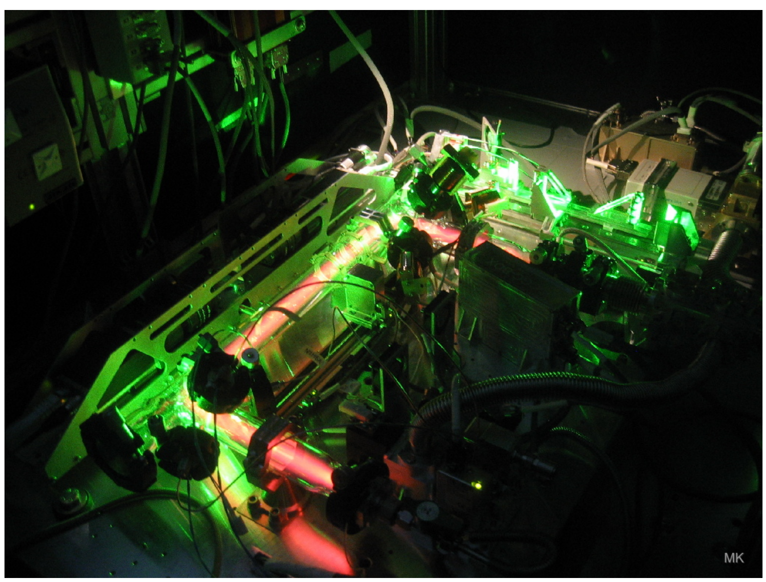

Figure 1 – The PK-4 experiment set-up

PlasmaLab/EKOPlasma – The next laboratory for complex plasma research on the International Space Station

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The PlasmaLab project was started in 2007 as a Russian-German cooperation, with the aim to develop new plasma chambers for future laboratories for the investigation of complex plasmas under microgravity conditions on the International Space Station (ISS). One of the developed chambers – the "Zyflex"-chamber (Fig. 1) – is now being prepared for the EKOPlasma mission, to be launched in 2019/2020, as follow-up lab to continue the ongoing research started with PKE-Nefedov, PK-3 Plus and PK-4.

The "Zyflex"-chamber is a large, cylindrical plasma chamber with parallel, rf-driven electrodes and a flexible inner geometry. It is designed to extend the accessible experimental parameter range, i.e. neutral gas pressure, plasma density and electron temperature, and also to allow an independent control of the plasma parameters, therefore increasing the experimental possibilities and expected knowledge gain significantly. With this system it will be possible to work at very low neutral gas pressures, thus reducing the damping of the particle motion to virtually undamped. A control of the electron temperature can be realized by using electrodes with an additional, dc-biased grid, and the particle motion will be recorded with real-time 3D optical diagnostics. Large, homogeneous 3D particle systems can be created for studies of fundamental phenomena such as phase transitions, dynamics of liquids or phase separation.

Here, we will present the current status of the project, the technological advancements, and the scientific outlook as projected from experiments on ground and in microgravity conditions during parabolic flight campaigns.

This work and some of the authors are funded by DLR/BMWi (FKZ 50WM1441).

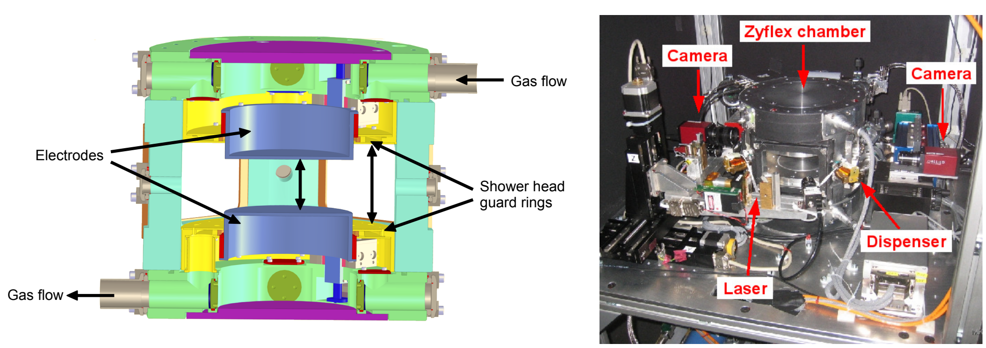

Figure 1: Left: Schematic of the Zyflex plasma chamber. Electrodes (blue) and guard rings (yellow) can be moved independently. Right: Parabolic flight setup of the Zyflex chamber.

A Dodecahedron Plasma Chamber for Future Complex Plasmas Research in Microgravity Environments

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Complex Plasmas have been studied since 1994 extensively in earthbound laboratories as well as in laboratories operated under microgravity conditions. The strong influence of gravity on the micro particle component of a complex plasma leads to sedimentation effects that often dominate the observed complex plasma properties and it's dynamics. These effects are particle size dependent and can be reduced by restricting the research to particles of low mass and thus small size or by avoiding the gravitational influence by performing experiments in a free fall situation. In earth bound experiments usually only dust clouds with "small" vertical extend can be realized, which means systems from a single up to a couple of hundred layers of dust. Like gravity also the kind of the operated discharge, like the often used parallel plate or a dc-discharges, usually introduces an anisotropy in the system. Finding ways to study an isotropic, homogeneous complex plasma with substantial extend is therefore challenging.
As part of the development of next generation complex plasma microgravity experiments for the International Space Station (ISS), some of the authors designed and build a spherical like discharge chamber. The goal of the development is to allow performing microgravity experiments of complex plasma in a quasi (time-averaged), isotropic plasma background. The device, which is based on a dodecahedron symmetry, is highly experimental and not much investigated yet, but it has a high potential for user defined complex plasma manipulations. We will present the design of this device as well as report on recently performed related experiments using the dodecahedron chamber and first approaches on a detailed characterization of the discharge.

Part of this work and some of the authors were supported by DLR by funding the project "Development of Plasma Chambers for the Investigation of Complex Plasmas under Microgravity Conditions aboard the ISS-PlasmaLab" under contract DLR/BMWi FKZ 50WM0700.

NASA Current and Planned ISS Research Activities on the Physics of Dusty Plasmas*

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NASA has provided some support to U.S. investigators over the past decade to collaborate with European scientists on research in dusty plasma planned for the International Space Station (ISS) using European facilities.

Following the Oct 2014 launch of ESA's Plasma Kristall 4 (PK4) experiment, ESA expressed an interest to accommodate additional U.S. researchers on the PK4 scientific team. After consulting with ESA and their PK4 partners, DLR, and Roscosmos, NASA has decided to release a NASA Research Announcement (NRA) to select additional U.S. researchers for PK4. A description and timeline for the planned NRA will be discussed.

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Poster Abstracts

Stable and metastable states of small elliptical dust clusters

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We study two-dimensional elliptical dust clusters by confining monodisperse spherical dust particles in a biharmonic potential energy well. In the strong-coupling regime the cluster arrangement depends on the number of dust particles n, the potential well anisotropy, and the Debye shielding parameter. For small values of n the arrangement is a straight line. As n increases the cluster undergoes a zigzag transition (the finite analog of a 2-chain) and then undergoes further transitions to elliptical arrangements with interior particles. For n greater than some critical value both stable and metastable particle arrangements should exist.

We have experimentally characterized the arrangement states and rearrangement dynamics of elliptical dust clusters with up to 32 particles. New arrangement states are created by applying a step increase to the plasma density, briefly melting the cluster. The cluster then rapidly quenches to either: a stable arrangement, a metastable arrangement, or an unstable arrangement. For $n < 15$, we always observe the same final arrangement. However, for $n \geq 15$ both stable and metastable equilibria are observed. We suggest that jammed interior particles prevent rearrangement into the lowest energy state.

The relaxation dynamics of unstable arrangements is also investigated. We find that unstable arrangements relax through a series of multi-particle shifts and rotations (Fig. 1) to a final equilibrium configuration (Fig. 2). The final state may be stable or metastable.

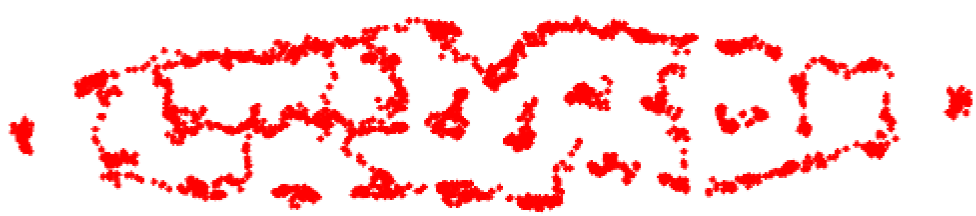

Figure 1 – Particle trajectories in the x-y plane showing the rearrangement of an unstable elliptical cluster of $n = 32$ dust particles.

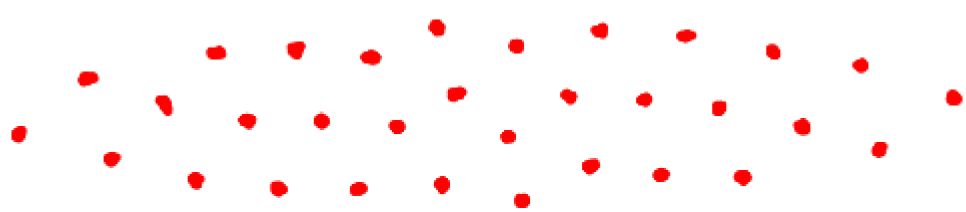

Figure 2 – Final equilibrium configuration of the strongly-coupled 2d cluster showing thermal motions for 50 frames.

Effect of strong coupling between the particles on the Mach cone structures in a complex plasma

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We address the effect of strong coupling induced modification of the fluid compressibility on the Mach cones in a complex plasma using a Generalized-Hydrodynamic (GH) model [1]. The expressions for the perturbed dust density and the velocity vector profile due to the motion of an energetic charged test particle are obtained and then numerically evaluated for a wide range of Mach numbers, dust-dust coupling strengths and the dust neutral collision frequencies. Strong coupling induced compressibility is seen to play an important role in the evolution of the Mach cones. With the increase of fluid compressibility (hence the coupling strength), the peak amplitude of the normalized perturbed dust density first increases and then decreases monotonically after reaching its maximum value. It is also noticed that the opening angle of the cone structure decreases with the increase of the compressibility of the medium and the arm of the Mach cone breaks up into small structures in the velocity vector profile when the coupling between the dust particles increases. The physical significance of these observed changes in the wake characteristics and their possible practical implications will be discussed.

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Steady state flow patterns and corresponding transport in gravitationally equilibrated Dusty (complex) plasma under an external extreme non-equilibrium conditions

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Strongly coupled plasmas, characterized by very high potential energy over kinetic energy per particle (Γ) and screening parameters (κ), are ubiquitous in nature, for example, in dusty (complex) plasma , astrophysical plasmas, charged colloidal suspension and ultra-cold plasma to mention a few. Using 2D Molecular Dynamics simulation, the equilibrium and dynamical properties of a gravitationally equilibrated dusty (complex) plasma (also known as strongly coupled Yukawa (SYC) liquid) have been investigated earlier [1,2] by the authors. We had observed that due to asymmetry introduced in one direction by gravity, several interesting features arise. In the present work, we study formation of transient and steady state flow patterns and corresponding transport in such gravitationally equilibrated systems when subjected to an external extreme non-equilibrium conditions. Results from several, very long time Molecular Dynamics simulations amounting to a total of over 100,000 ω_{pd}^{-1} for various values of (Γ, κ) will be presented. Generation of these flow patterns and their effect in turn on strongly coupled plasma will be addressed. Some of these results are obtained perhaps for the very first time in this context

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Electrodynamical properties of the dense semmiclassical plasmas

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In this work the dielectric function of the dense semiclassical collisionless plasmas was investigated on the basis of the interaction potential which takes into account the effects of diffraction in a wide range of temperatures and densities [1]. The dielectric function was investigated analytically and numerically in approximation of the high frequencies. The obtained results are in a good agreement with each other. Also dielectric function of the dense semiclassical plasmas was investigated taking into account electrons and atoms collisions on the basis of the interaction potential including the effects of diffraction and screening [1].

In first part of this work dielectric function of the dense semiclassical plasma was obtained on the basis of the following potential:

$$\Phi_{\alpha\beta}(r) = \frac{Z_\alpha Z_\beta e^2}{r}\left(1 - th(\sqrt{2}\frac{\lambda_{\alpha\beta}^2}{a^2+br^2})e^{-th(\sqrt{2}\frac{\lambda_{\alpha\beta}^2}{a^2+br^2})}\right)\left(1-e^{-r/\lambda_{\alpha\beta}}\right), \quad (1)$$

$$b = 0.033,$$

where α and β are the sorts of charged particles (electron or ion), a is the average distance between particles, $\lambda_{\alpha\beta}$ is the de Broglie wavelength of the particles. This micropotential takes into account the quantum diffraction effects at small distances in a wide range of temperatures and densities.

As we noted the dielectric function of the dense semiclassical plasma was also investigated with taken into account electrons and atoms collisions on the basis of the effective interaction potential [2].

In the framework of this pseudopotential model of the particle interaction the phase shifts were calculated. Phase shifts enable us to calculate the transport scattering cross section Q_T^{ea}. The collision frequency of electron with atoms ω_{ea} can be calculated on the basis of the obtained transport cross section. After that the dielectric function was calculated using the generalized Drude - Lorentz equation.

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Rayleigh-Taylor Instability in a Gravitating Viscoelastic Quantum Fluid

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The gravity induced Rayleigh-Taylor (R-T) instability in a viscoelastic quantum fluid is investigated using the generalized hydrodynamic (GH) model. The internal waves and dispersion relation modified due to the presence of quantum corrections and viscoelastic effects have been obtained. The explicit expression of R-T instability criterion is derived which is influenced by shear velocity and quantum corrections. Numerical calculations are performed in astrophysical and experimental relevance and it is examined that both the shear and quantum effects suppresses the growth rate of R-T instability. The results of the present work are applied to understand the R-T instability suppression in Inertial Confinement Fusion (ICF) device when quantum corrections in low temperature and high dense quantum plasma exists.

Obliquely propagating unstable DIA solitary waves in magnetized dusty plasmas with bi-maxwellian electrons

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The nonlinear propagation characteristics of dust-ion-acoustic (DIA) waves in an obliquely propagating magnetized dusty plasma, consisting of bi-maxwellian electrons (namely lower and higher temperature maxwellian electrons), negatively charged immobile dust grains, and inertial ions are rigorously investigated by deriving the Zakharov-Kuznetsov equation. Later, the multidimensional instability of the DIA solitary waves (DIASWs) is analyzed using the small-*k* perturbation technique. It is investigated that the nature of the DIASWs, the instability criterion, and the growth rate of the perturbation mode are significantly modified by the external magnetic field and the propagation directions of both the nonlinear waves and their perturbation modes. The implications of the results obtained from this investigation in space and laboratory dusty plasmas are briefly indicated.

Waves in a quasi-2D strongly coupled paramagnetic dusty plasma

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Superparamagnetic dust grains suspended in a plasma that is immersed in a magnetic field **B** acquire both an electric charge and a magnetic dipole moment. The grains thus interact via combined Yukawa and magnetic dipole-dipole potentials. The Yukawa potential is isotropic and repulsive, while the magnetic dipole potential can be repulsive or attractive depending on the orientations of the magnetic moments. Here, we consider a model dusty plasma comprising a 2D layer of charged superparamagnetic grains that is confined by an external force perpendicular to the layer. The magnetic dipole moments of the grains all lie along **B**, and when **B** is tilted with respect to the layer, the interaction between the grains becomes anisotropic. The interaction remains repulsive in the layer between tilt angles 90^{o} and a critical 54.74^{o}. We confine our analysis to this domain, which allows for a stable equilibrium.

We theoretically investigate the dispersion of waves in the strongly coupled liquid phase of this system. The approach uses the Quasi-Localized Charge Approximation (QLCA) reformulated to treat dipole interactions, combined with Molecular Dynamics (MD) simulations of the system. The MD simulations generate fluctuation spectra and provide pair correlation functions which are needed as input for the QLCA calculations. Our previous work [Hartmann, *et al*., *Phys*. *Rev*. *E* **89**, 043102 (2014)] investigated the dispersion of in-plane polarized longitudinal and transverse waves. In the present work we study a more realistic model, where the grains are confined by an external potential and can undergo small oscillations perpendicular to the layer. We now find an out-of-plane transverse wave in addition to the previously described in-plane modes. The QLCA results show reasonably good agreement with the dispersion relations obtained from the fluctuation spectra generated by the MD simulations. The wave dispersion relations depend on the direction of propagation in the layer, the relative strengths of the magnetic dipole and Yukawa interactions, and the strength of the confining force. Possible experimental parameters for observing the waves are discussed.

To understand the underlying structure in liquid phase we have also investigated what type of lattice structure the system would adopt in the solid phase, as the tilt angle moves from the perpendicular to the critical angle. We varied the aspect ratio, the rhombic angle and the orientation of the crystal axes to find the lattice structure that corresponds to the minimum interaction energy.

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On dust wave instabilities in collisional magnetized plasmas

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The physics of dusty plasmas immersed in large magnetic fields is an area of current interest. The presence of a large magnetic field is expected to affect the excitation of dust acoustic (or dust density) waves. These waves have been observed in laboratory dusty plasmas with no or weak magnetic fields and may be excited by the flow of ions relative to dust. We consider a collisional dusty magnetized plasma where the ions and electrons are magnetized, and the dust is unmagnetized. In this regime, a variety of instabilities that may excite dust waves have been considered theoretically in the literature. These include, for example, instabilities driven by ions streaming either along or across the magnetic field [e.g., 1-2] and instabilities driven by diamagnetic drifts [e.g., 3]. In this poster, we categorize several of these instabilities according to wavelength and plasma parameter regimes, and discuss possible applications to dusty plasma experiments with large magnetic fields. We also point out directions for future theoretical work.

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Trajectory frequency analysis of a simulated, magnetized dusty plasma in a radially-increasing electric field

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Using the DEMON (Dynamic Exploration of Microparticle clouds Optimized Numerically) code [1], a molecular dynamics simulation of dusty plasma was performed. In this simulation, an initial grid of particles is subjected to a uniform magnetic field and a perpendicular electric field whose magnitude increases radially. To analyze the output of the simulation, a single particle was chosen and a Fourier analysis of its trajectory is performed, revealing two primary frequencies that contain information about the E x B drift motion and the gyromotion of the particle. If the electric field only increases linearly, the difference between the two frequencies is the cyclotron frequency, which agrees with analytical results. If the electric field model is modified by an exponential decay term, then the frequencies depend on the particle's initial conditions. These effects are shown to break down when the interparticle spacing is less than 2 mm and inter-particle collisions dominate the motion. These results will help to understand the electric field configuration of the MDPX device as well as highlight interesting parameters for further study.

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Probe-induced voids at high magnetic field

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The presence of voids (dust-free regions) in dusty plasmas has been considered for some time. Early studies include the observation of the "great void mode" in a laboratory experiment with growing dust grains[1] and self-generated voids in microgravity experiments generated by a balance of an outward ion drag force and an inward electrostatic force acting upon the dust grains[2]. In addition to self-generated void structures, there have also been studies of void regions formed around biased probes in dusty plasmas[3,4].

In the presence of a magnetic field, it is anticipated that the ion drag force will become modified as the transport of ions in the plasma becomes constrained to magnetic field lines. As a result, the balance between the electrostatic and ion drag forces may be modified, leading to changes in void formation. This presentation will discuss an experimental study of the modification of the void region around a negatively biased probe in a dusty plasma at high magnetic field. The effects of an external magnetic field on void size and eccentricity are investigated.

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A comparative study of dust behavior in plasmas modeled by local-field and local-mean-energy approximations

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Numerical models of plasmas require rate coefficients to determine the amount of ionization in the plasma. The two common methods of determining rate coefficients are the local-field approximation and the local-mean-energy approximation. The local-field approximation relates the ionization to the electric field and does not require knowledge of the electron energy. In contrast, the local-mean-energy approximation relates the ionization to the mean energy of the electrons and requires solving the electron energy equation. Previous studies showed a significant difference between the two models for the plasma but did not include in dust.

In this study, a low pressure argon radio-frequency plasma reactor is modeled numerically using each of the two ionization models, then a small number of micron-sized dust grains are added to the plasma. Because of a low number of dust grains, the effect of the dust on the plasma is neglected; therefore, the back-way coupling effects of dust on plasma are neglected. The plasma reactor is a cylinder with a height of 2cm and a radius of 1cm. The lower edge is an electrode that is powered with an RF voltage, the upper edge is a grounded electrode and the outer wall is a dielectric. The plasma model is axisymmetric; however, the dust grains are traced in the domain through three-dimensional equations. The numerical method used for the plasma is a semi-implicit finite volume approach that uses first-order upwind for the convective fluxes and central difference for the diffusive fluxes. The mesh is non-uniform with grid points clustered in the sheath regions. Once the plasma has reached quasi-steady state, it is averaged over one RF cycle and the RF-averaged plasma is used as the input to the dust code. Silica dust grains are released from the top electrode and tracked in a Lagrangian framework. The grain charge is determined by OML theory and each grain is subject to gravity, the forces due to the plasma (electric, neutral drag and ion drag) and the interaction force due to the other grains. Since the plasma is assumed to be unaffected by the dust, the ion wake or charge focusing effect that is due to the grain effect on the plasma is modeled in the interaction force. The differences in the plasma profiles for the two different ionization models are examined and the effect of those differences on the dust crystal is investigated.

Charge variations of a dust grain levitating above the lunar surface during a pass of the Moon around the Earth

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A presence of dust levitating above the charged lunar surface has been observed in the terminator area by several spacecraft and by astronauts during Apollo missions and this effect was attributed to electrostatic forces. These grains as well as the lunar surface are charged by different processes as photoemission, collection of primary particles, and secondary electron emission. The parameters of a plasma environment strongly influence their charging because the energy of electrons and ions is significantly higher in the magnetosphere than in the solar wind, while the particle density is lower in the magnetosphere. Thus dominant charging currents depend on a lunar position relative to the Earth. We present model calculations of temporal variations of the potentials of dust grains levitating above the lunar surface as well as the surface itself. As input data for calculations, we use the ARTEMIS observations from a crossing of the Earth magnetotail. In the study, we are focused on the terminator area where the photoelectron current is influenced by the solar zenith angle. We show effects of dust grain size and a lunar position relative to the Earth on potentials of the dust grain and surface charging. The lunar surface and levitating dust can be charged to different potentials under the same plasma conditions. We discuss a possibility of the dust grain levitation in different regions crossed by the Moon and show an important role of charging history. Figure 1 demonstrates the discussed effects.

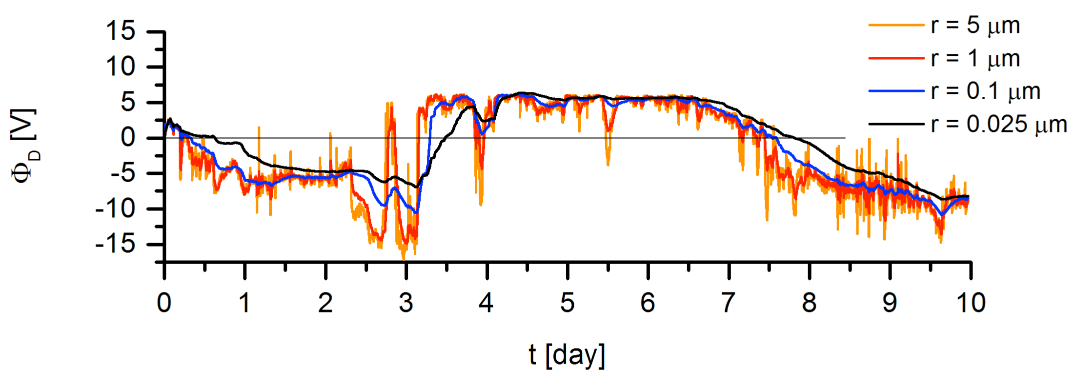

Figure 1 – The influence of the dust grain size on the surface potential changes through a Moon crossing of various regions.

Secondary emission from clusters composed of spherical grains

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Dust grains or their clusters can be frequently found in many space environments—interstellar clouds, atmospheres of planets, tails of comets or planetary rings are only typical examples. These grains can be exposed to electrons of various energies and they acquire positive and negative charge during this interaction. The impinging electrons lose their energy and they can be scattered, especially in the case of submicron grains. Besides scattering of primary electrons, secondary electrons can be released when the incident electron energy exceeds the grain work function.

In the paper, we present systematic study of a well-defined system—clusters consisting of several small spherical grains. These clusters can be considered as examples of real irregularly shaped space grains. Our experimental set-up allows us to trap a single dust grain or cluster of grains in the electrodynamic quadrupole and to expose it by the electron/ion beam with the energy up to 10 keV. Using the precise measurements of a stepwise change of charge-to-mass ratio induced by an elementary charge, we can determine the mass and specific capacitance of the object. The variations of the charge acquired by an investigated object are compared with a prediction of the secondary emission model of dust grain charging. For two spheres, the model predicts the decrease of the first maximum of the equilibrium potential by about 3 %, for six spheres in the cluster, this decrease is around 8 %. The surface potential is influenced by a number of grains and their geometry in a particular cluster (Figure 1).

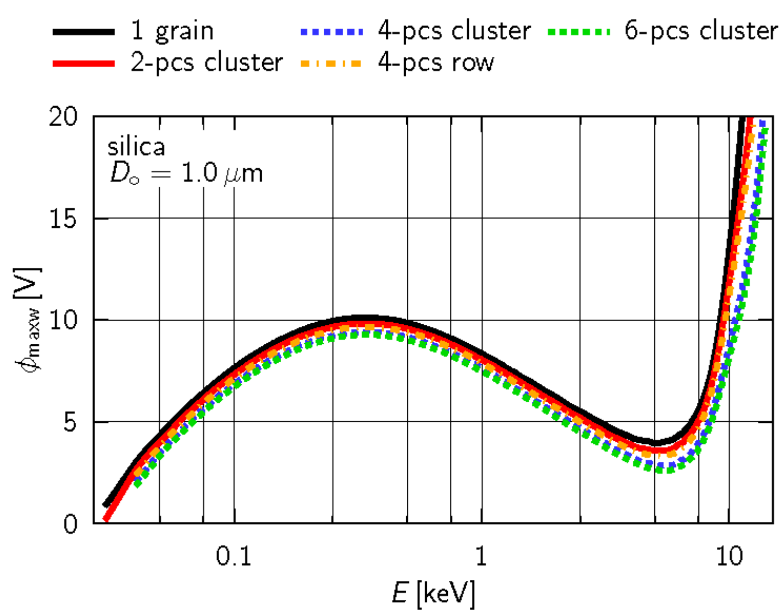

Figure 1 – The surface potential profiles for different numbers of grains in the cluster and grain configurations.

Transient states of charging dusts accordance with dust quantity in large RF Helium plasma

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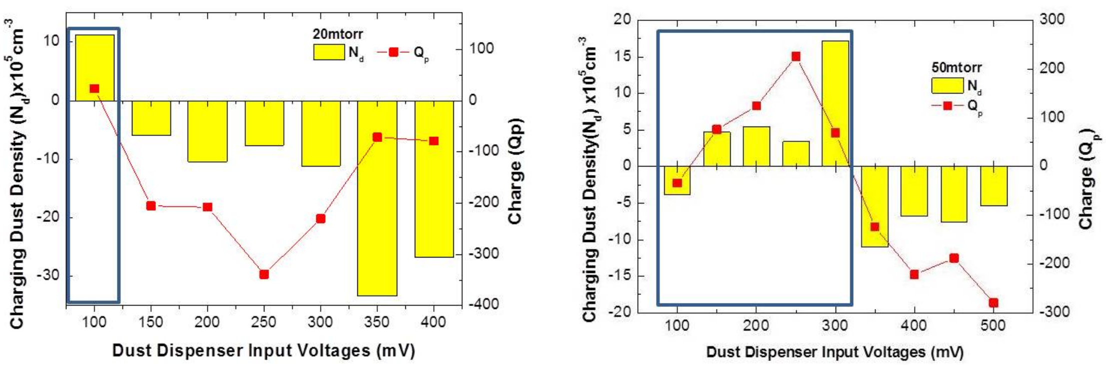
A large rectangular RF plasma device (44 x 50 x 120 cm^3) have been developed, called Transport and Removal experiments of Dust (TReD) device. Helium plasma is generated at the upper part of the rectangular vacuum chamber by inductive coupled method using four parallel antennas with RF power. Tungsten dusts with average size of 1.89 micrometer are injected into the plasma by a dust dispenser, and the dusts are negatively charged by electron attachment, and they are levitated by sheath potential. In order to observe dusty helium plasma, a planar electric probe with 13.56MHz compensation circuit is installed at the center of the device.
Dusty plasma is investigated with increasing dust quantity. Charging dusts states and charge on dust are calculated by comparing pure helium plasma to dusty helium plasma. As increasing dusts quantity in plasma, dusts were positively charged by their strongly negatively charging potentials before the dusts are normally negatively charged. And these effects are related to dusts quantity in plasma, and the charging states to be affected on background plasma. Low dusts quantity in plasma, dusts are positively charged by ion attachment and/or scattering to dusts. High dusts quantity in plasma, dusts are normally negatively charged and ions are trapped.



(a) (b)

Figure 1 – Calculation of charging dusts density and their charge. Blue square line is transient region that dusts are positively charged. (a) shows normally negatively charged dusts (high dusts quantity in plasma). (b) shows positively charged dusts (low dust quantity in plasma).

Photoemission and work function of the lunar dust simulant

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The lunar surface (covered by a layer of granular material) is exposed to UV and soft X-ray radiations and time-varying fluxes of electrons and ions from the ambient plasma. A balance of several charging processes on both sunlit and night sides has not been completely understood so far. On the sunlit side, the work function of the grain plays a key role for the energy of the produced photoelectrons and, as a consequence, for the grain dynamics. We present a laboratory estimation of the work function of a single micron-sized lunar simulant grain caught in the electrodynamic trap. The grain's specific charge is evaluated by an analysis of its motion within the trap. In the measurements, we observe a time evolution of the charge-to-mass ratio of the grain irradiated by UV (He I 21.2 eV and He II 40.8 eV) photons (Figure 1). A comparison of the photoelectron currents caused by different emission lines of known energies (in the UV discharge) allows us to establish the work function of a trapped grain. Various lunar soil simulants including glass are compared — the first results indicate that the work function of such grains is about 5 eV.

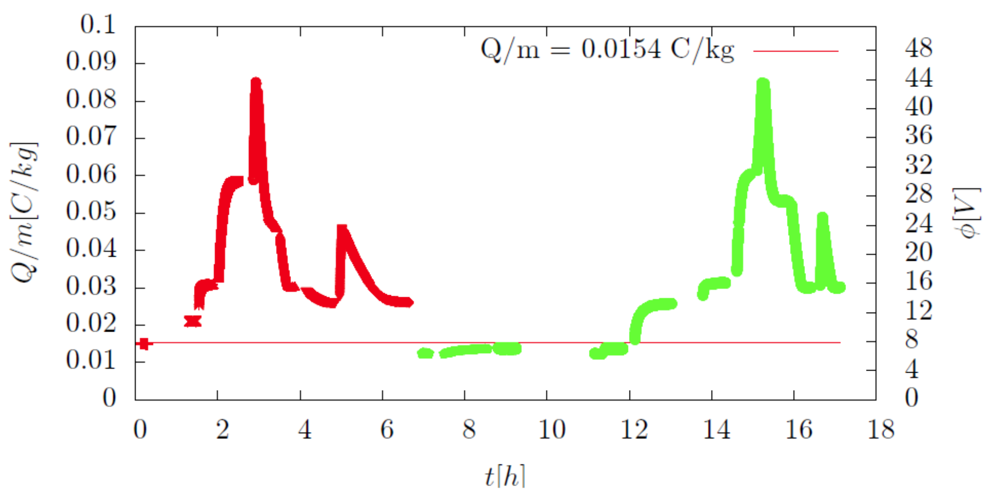

Figure 1 – Temporal changes of the dust charge — in the course of the experiment, the UV radiation was switched on/off and the ratio of emission lines was varied.

SMALL DISPERSED PARTICLES SYNTHESIS IN THE PLASMA OF ARC AND RADIO-FREQUENCY DISCHARGES

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In the plasma of combined discharge the small dispersed graphite particles were obtained. The synthesis process of small dispersed particles in the plasma of combined discharge represents two parallel processes which are synthesis process of polydispersive graphite particles using arc discharge graphite electrode evaporation and extraction of small dispersed graphite particles using separation method of polydispersive dust structure in the plasma of radio-frequency (RF) discharge. The arc-discharge evaporation method is well known method for obtaining of different particles [1,2], whereas separation method in plasma of radio-frequency is a new method of obtaining small dispersive particles [3-5].

Obtained samples of polydispersive graphite microparticles have diameter in range of 1-100 μm. The size and chemical composition of samples were examined using a scanning electron microscope Quanta 3D 200i (SEM, FEI, USA). The average size of graphite particles after separation in RF discharge was equal to 5 μm.

The advantage of proposed method in the plasma of combined discharge is the simplicity of technology for obtaining small dispersed particles without limitations on the choice of materials.

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Expansion of Yukawa dust clouds

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We have studied the free expansion of charged dust clouds composed of 1 micron diameter glass spheres suspended in a DC glow discharge. The discharge was produced in a one cubic meter stainless steel vacuum chamber (60 cm diameter by 90 cm length), between a positively biased (250-300 V), 3.2 cm diameter anode located on the axis of the device, and the grounded chamber walls (see Fig. 1). The working gas was argon at neutral pressures of 100-200 mtorr (13-26 Pa). A magnetic field of 3 mT was applied along the axis of the anode by a set of six external field coils. Dust was incorporated into the plasma from a tray located below the anode. A secondary dust suspension of roughly 1 cm size was formed using a biased conical mesh electrode located 20 cm from the anode. Expansion of this secondary dust suspension was initiated by simultaneously switching off (electrically floating) the bias voltages to the anode and the mesh electrode. The evolution of the expanding dust cloud was monitored using a Photron CMOS video camera operating at 2000 fps. The dust particles were illuminated by a vertical sheet of 532 nm laser light.

The dust cloud expansion occurs under conditions of relatively high neutral pressure in the afterglow plasma in which the electron temperature decreases (causing the dust charge to decrease) while the plasma density decays more slowly. Under these conditions, plasma screening of the repulsive interparticle interaction persists in the afterglow. The expansion of the dust cloud is characterized as a fission process in which a portion of the cloud blows off very quickly. The evolution of dust clouds formed at neutral pressures of 100, 150 and 200 mtorr was studied. The observations will be discussed in relation to molecular dynamics simulations that have been performed.[1, 2]

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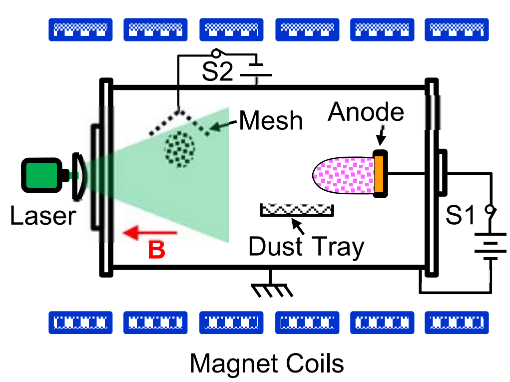

Figure 1 – Schematic of the experimental device – a DC glow discharge dusty plasma.

The Dust Particle Evolution in Divertor Plasma

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Investigation of the dust effect in fusion devices has become an important research area in the implementation of large-scale fusion plasma experiments. Determination of the mechanism of dust production, study of dust-plasma interaction, interaction of dust with surface of fusion reactor, dust transport, assessment of dust influence on the characteristics of the reactor and safety of fusion devices - all these issues occupy an important place in the study of modern problems of controlled thermonuclear fusion [1-3].
In this work, the influence of magnetic field on the charge of dust particles, dust dynamics and lifetime in the divertor plasma is studied. The magnetic field can have a significant effect on charging of dust particles in the divertor plasma. Dust transport and evaporation of dust particles determine composition of the edge plasma, and, hence, its transport properties.
In [4, 5] the charge of dust particles taking into account the magnetic field was calculated in the approximation of the orbit motion limited theory (OML). In this work, the charge of dust particles was determined by particle in cell method, taking into account collisions of ions with atoms, using the Monte Carlo method. The charges of dust particles of a radius of 0.5; 1; 2μm at values of the magnetic field in the range of $B = 10 \div 10^6$ Gs were calculated. As a result of these calculations the dependence of the dust charge and fluxes of plasma particles on its surface were obtained. These data are used to model dynamics and lifetime of dust particles.
The evolution of dust formed on the surface of the divertor walls was studied for typical parameters of the plasma in the divertor [6]. For this purpose, the equations of motion in the given electric and magnetic fields and the equations of mass and energy balance were solved. The dependence of the temperature and radius of dust particles on time was determined. Based on these calculations, we obtained estimates of lifetime and paths of dust particles in the edge divertor plasma.

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Experiments on sputtering of dust grains

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Dust grains in the laboratory as well as space plasmas either float within plasma or lie on nearby surface (e.g., surfaces of asteroids, comets, moons in space). In both cases, they are exposed to plasma particles and UV radiation. Therefore, they get charged and can also be sputtered. Since the floating grain can spin along an arbitrary axis, it is sputtered uniformly, while the lying one is steady and exposed from a given direction only. This process leads to non-regular grain sputtering and to changes of a grain shape. We have investigated sputtering of spherical glass, carbon, and gold grains with diameters in the range of microns.
The floating grains are studied in the electrodynamic trap and exposed to ≈ 3 keV Ar^+ (the impact energy is reduced by the grain charge). The grain mass is measured after each sputtering session and the sputtering yield is calculated from its temporal variations. On the other hand, the lying grains are investigated using the SEM+FIB facility (scanning electron microscope equipped with the focused ion beam) where they are sputtered by 30 keV Ga^+. Sequential SEM images of the grains are recorded and the sputtering yield is estimated from temporal changes of the grain shape and size (Figure 1).
Both approaches are compared with a simple numerical model in order to better understand the physical background of sputtering of small objects. Finally, we discuss the different behaviors of compound and elementary material and draw some conclusions regarding space dust.

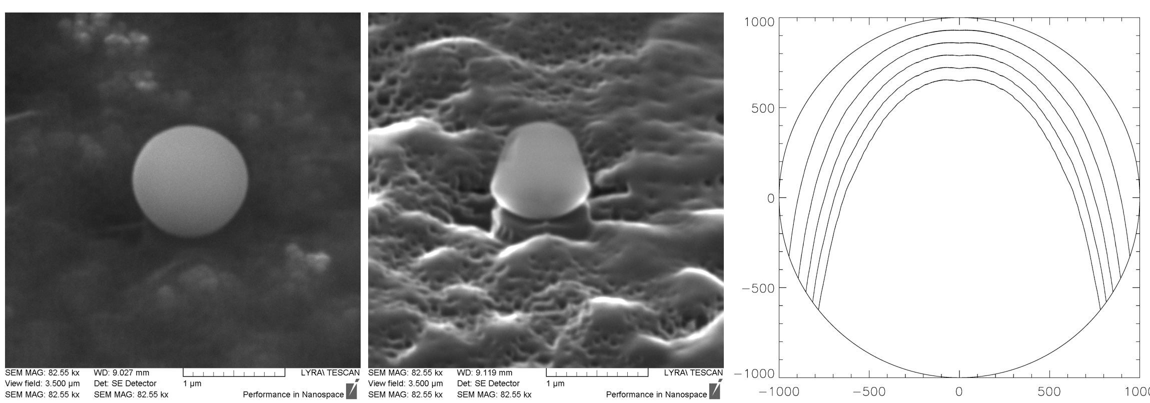

Figure 1 – SEM images of original (left) versus partially sputtered (middle) silica sphere and the result of the sputtering model (right).

A sensor deployment algorithm for underwater sensor networks inspired by dusty plasma crystallization

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Underwater sensor networks (UWSNs) have emerged as an enabling technology for underwater monitoring and exploration applications and attract a growing interest recently. Potential applications of UWSNs include environment monitoring, resource exploration, disaster prevention, pollution detection, and military surveillance etc.. UWSNs consist of sensors that are deployed to perform collaborative monitoring tasks over a given body of water. Similar to terrestrial sensor networks, it is essential to provide communication coverage in such a way that the whole monitoring area is covered by the sensor nodes in UWSN. However, most of the available deployment strategies for terrestrial sensor networks cannot be directly applied to UWSN due to its unique 3-D characteristics introducing new challenges in terms of connectivity, coverage and mobility.

According to the application requirements, different kinds of sensor nodes can be deployed in UWSNs, that is, two-dimensional surface sinks, bottom nodes, and three-dimensional underwater nodes, automatic mobile nodes. In this paper, a sensor deployment strategy inspired by dusty plasma is proposed. Each sensor node is seen as a dust particle and through crystallization to find the optimal position in 2-D surface sinks and 3-D underwater nodes. Unlike terrestrial wireless sensor networks, underwater sensor networks cannot use electromagnetic waves due to the quick absorption in water. Acoustic waves are usually considered a practical solution for UWSNs so first the combination of acoustic communications and the dusty plasma is discussed. Unlike the ideal 2-D or 3-D deployment, water current must be considered in UWSNs, in the proposed approach, the force exert by water is added to the Yukawa potential equation of dust particle. Different water current models are attempted and analysis of the effect of water current is provided. Simulation results showed that the proposed algorithm is an effective UWSN deployment strategy and can also be applied in aerial wireless network such as Project Loon.

Parameter Study in Mobile Sensor Network Deployment Algorithm Based on Dusty Plasma Simulation

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Wireless sensor networks (WSN) is a technology with a wide range application in both civilian and military areas due to its low power consumption, low cost, distributed and self-organization property. WSN typically consists of a large number of sensors which can be used for target tracking, environment monitoring, and under water detecting, etc. Mobile sensor deployment is a key issue in WSN application. Recently, Wen et al. presented a virtual force algorithm based on the physical law in the dusty plasma system, and introduced a performance metric, based on the pair-correlation function, to evaluate the deployment results[1].

In this paper, we focus on the parameter study of this virtual force-based sensor deployment application based on dusty plasma simulation. We test the effects of different levels of adapted neighbors which can exert the virtual force, and discuss the shielding rule evaluation. Furthermore, we investigate how the different sets of parameters affect simulations results such as time taken to reach convergence, network overhead comparison. Simulation results show that the proposed approach exhibits a good performance in coverage rate, convergence speed and uniformity in configuration.

Structural and transport properties of the complex plasmas in the combined gas discharge

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Gas discharge of combined RF and DC is used in many technological fields, particular in the processing, cleaning and sterilizing the surfaces of various materials [1-5]. This is due to the fact that the imposition of an additional electrostatic field on the RF discharge extends the capabilities of control the parameters of the buffer plasma [6].

In this paper the results of experimental studies of the properties of complex plasma in the high-frequency discharge with additional electrostatic field are presented. The following most important parameters such as the spatial distribution of the emission intensity, electrical characteristics and kinetic properties were determined. The structural and transport properties of complex plasmas in the combined discharge are investigated, in the result the explanation of the mechanism of chain formation of dust structures is given.

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Resolution of Forces in Poloidal Rotations in Dusty Plasmas

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Dusty plasmas are a four-component plasma system consisting of electrons, ions, neutral atoms, and charged nanometer- to micron-sized micro particles (i.e., ``dust"). A prominent feature of dusty plasma experiments is the ability of the charged dust grains to form a variety of ordered structures - from two-dimensional plasma crystals to three-dimensional Coulomb clusters. It is also well known that dusty plasmas have the ability to form a variety of flowing and vortex-like structures.

In recent experiments at the Institute for Plasma Research (IPR) in India, observations of toroidally shaped dust rings, with strong poloidal rotation were reported In a collaboration with the IPR group, experiments at Auburn have reproduced this phenomenon. These experiments are performed using the large, octagonal vacuum chamber designed for the Magnetized Dusty Plasma Experiment. These studies use a dc discharge plasma at high pressure (p > 200 mTorr), over a broad range of discharge currents (up to 10 mA), to produce toroidal, semi-toroidal, disc-shaped, or ring-like dust structures. Frequently, these structures exhibit a steady-state poloidal flow. In these studies, particle image velocimetry (PIV) is used to characterize the transport of the charged microparticles. Our experiment duplicated these results using 0.5-micron silica spheres in an Argon plasma using an anode and cathode biased to 260 V relative to each other. Results will be presented on the extension of the velocity vector fields to acceleration vector fields and the resolution of the total force into gravitational, Coulomb, neutral drag, and ion dragforce components.

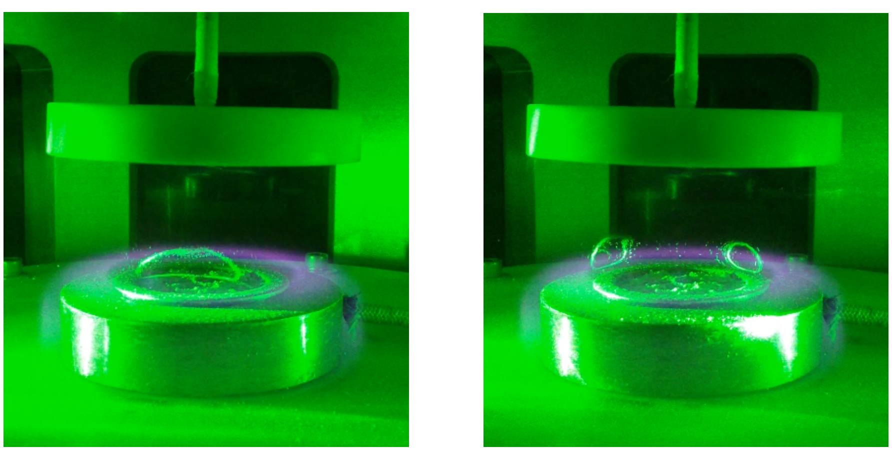

Figure 1 – Result of scanning a laser sheet through a toroidal dust cloud. In this image, particles of size x are shown. The laser sheet is shown at two locations (a) near the center of the cloud [RIGHT] and (b) near the front of the cloud [LEFT].

Rotational dust clusters in complex (dusty) plasmas

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Spontaneous rotation of small dust clusters have been observed experimentally within an indium-tin-oxide (ITO) glass box placed on the lower, powered electrode in a GEC rf Reference Cell. Clusters exhibit rigid-body rotation around their central axes through their center-of-mass, due to strong interparticle coupling. In this paper, it will be shown that dust cluster rotation is dependent upon both the configuration and symmetry of the cluster, which in turn determines its net electrical dipole moment. It will also be shown that the application of a positive electrical potential to the ITO coated glass box damps the rotation due to modification of the radial confinement electric field. It will be argued that the net electrostatic torque produced by the interaction of this non-zero dipole moment and the local radial confining electric fields exerted on the cluster may drive the rotation observed.

Generation and control of void in cogenerated dusty plasma

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Void (complete absence of macroscopic particles) in dusty plasma was first observed in ground based laboratory [1] and later in microgravity condition [2] due to collective ion flux in the whole discharge volume. Dust void is not only static (due to balance between inward electrostatic and outward ion drag force) but also exhibits dynamic features like heart-beat instability [3].

In this experimental work, we have shown that by designing suitable electrode geometry and applying external positive bias voltage through a ring electrode, a void (within dense dust cloud) can be formed as well as can be effectively controlled. Our experiment was carried out in a stainless steel (SS-304) cylindrical vacuum chamber with 500 mm length and 400 mm diameter. The Schematic diagram of set-up and details of experimental technique may be found in [4] & [5]. Void closure and reopening were achieved here by varying the external positive bias voltage while the main plasma discharge voltage and gas pressure remains fixed.

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Study of a two-dimensional shear flow

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A molecular dynamics simulation is being developed to study microscopic quantities in a two-dimensional (2D) shear flow. The physical system that we investigate is a dusty plasma crystal that has been melted and is experiencing a shearing force. To model this system, we use a molecular dynamics simulation that includes inter-particle Yukawa forces, with no background gas damping or collisions with gas atoms. The shear is sustained by using Lees-Edwards boundary conditions and a SLLOD algorithm for integrating the equations of motion. Work supported by NSF and NASA.

Experimental Observations of Vertical Clouds In a Boundary-Controlled Dusty Plasma Environment

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Phenomenologically there appears to be a correlation between the behavior of negatively charged monodisperse dust particles immersed in a capacitively coupled plasma and a diverse number of unaffiliated research areas examining such things as metallic glasses, coulomb explosions and DNA molecular dynamics. Under appropriate boundary conditions, charged dust particle systems (i.e., complex plasmas) are proving to be a reasonable analog for examination of the physics behind these systems. The strong dependence on the boundary conditions in each of these cases has created an increased interest in establishing the plasma parameters required for producing user-controlled boundary conditions. In this paper, the potential field inside an Indium Tin Oxide (ITO) coated glass box, placed on the lower powered electrode of a GEC rf Reference Cell, was mapped employing a Langmuir-type probe. Dust particles with a mixture of sizes placed inside the box produced vertical hexatic structures (see Fig 1). The physics behind linking the potential fields and the dust structures formed will be discussed.

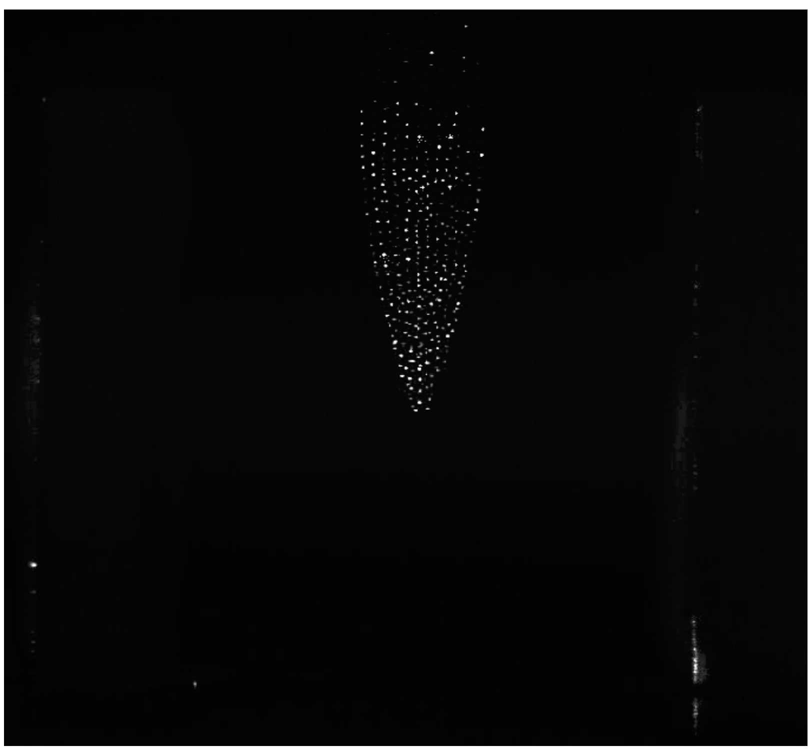

Figure 1 – A vertical hexatic dust cloud inside a 12.7 x 12.7x 12.7 mm glass box (Ar plasma).

Static properties of dusty plasmas

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One of the hot problems of modern plasma physics is the study of various properties of dusty plasmas, which contain, along with electrons and ions, micro-sized particles. For this purpose, so-called effective potentials are widely used to designate that the interaction of micro-sized charged particles in plasmas differs from the pure Coulomb interaction. Such effective potentials inevitably take into account the collective events that result in various self-consistent field theories like the well-known Yukawa potential corresponding to the pair correlation approximation valid for rather small number densities [1]. However, such potentials do not incorporate the finite size of dust particles. It is therefore of interest to construct an effective potential taking into account the finite size of the dust particles. To do so there is a practicable tool which is the dielectric medium approximation that provides the following simple formula for the Fourier transform $\tilde{\varphi}_{dd}(k)$ of the effective interaction potential between two dust grains:

$$\tilde{\varphi}_{dd}(k) = \tilde{\phi}_{dd}(k)\varepsilon^{-1}(k,0), \tag{1}$$

where $\varepsilon(k,0) = 1 + 1/(k^2 r_D^2)$, stands for the static dielectric function of the plasma with r_D being the Debye radius, $\tilde{\phi}_{dd}(k)$ denotes the Fourier transform of the interaction potential between two dust particles of radius R in a vacuum which is found within the charge image approximation in the form [2]:

$$\tilde{\varphi}_{dd}(k) = \frac{4\pi Z_d^2 e^2}{k^2} - \frac{8\pi Z_d^2 e^2 R}{k}\Big[\mathrm{Ci}(2kR)\sin(2kR) + \\ + \frac{1}{2}\cos(2kR)(\pi - 2\mathrm{Si}(2kR))\Big]. \tag{2}$$

Here $\mathrm{Ci}(x) = -\int_x^\infty \frac{\cos t}{t}dt$ and $\mathrm{Si}(x) = \int_0^x \frac{\sin t}{t}dt$ are cosine and sine integrals, respectively, and $-Z_d e$ is the charge of the dust particles expressed in terms of the elementary charge (e).
Knowledge of the effective interaction potential allows one to calculate the radial distribution function of charged dust particles within the Ornstein-Zernike relation. Such an approach assures that the finite dimensions of the dust particles are thoroughly treated and the obtained results are in good agreement with the known data [3].

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Molecular dynamics simulation of 2D dusty plasma taking into account the induced dipole moment of a dust particle

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This paper presents the results of molecular dynamics simulation of a 2D charged dust system taking into account the effect of the induced dipole moment of a dust particle. As it is known, in gas discharge the dust particle and ions focused by the dust grain can be considered as a one compound particle with non-zero dipole moment [1,2]. Such a picture is especially suitable for the description for a 2D dust system as there is no dust grain above the given dust particle which can strongly effect focused ions. Non-symmetric dust particles can also have an induced dipole moment due to charge separation in the external electric field.
The interaction between particles located in the same horizontal layer was taken in the following form [4]:

$$\Phi = \frac{Q^2}{R}\exp\left(-Rk_S\right)+\frac{d^2}{R^3}\left(1+Rk_S\right)\exp\left(-Rk_S\right) \tag{1}$$

here k_S is the screening parameter, Q is the dust particle charge, and d is the dipole moment of the dust particle or of the given compound particle. As it is seen the interaction potential (1) gives a stronger repulsion between dust particles than the Yukawa potential.
Using the interaction potential (4) the structural properties and waves in the 2D dust system were studied. It was found that the maximum of pair correlation function is higher than that of the Yukawa system and that the collective oscillation frequency is more than that of the Yukawa system.

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A Consistent Model of Plasma-Dust Interactions in a Glass Box

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Numerical modeling has become a valuable diagnostic tool for experiments in the modern physical world. In modeling the dynamics of dust particles confined in a glass box placed on the lower electrode of a GEC cell, there are many interactions between the dust, plasma, and boundaries that need to be accounted for more accurately. The dust particle dynamics are governed by the forces from the confining electric fields in the vertical and radial directions, the interparticle forces including the asymmetric wake field effect, gas drag, and Brownian motion. The electric fields and particle charges depend on the ambient plasma conditions, which vary in time and space in response to the dust particles and the boundaries. In physical experiments, the variables which can be controlled are the number and size of particles, the gas pressure, and the power delivered to the plasma, each of which can affect more than one of the previously mentioned forces in sometimes subtle ways. This work describes the steps taken to build a consistent model of the relationship between the forces acting on the dust particles and the surrounding plasma conditions.

Coexistence of DA Shock and Solitary Waves in Dusty Plasmas with Two-temperature Ions

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The nonlinear propagation characteristics of cylindrical and spherical shock waves in a unmagnetized dusty plasma comprising of inertial negative dust, Boltzmann electrons, and ions with two distinct temperatures, are rigorously investigated by deriving the modified Burgers (mB) equation. Later, the nonplanar KdV-Burgers (nKdVB) equation is derived to show the presence of dispersive and dissipative effects on nonlinear waves. The standard reductive perturbation method is employed to derive the mB and nKdVB equations. The basic features of nonplanar dust-acoustic (DA) waves (viz. amplitude, profile structure, etc) are discussed. The present analysis can play important role to understand the basic features of nonlinear electrostatic waves in astrophysical plasmas.

Dust-acoustic Shock Waves in Dusty Plasmas with Dust of Opposite Polarity and Trapped Ions

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A rigorous theoretical investigation has been made on dust-acoustic (DA) shock structures in an unmagnetized dusty plasma system containing charged dust of opposite polarity (negative and positive), Boltzmann electrons, and trapped (vortex-like) ions. The standard reductive perturbation method has been employed to derive the Burgers' equation. The effects of dust of opposite polarity and trapped ions, which are found to significantly modify the basic properties (amplitude, width and polarity) of small but finite-amplitude DA shock waves (DASHWs), are explicitly examined. Our present investigation can be effectively utilized in many astrophysical situations (e.g. satellite or spacecraft observations, Saturn's E ring, etc.), which are discussed briefly in this analysis.

Rayleigh Taylor and Kelvin Helmholtz instabilities in the anodic dusty plasma experiment

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A model for the Taylor instability that is observed in the Iowa anodic dusty plasma experiment [1] is proposed. In the model two mechanisms have been identified as the source of instability. First, the acceleration of dense fluid into lighter fluid caused by the curvature of the interface may cause the Taylor instability. Second, in the experiment, the dust cloud that is formed close to the biased anode, is tilted downwards. This brings a small component of gravity aligned in the direction opposite to the dust density gradient in the cloud. This mechanism will excite the usual gravity driven Rayleigh Taylor instability. Besides these two factors the dust flow along the interface may excite the Kelvin-Helmholtz instability. We have obtained a generalized dispersion relation which takes into account these instabilities. In the experiment the dust charge was estimated to be in range 2000-10,000 times the electronic charge while at high neutral pressure in the experiment, the dust temperature is expected to be close to room temperature. For these parameters, the dust coupling parameter Γ ranges from 10^3 to 10^4 indicating importance of dust correlations. Hence in the second part of our model we have studied the effect of dust correlations on the growth of the instability. Our results show that strong coupling effects stabilize the instability. The implication of the results of our model on experimental observations is discussed.

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Defect structure of probe induced dust density waves in cogenerated dusty plasma

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Dust density wave (ddw) is low frequency wave in dusty plasma which shows both linear as well as nonlinear properties. Since its discovery ddw has been an active area of research for decades [1]. Frequency clusters in ddw fields were observed in microgravity condition [2] and also in dc glow discharge dusty plasma [3]. To analyze spatiotemporal wave data of this wave, a time resolved Hilbert transform (HT) technique was used [2, 3]. They have shown that frequency clusters were strongly correlated with topological defect (at the position of wave front splitting or merging)

In our experimental work, spatiotemporal evolution of positively biased probe induced ddw in cogenerated dusty plasma is reported. This experiment was carried out in a stainless steel (SS-304) cylindrical vacuum chamber with 500 mm length and 400 mm diameter. The Schematic diagram of set-up and details of experimental technique may be found elsewhere [4, 5]. A probe, with 65 mm length and 1.2 mm diameter, was positively biased to excite the wave and placed inside the plasma. The plane parallel to probe was illuminated to study the ddw's, which was excited due to a threshold positive bias voltage in the probe. Spatiotemporal evolution of ddw exhibits wave defect and non-propagating wave. Our experiment reveals that the defect in wave field increases with increasing probe bias voltage. A Kymograph and time resolved Hilbert-Huang transform (HHT) was employed to analysis the spatiotemporal wave data.

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Dust Plasma

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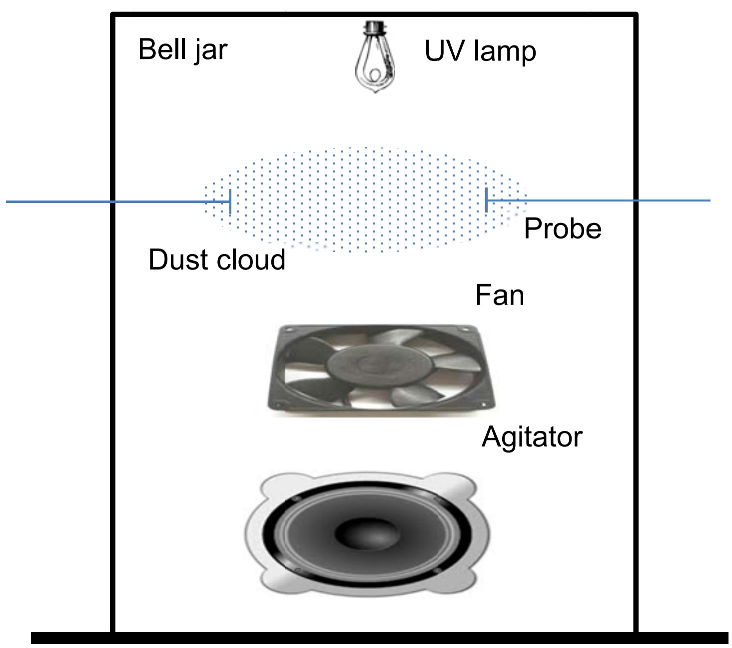
Dust plasma (rather than dusty plasma) is plasma consisting of positive and negative dust particles with a much smaller number density of free electrons and ions. We use numerical modeling with electron mean free path both larger and smaller than the dust separation to find the parameter space in which dust plasma might be observed in a lab with normal gravity and in the absence of a sheath to suspend the particles. An updraft of air at local atmospheric pressure (see figure) or thermophoresis at lower pressure could be used to suspend glass microballoons or ceria particles (with low work function) illuminated by UV. Rate equations for charge balance show that for sufficiently low photoemission rates the charged species are primarily positive and negative dust particles and that for sufficiently high ionizations rates the charges are primarily electrons and positive dust particles. Coulomb crystallization could occur in a volume (rather than in a layer) if the electrostatic force is much greater than shear forces associated with the levitation mechanism.



Heating and Stability in Magnetized Rotating Dusty Plasmas

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An experimental setup is under construction at the Dusty Plasma Laboratory of the University of Maryland, Baltimore County (UMBC) to study viscous heating and stability in magnetized rotating dusty plasmas. Azimuthal rotation is imposed on dust, electrons, and ions by having an axial magnetic field **B** in a vacuum chamber placed inside a 16 cm bore Bitter-type magnet, and a radial electric field **E** centered at the chamber axis. The resulting **E** x **B** rotation is expected to have sheared rotation, which leads to viscous heating from the radial velocity profile. However, heating may also lead to interchange modes that destabilize the rotation. The planned experiments are motivated by observations of parabolic ion and electron temperature profiles in hydrogen plasmas in a supersonic rotating magnetic mirror,[1, 2] where ohmic and viscous heating were the only mechanisms available for heating the plasma. The goal of the experimental setup is to magnetize and rotate dust with diameter ~1 μm that can be individually captured by particle velocimetry cameras and software. The Bitter-type magnet is planned for a steady field of 10 T with a minimum duration of 10 s per experiment. Details of the setup, including the diagnostics, are presented.

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Vacuum Compatibility of 3D-Printed Parts

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We present the design and preliminary results of a mass spectrometry system to assess vacuum compatibility of 3D-printed parts. The setup consists of sectional vacuum chamber with a residual gas analyzer (RGA), a radiation heater, windows, and access port for quick sample exchange. The signal from the RGA is analyzed by creating a system of equations that uses the calibration signal for known molecules (cracking patterns) and the measured spectra. The equations are then inverted to find the most likely true elements in the chamber. The vacuum chamber is set up so samples can be inserted and retrieved with minimal contamination to the vacuum system. We perform this by having two connected chambers with independent vacuum pumps, and using one for sample access at atmospheric pressure, and then transferring the sample to the main chamber once vacuum is equalized. The equipment will be used as part of the Dusty Plasma Experiment at UMBC, since many of the plasma facing parts are 3D-printed.

Development of a Bitter-type Magnet System

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A 10 Tesla water-cooled Bitter-type magnetic system is under development at the Dusty Plasma Laboratory of the University of Maryland, Baltimore County (UMBC). We present here an optimization technique that uses differential evolution to minimize the ohmic heating produced by the coils, while constraining the magnetic field to a user-defined value. The code gives us the optimal dimensions for the coil system needed for preliminary designing. Analytical parametric methods are then used to establish the optimal design for placement of water-cooling holes on the Bitter conductors. The resulting subsystems, such as the pressure vessel and vacuum chamber, are then built around or accommodate the coil design. Our analysis accounts for the radial and clamping magnetic forces that act on the copper alloy and insulating disks, as well as other supporting material inside the pressure vessel to ensure the system is not compromised during operation. The proposed power and cooling water delivery subsystems that drive and cool the magnet are also presented. A 1/10th magnetic field scaled model of the magnet is currently being constructed. Upon completion and testing of the prototype magnet system the large scale model will be produced. Planned experiments include the propagation of magnetized waves in dusty plasma under various boundary and rotational shear flow conditions, among others in a 10 Tesla field on a time scale of at least 10 seconds.

The Effect of Dust Particle Polarization on Scattering Processes in Complex Plasmas

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In this paper scattering angles and scattering cross sections of the ion-dust and dust-dust interactions are considered. The finite size effect and polarization of the dust grain are taken into account.
The ion-dust interaction was taken in the form [1, 2]:

$$\varphi(\mathrm{r}) = -\frac{e^2 Z}{r} - \frac{\xi}{2}\frac{e^2 a^3}{r^2(\mathrm{r}^2 - a^2)} \tag{1}$$

where a is the dust radius, $\xi = 1$ for the metallic grain and $\xi = (\varepsilon_d - 1)/(\varepsilon_d + 1)$ for the dielectric grain. In order to take into account the screening effect, the method of dielectric function was used. The effective screened potential was obtained using the following formula:

$$\tilde{\Phi}(\mathrm{k}) = \frac{\tilde{\varphi}(\mathrm{k})}{\varepsilon(\mathrm{k})} \tag{2}$$

where $\tilde{\varphi}(\mathrm{k})$ is the Fourier transform of the potential (1) and $\varepsilon(\mathrm{k}) = 1 + k_D^2 / k^2$ is the static dielectric function.
It was found that polarization of the dust particle gave smaller ion scattering cross section. It was also found that for some parameters the dust-dust scattering angle was practically equal to zero. This effect can be checked experimentally.

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Dust as discharge probe: single and two particle oscillations

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Using dust grains as probes in gas discharge plasmas is a very promising, but at the same time very challenging, method. Not only does the problem of the external control of dust grains have to be solved, but the interaction between the dust and the background plasma needs to be understood in great detail.

Inserting a single dust particle with known size and mass into the gas discharge enables us to map the effective confinement field surrounding the dust grain through the spectrum of its thermal oscillations around the equilibrium position in both horizontal and vertical directions. A system of two dust grains of the same kind shows two peaks in the horizontal oscillation spectrum, representing the center-of-mass and inter-particle (breathing mode) principle oscillation modes. From these frequencies one can derive the charge state of the dust and the Debye screening length in the discharge using the harmonic approximation framework shown in [M. Bonitz et.al. Phys. Rev. Lett. 96, 075001 (2006)].

We have conducted a series of single and two-particle oscillation measurements in capacitively coupled RF argon discharges over a wide parameter (pressure and voltage) range in a GEC reference cell setup. We have found that the dust oscillation frequencies sensitively follow the state of the discharge, especially the alpha – gamma mode transition, where the dominating electron impact processes move from the bulk plasma to the electrode regions, where secondary electron emission from the electrodes become important. We apply 1d3v particle-in-cell with Monte Carlo collisions (PIC/MCC) numerical simulations to the experimental conditions. The simulations support the presence of the transition and give deeper insight into the fundamental processes acting in the gas discharge.

The work has been supported by CASPER and OTKA through grant NN-103150

Heating of Dust Particles in the Experimental Setup via "Second Order Fermi Acceleration"

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Nowadays, dusty plasma is studied as a non-Hamiltonian system with additional variables [1]. Fluctuations of the dust charge lead to heating of dusty particles [2]. This process is similar to the well-known second-order Fermi acceleration. Usually, fluctuations of the dust charge are considered as a random process with the Gaussian distribution. Such a mechanism may explain a rather high kinetic temperature, up to several eV, of the dust component in the complex plasma in gas discharge [3]. For the case of astrophysical grains, this mechanism can strongly affect the rate of grain coagulation [2]. Therefore, the fluctuation of the dust charge is considered as an important characteristic of the dusty plasma.

In this paper a virtual experimental set-up for complex plasma with alternating dust charge is discussed. The PIC simulation of the buffer plasma and MD simulation of the dust component are carried out. Heating of the dust system is illustrated. This heating is characterized by a controllable heating rate, which makes it attractive for theoretical and experimental investigation of non-equilibrium processes in the multi-particle system.

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Improved two-beam method for heating of dusty plasma crystals

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We have improved a laser heating scheme for melting dusty plasma crystals. Two laser beams are rastered across a two-dimensional layer of dust particles suspended in a plasma. Starting with the dust particles in a crystallized form, moving laser beams are applied to impart momentum to the dust particles as they pass over the dust layer. Ideally, a melted dust crystal will behave like a liquid in that its particle motion will be more energetic and purely random. However, previous laser heating methods, which raster laser beams across a crystal at constant frequencies in a triangular pattern, drive coherent motion and create peaks in the frequency spectra of the particle motion. We have found that the peaks in the spectra can be diminished by scanning the beams with a different waveform, one that causes the beams to move in a pattern of circular arcs with randomized parameters. Work supported by NSF and NASA.

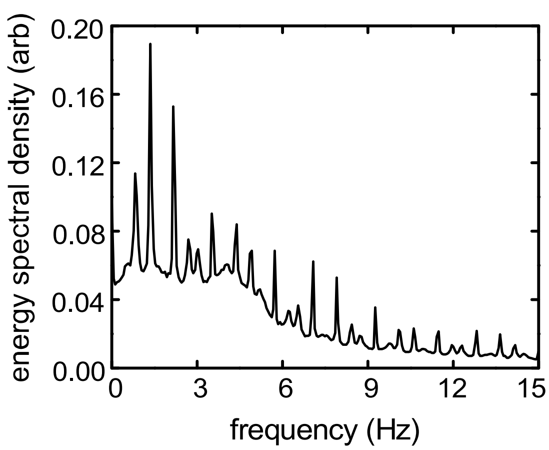

Figure 1 – Power spectrum of particle velocities in a liquid-state dusty plasma monolayer heated by rastering beams with triangular waveform.

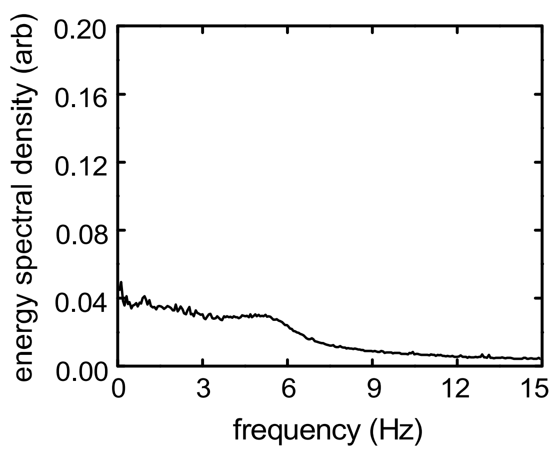

Figure 2 – Power spectrum of particle velocities in a liquid-state dusty plasma monolayer heated by rastering beams with a new waveform yielding circular arcs. Note that collective motion, indicated by peaks in the spectrum, is greatly diminished with this method.

Three-dimensional energy transfer of single particles in dust-density waves

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Dust-density waves occur in a wide parameter regime and are subject to research for many years. However, experimental access to the three-dimensional single particle motion was only gained recently. There, the particles that constitute the "dust-density wave" or "dust-acoustic wave" can be tracked in 3D on the kinetic level of individual particles?

In this presentation, we present investigations of the energy transfer between the different motion components of single particles participating in dust-density waves. Measurements have been performed with a three-camera stereoscopic setup under microgravity and laboratory conditions. Additionally, molecular-dynamics (MD) simulations describing particles in dust-density waves in a given force field have been performed. The energy transfer behavior in the experiment is compared to that from the simulations.

Wakefields, normal modes and information entropy in dusty plasmas

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The dynamics of a system of dust particles trapped in the plasma sheath is often determined or influenced by wakefields, or ion focus, which are formed by ions streaming past the dust particles. The presence of an ion focus leads to two types of instabilities: the Schweigert instability in multilayer systems and the mode-coupling instability that already appears in single-layer dust systems. Here, a model is presented that treats both types of instability in a common description. The parameter space for the onset of the instabilities is determined. A new variant of the mode-coupling instability is found to arise from the interaction among the layers. For weak confinement, all instabilities continuously merge into each other. For stronger confinement of the dust mainly the Schweigert type of instability is observed.

Further, the method of symbolic transfer entropy has been applied to analyze the behavior of systems under the influence of an ion focus. It is seen that the symbolic entropy transfer can be judged as a reliable measure for information asymmetry, and hence interaction asymmetry, in dusty plasma systems.

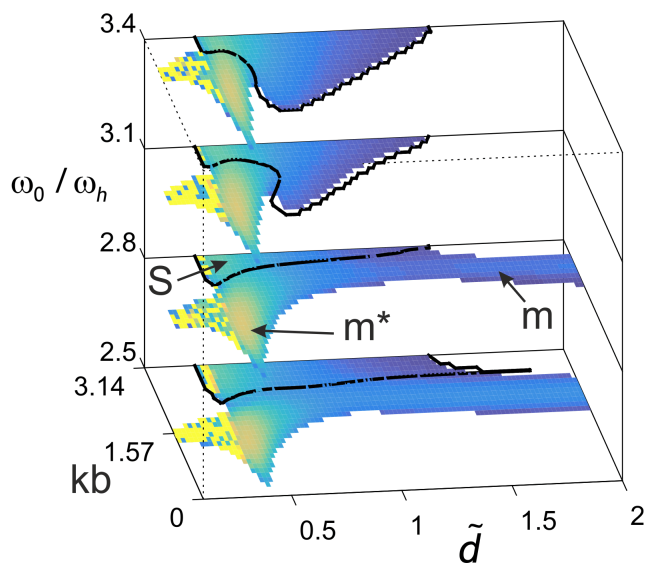

Figure 1 – Color-coded imaginary part of the unstable wave frequency as a function of the wave vector *kb*, the interparticle distance *d*, and the confinement strength ω_0. The mode-coupling regime is indicated by *m* for large interlayer distances, the Schweigert instability (marked by *S*) is found for large values of *kb*, and the interlayer mode coupling is denoted by *m**.

Phase Correlations in Turbulent and Unstable Particle Trajectories

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The description and analysis of turbulence phenomena in, e.g., dusty plasma is still one of the big open questions in statistical physics. Vortex structures and shear flow instabilities often emerge in three-dimensional experiments but are difficult to characterize. One reason for this is that particles irregularly appear and disappear in a two-dimensional slice of a three-dimensional particle cloud - a result of common data detection setups, where only a plane of the complex plasma is illuminated by a line laser and filmed from an orthogonal angle. Therefore, one is often forced to conduct the analytical studies in a Eulerian frame of reference, although, ergodicity is, strictly taken, not provided in most setups.

As an attempt to overcome this partly, I will present a novel tool for data analysis that sensitively, and exclusively captures nonlinear features. This new technique, called *Phase Walk Analysis,* applies statistical measures, usually used to classify random walks, to the unwrapped Fourier phases of time series.
The method allows to trace and quantify nonlinearities - and hence turbulent influence - in single particle trajectories. To demonstrate this, simulated as well as experimental data sets are tested for anomalies with surrogate assisted reference. The results can be used to decide whether nonlinear dynamics influenced the particle movement or not.
Moreover, it will become clear in which direction experimental data acquisition setups must evolve to allow proper and clean analysis of unstable, dynamic phenomena in future experiments.

Mapping the Confining Force in a Glass Box

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The confinement provided by a glass box placed on the lower electrode of a GEC rf Reference Cell is proving to be ideal for the formation of vertically aligned 1D, 2D and 3D structures, which are difficult to obtain under other types of confinement. The glass box also provides a mechanism for controlling the number of dust particles comprising these dust structures as well as their size and shape. Given that the confinement is a primary driver for producing ordered dust particle structures, a better understanding of this confinement is sorely needed. Unfortunately, due to the complexity of the sheath, very few details concerning the confinement have been reported. In this experiment, trajectories of dust particles falling through the glass box under different plasma environments are tracked and analyzed. The resulting data provides a map for the confining force at various positions within the glass box under the plasma conditions measured, which will be shown to aid in understanding the formation of particle structures.

Particle Tracking in Complex Plasmas

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Complex plasma contain, in addition to the usual electrons, ions, and neutral atoms, macroscopic electrically charged (nanometer to micrometer) sized “dust” particles. Based on the ratio of the electrostatic potential to kinetic energy, these micro-particles can exhibit gaseous, fluid, and crystal-like behavior. For this reason, complex plasmas are a unique testing ground to study multi-particle systems. The dynamics of these systems can be studied using the Particle Tracking Velocimetry (PTV) analysis technique. The PTV technique provides a spatially resolved particle phase space distribution (PSD) function, which can be used to calculate correlation functions and thermal properties of the system. In this presentation, we outline recent work developing real-time tracking software, so that PSD information can be updated in real-time (without recording large amounts of data). Additionally, we present initial efforts to trap single dust grains and drop them to observe single particle g x B deflection in a magnetic field.

Using dust to measure the plasma sheath over a rectangular depression

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The sheath is the charged boundary layer which separates quasi-neutral plasma from a material surface. The large electric field in the sheath confines the more mobile electrons and pushes positive ions out of the plasma, balancing the electron and ion loss rates. The directed energy ions gain in falling through the sheath is exploited in processes such as plasma based ion implantation (PBII) and the anisotropic etching of semiconductors.

The sheath electric field can also levitate micron-diameter dust particles, balancing their weight with an upward electric force. In particular, the steep field gradient causes the vertical confining well to be much deeper than the horizontal well, resulting in two-dimensional dusty plasmas. These dusty plasmas can be studied as a unique physical system, or can be used to provide information about the sheath which confines them.

Experimentally characterizing the plasma sheath challenging due to the small scale lengths, large gradients, and sensitivity to perturbations. However, microscopic dust particles provide local measurements of sheath properties, including the sheath width, electric field and Debye length.

We have used a cluster of two spherical dust particles to characterize the rf plasma sheath over a rectangular depression vs rf discharge power. The sheath width is inferred from the height of the dust. The in-plane normal mode frequencies provide information about the the ellipticity of the sheath edge, the local Debye length (Fig. 1), and the vertical electric field. The product of the vertical electric field and the Debye length approximates the electron temperature

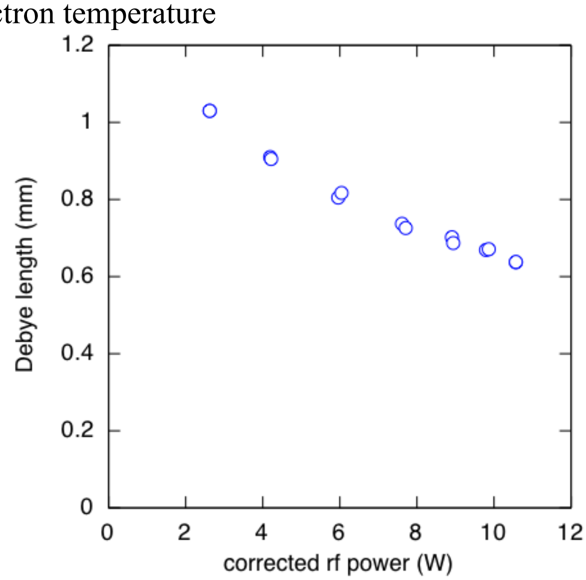

Figure 1 – The Debye length vs rf power measured using the breathing frequency of two dust particles showing the Debye length decreasing as the plasma density increases.

Initial result of three-dimensional reconstruction of dusty plasma with integral photography technique

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Fine particles are spontaneously generated in various plasma processes, changing the plasma conditions or spoiling the substrate. Moreover, three-dimensional (3-D) information of positions of fine particles in plasma is important for studying physics such as the investigation of transition processes in real crystal. Therefore, diagnostic methods, and removal and/or control techniques for these dust particles have been widely researched. Among the various dust diagnostic methods, 90° separated two CCD camera are widely used to determine the 3-D position of each fine particle [1]. Laser scanning also can obtain the 3-D information with a CCD camera, but it takes a little while to scan across wide field of view [2].

Integral photography is one of the 3-D imaging technologies based on a lenslet array to capture scattering light rays from slightly different directions [3]. The rays emerging a 3-D objects pass through a lenslet and are captured on a CCD device. Then the 3-D reconstruction is carried out computationally by generating inverse propagating rays with virtual system similar to the recording one. This method has great advantage that momentary 3-D information is estimated from one picture obtained from a viewing port.

In order to study of 3-D structures of dusty plasma, above technique has been applied to observe fine particles floating in a horizontally-parallel-plate radio-frequency (RF) plasma. The fine particles are monodiverse polymer spheres of 6.5 micro-meters in diameter. In preliminary experiment, we have set a lenslet, which has 5 x 5 circular refractive lenses in a 15-mm-square area, on a certain viewing port. The distance between the dusts and the lenslet is around 70 mm.
From reconstructed image, we can estimate that the particles form quasi-ordered structure with averaged distance between each particle of 100 micro-meters.

We have succeeded in distinguishing 3-D structure of dust plasma from a certain image obtained from one viewing port. The most recent results using above techniques will be presented, together with discussion on possible reconstruction methods from 3-D imaging.

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Investigating Ion Drag in Ground and Microgravity Dusty Plasma Studies Using PIV

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Complex, or dusty, plasmas are plasmas which contain charged microparticles, for example small silicon dust grains. In this study, we are particularly interested in the interaction between the charged dust particles and plasma ions through the ion drag force in a dc glow discharge plasma. Measurements of the dust particles are carried out through a technique called Particle Image Velocimetry (PIV) which calculates the average velocity field based on small particle groups. As an electrostatic perturbation is applied to the dust cloud, the particle motion is observed to change its direction of motion as the gas pressure is increased. Density and temperature measurements on the background plasma are conducted for both low and high voltage states of the perturbation. An analysis of the dust particle motion and background plasma parameters suggests that there is a competition between the electrostatic force and the ion drag force on the particles. These ion drag and electric forces on the dust particles are calculated using the most up to date models of the ion drag. Langmuir probe data is used to create a mapping of the electric field along the perturbation direction in the experiment. The results are suggestive that a change in direction of the Coulomb collision ion drag is a major contributor to the observed change in direction of the dust particles as a function of the gas pressure.

Structure characterization of three-dimensional dusty plasmas using two-dimensional images

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The pair correlation function $g(r)$ and number density n are widely used to characterize the structural arrangement of particles such as molecules in liquids and microspheres in colloidal suspensions or dusty plasmas. Here we are mainly interested in dusty plasmas where the particles fill a three-dimensional (3D) volume, but are viewed experimentally with only two-dimensional (2D) images. The problem with using a 2D image to obtain the 3D $g(r)$ and n is that there is seemingly no unique answer. This can be seen by comparing the experimental images in Figs. 1(a) and 1(b), where more particles are visible if the laser sheet is thicker.

Using an experiment, we demonstrate a method to determine $g(r)$ and n for a 3D dusty plasma with surprising accuracy using only the 2D coordinates along with the brightness of each particle. The key for attaining high accuracy is to exploit the variation of brightness of particles. In our method, we filter the particles according to their brightness to determine which will be included in the calculation of $g(r)$. After filtering, we first obtain a 2D $g(r)$ with a two-step determination, as an experimental representation of 3D $g(r)$. From this representation of $g(r)$, we can then also compute the 3D number density.

The accuracy of the method is quantified using simulation data. We use known true positions from the simulation to generate synthetic images that resemble those in the experiment. We found that we can achieve errors as small as 2% for both $g(r)$ and n.

Work supported by NASA and NSF.

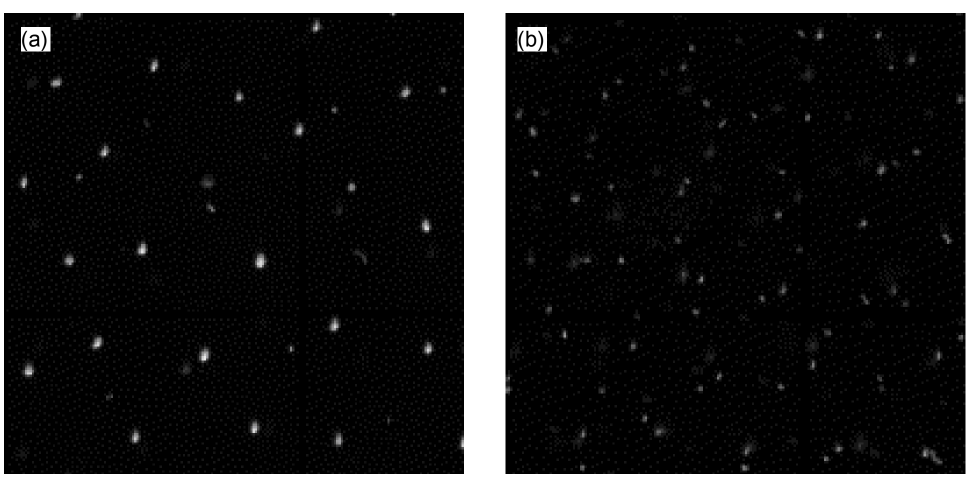

Figure 1 – Experimental images of a slab of particles in a 3D dusty plasma. These images were recorded for the same sample, but a different width for the illuminating laser sheet: (a) 0.64 mm and (b) 2.75 mm. Melamine-formaldehyde microspheres of diameter 4.8 μm were confined in the sheath of an RF plasma using a glass box to enhance the height of the 3D suspension.

Perpendicular diffusion of a dilute beam of charged particles under PK-4 conditions

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Diffusion has been previously studied for strongly-coupled dusty plasmas numerically and experimentally. In the previous numerical studies, diffusion was characterized under equilibrium conditions. Here, we investigate diffusion under a nonequilibrium condition, i.e., the random walk of a dilute beam of projectile particles that drift through a target dusty plasma. Furthermore, this random walk is not a self-diffusion; it is a diffusion that occurs mainly due to collisions with target particles that have a different size. We study the random walk in the direction perpendicular to the drift direction, i.e., the perpendicular diffusion. In the direction parallel to the drift, projectiles exhibit mobility-limited motion with a constant average velocity.

This work is motivated by microgravity experiments, with the expectation that the scattering of projectiles studied here will be observed in upcoming PK-4 experiments. The conditions would generally be the same as for lane formation, with an injection of projectiles of a second size, after filling the plasma already with particles of a different first size. Unlike the lane formation [1] experiments, however, here the projectiles would be dilute so that they scatter independently of one another.

We use a 3D molecular dynamics (MD) simulation [2]. In our simulation, Langevin terms are used to account for gas friction, and a Yukawa interparticle potential to account for shielding by electrons and ions. A constant force is applied to the projectiles due to a misbalance of the ion drag and electric forces. The simulation parameters are based on PK-4 parameters [3].

Using the simulation data, we characterize the random walk of the projectiles, yielding the perpendicular diffusion coefficient. We found that the diffusion depends on the mean kinetic energy for perpendicular motion. The driving force, in addition to sustaining a mobility-limited drift of projectiles, can also affect the projectile's diffusion by enhancing the kinetic energy associated with the random motion in the perpendicular direction.

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Dusty Plasma Physics Facility for the International Space Station

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The Dusty Plasma Physics Facility (DPPF) is an instrument planned for the International Space Station (ISS). If approved by NASA, JPL will build and operate the facility, and NASA will issue calls for proposals allowing investigators outside JPL to carry out research, public education, and outreach.

The facility is expected to support multiple scientific users. It will have a modular design, with a scientific locker, or insert, that can be exchanged without removing the entire facility. The first insert will be designed for fundamental physics experiments. Possible future inserts could be designed for other scientific purposes, such as experimental simulations of astrophysical or geophysical conditions or engineering studies. The design of the facility will allow remote operation from ground-based laboratories, using telescience.

3D particle diagnostic for complex plasma laboratories on the ISS

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Complex plasmas are an almost ideal model system to study dynamics and kinetics of fundamental effects like phase transitions, waves, and laminar as well as turbulent flows. This studies are performed in 2D views for many years with comparatively simple camera setups. To get 3D information about the particle cloud you can either move the 2D camera and laser in the direction of sight or use much more complicated and less robust systems like rotating or swinging mirrors. This scanning methods have the disadvantage that the 3D information of the particle motion is obtained at different time steps. For a real-time optical 3D diagnostic, holographic camera systems or multi view systems (stereoscope) can be used. Some of this methods require complicated and also not very robust setups, which is no problem for lab experiments, but there gravity prevents the generation of large 3D particle systems.
So a 3D particle diagnostic small enough to integrate into a space setup and robust enough to stand a launch to the international space station (ISS) is needed for the investigation of long term experiments in good micro gravity conditions. For this goal our group is developing a robust and compact stereoscopic camera system. In addition we compare this to a light field motion picture camera system, which its build by the german company raytrix. The systems will be optimized with regard to the needs of the next generation complex plasma laboratory PlasmaLab which is to be launched within EKOPlasma mission in 2019/20.
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Instabilities in complex dc plasmas

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The PK-4 setup uses a hv dc plasma in an elongated glass tube to produce complex plasmas that are mainly in the liquid phase. This allows to study flow phenomena on the level of individual particles (fig. 1) [1]. PK-4 was launched to the International Space Station in Oct. 2014 and will begin its operational phase in 2015, following the successful plasma laboratories 'PKE-Nefedov' and 'PK-3 Plus' on the ISS. [2]

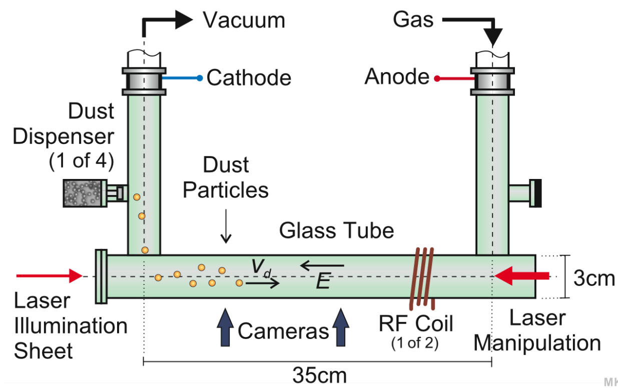
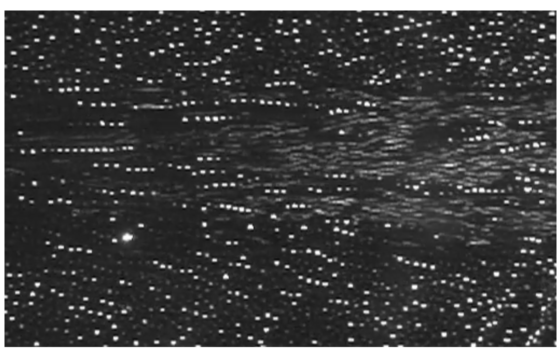


Figure 1 – Scheme of the PK-4 setup.

We used a prototype of PK-4 for experiments in the lab and on parabolic flights. There, we observed flow instabilities and analyzed them on the particle level. Two – lane formation [3] and a "deep water" RT instability [4] – will be presented here. (Fig. 2a, b)



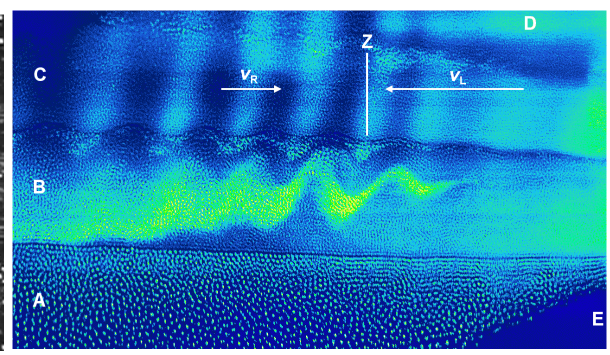


Fig. 2a – Lane formation in microgravity: Fig. 2b – Interfacial instability in the lab.

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Electron Temperature Control in the Zyflex Chamber

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In a complex plasma, the electron temperature T_e of the surrounding plasma is an important factor in defining the particle charge and interaction. T_e in a capacitively driven rf-discharge is mainly given by ohmic heating in the plasma bulk and stochastic heating due to reflection of the electrons at the sheath edge. By inserting a grid between the rf-electrode and the rest of the plasma chamber, the latter is separated from the region of plasma production (Fig. 1). The grid represents a barrier for slow electrons if it is grounded or negatively biased, but fast electrons can pass through the grid and create a low temperature electron population by ionizing neutral gas atoms on the other side. There are no further heating mechanisms for these electrons, and T_e can be controlled by e.g. varying the dc bias of the grid, thus selecting the electron energies allowed to pass [1].

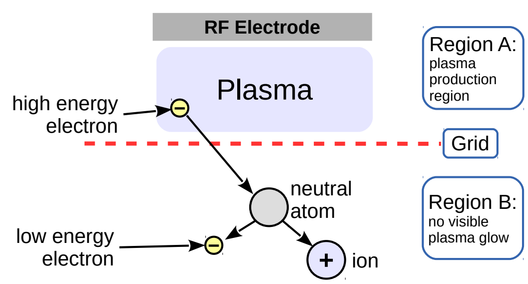

Figure 1: Plasma is generated between an rf electrode and a grid (Region A). Fast electrons pass through the grid and ionize neutral gas atoms on the other side, generating a low temperature electron population (Region B).

First results of experiments are presented where particles were inserted into Region B (Fig. 1) of the discharge chamber, and the influence of changing the dc bias of the grid, thus controlling T_e, on the particle behavior was studied. The experiments were conducted in the "Zyflex" chamber – a large, cylindrical plasma chamber with parallel, rf-driven electrodes. The chamber is currently being developed as part of the PlasmaLab project, an experimental setup for complex plasma research on board of the International Space Station (ISS) to study fundamental properties of complex plasmas in large 3D systems in microgravity.

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Notes

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