FINAL SCIENTIFIC/TECHNICAL REPORT

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PUBLIC ABSTACT

A plasma is a gas of charged particles – electrons and positive ions in roughly equal concentrations. Plasmas are formed by stripping electrons from neutral atoms and molecules. It is believed that the plasma state of matter comprises over 99% of the universe. Often the plasma coexists with small (1/1000 of a millimeter) dust particles. Some of the plasma particles collect on the dust grains which cause it to be electrically charged, and so become an integral part of the plasma, forming what is called a "dusty plasma". The large objects in the universe (planets, asteroids, comets, stars) are formed by combining dust grains into larger and larger objects, eventually held together by their self-gravitational attraction. Thus, an understanding of the processes that control the structure and evolution of the universe, requires that we understand the behavior of dusty plasmas. These plasmas also often are embedded in magnetic fields which has a strong influence on their structure and behavior. Thus, developing an understanding of dusty plasmas in magnetic fields, so-called magnetized dusty plasmas, is also essential. In addition to the dusty plasmas occurring in nature, dusty plasmas play an important role in many plasma-based technologies, such as the production of semiconductor devices, and in the next generation of *clean-and-green-energy* producing devices based on nuclear fusion. The purpose of the work performed with funding provided in this grant by the United States Department of Energy was to produce and investigate the physics of magnetized dusty plasmas.

EXECUTIVE SUMMARY

The project goal was to investigate the physics of magnetized dusty plasmas. A dusty plasma is a plasma (an ionized gas of negatively charged electrons and positively charged ions) that also contains small (micron to sub-micron size), electrically charged particles (dust).

The motivation for studying dusty plasmas is due to the fact that they are commonly found in nature (e. g., cometary tails, planetary rings, planetary and solar nebulae, the earth's mesosphere), and occur in various technological settings, such as semiconductor processing devices and magnetic fusion devices. The interaction between the plasma electrons and ions with the charged dust component leads to a complex system that exhibits collective behavior. Due to the ubiquity of dusty plasmas in nature and anthropogenic systems, it has become essential over the last 30 years to develop an understanding of the physics of dusty plasmas.

The first foray of research into dusty plasmas focused on dusty plasmas in unmagnetized plasmas, plasmas in which there is no external magnetic field. Since many of the dusty plasmas in nature and applied systems, such as magnetic fusion plasmas, occur in conjunction with magnetic fields, it has now become necessary to investigate the behavior or magnetized dusty plasmas. **This was the essential purpose of this project—to produce and investigate the properties and behavior of magnetized dusty plasmas under controlled laboratory conditions**.

The formation of a magnetized dusty plasmas is a technically challenging undertaking, and due to the particular properties of the dust particles, requires the use of magnetic fields with strengths on the order of several tesla (some ten to fifty times stronger than common permanent magnets). The proposed device (The Magnetized Dusty Plasma Experiment, MDPX) was constructed at Auburn University in Auburn, AL, under the direction of Dr. Edward Thomas, Jr., in collaboration with the University of Iowa (R. L. Merlino), and The University of California at San Diego (M. Rosenberg). The collaborative efforts of the University of Iowa investigator were initially focused on the design criteria of the device, and after the commissioning, to perform experiments aimed at (1) verifying the formation of the magnetized dusty plasmas, and (2) studying the behavior of the magnetized dusty plasmas. The outcome of this work has successfully demonstrated the formation of the magnetized dusty plasma, and also led to several discoveries of new (unexpected) phenomena of both basic and technological significance. The MDPX operates as a user facility, and has been used by a number of domestic and international researchers to perform experiments requiring its unique capabilities.

Scientifically significant findings were (1) the observation of imposed order (several published articles), and (2) the effect of the magnetic field on the dust charge.(manuscript for journal submission now in preparation).

Due to the intervention and subsequent travel and operational restrictions of the Covid-19 pandemic in early 2020, one of the major planned experiments on the MDPX device could not be performed – the observation of a plasma wave mode connected directly to the presence of magnetized dust particles—the electrostatic dust cyclotron wave (EDC). The investigation of this unique dusty plasma wave mode will continue, and the University of Iowa PI, will continue his involvement in this project on an unfunded basis. Pandemic restrictions also prevented the performance of complementary experiments at the University of Iowa. The PI at the University of Iowa has devoted a significant period of time over the last two years, preparing an extensive review article in Advances in Physics X (in production) on the basic physics and applications of dusty plasmas from the unique perspective of the PI who had been involved in some of the earliest experimental laboratory investigations of dusty plasmas, including magnetized dusty plasmas.

COLLABORATIVE RESEARCH ACTIVITIES

The grant SC0016472 to the University of Iowa was part of a collaborative project involving Auburn University, where the MDPX device is located, (PI: E. Thomas, Jr.), The University of Iowa (PI: R. L. Merlino), and the University of California at San Diego (PI: M. Rosenberg). Initial funding for the construction of the MDPX device was provided by an NSF Major Instrumentation grant in 2009. The PI at the University of Iowa collaborated directly with Auburn University Professors Thomas and Konopka and Auburn University graduate students B. Lynch, S. Leblanc, T. Hall, and M. McKinlay on specific experimental projects, and with M. Rosenberg of USCD on theoretical work related to these projects. The PI at the University of Iowa traveled to Auburn to participate directly in experimental work. Monthly conference calls were conducted by the project manager (Thomas) to update all investigators on the status of the various experimental projects and operational details of the MDPX device, to discuss the results of ongoing experiments, and in formulating plans for future experiments.

Major Research Findings

(a) *Externally imposed ordered dust structures under high plasma magnetization*

The MDPX device uses a parallel-plate rf discharge to produce the plasma. Dust particles (typically 1 micron diameter glass microspheres) are introduced into the plasma using the standard "dust salt-shaker" method. The external magnetic field is applied in the direction perpendicular to the surface of the plates. The dusty plasma is formed in the region between the plates with levitation provided by the sheath electric field of the lower electrode. The dust particles are illuminated with a standard green diode laser spread into a narrow sheet. The motion of the dust cloud is recorded using fast video cameras. To allow viewing of the cloud from above, the upper electrode is a segmented annular disk and a central circular mesh.

One of the first unexpected discoveries in MDPX was the observation of a two-dimensional self-consistent structuring of the dust suspension in a pattern that mimicked the structure of the mesh which was located several centimeters above the layer. These structures were observed under conditions in which both the electrons and ions in the plasma were highly magnetized with gyroradii smaller than or comparable to the spacing of the mesh wires. This is an entirely new form of dust organization that is not related to the formation of the well-known dust crystals that form in strongly coupled dusty plasmas. This new structuring phenomenon is directly related to the magnetization of the electrons and ions in the plasma. Several follow-on experiments were performed to attempt to uncover the specific mechanism for this structure formation process. These experiments were part of the PhD thesis of graduate student T. Hall. Our present understanding is that under high magnetization, the motion of the electrons and ions is severely restricted spatially, which allows the formation of micro-potential wells in positions related to the presence of the mesh wires. The dust particles then settle self-consistently into positions defined by the micro-potential wells. This is the **first observation of dust structuring in a strongly magnetized plasma**. It is important to note, that this effect is not due to magnetization of the dust particles themselves, but only requires magnetization of the background plasma. This process may be of substantial technological importance, since is provides a mechanism of synthesizing a dust cloud with a specific imprinted structure defined by the geometry of the mesh. From an astrophysical point of view, any mechanism that gives rise to structuring of dust particles may be important for understanding planetary evolution in dust clouds.

(b) *Demonstration of dust magnetization by observations of the* ***g×B*** *force on dust particles*

The MDPX device was designed and constructed specifically to produce a dusty plasma in which the dust particles are *magnetized*, *i.e.*, the dynamics of the dust particles is influenced *directly* by the externally applied magnetic field. There are two criteria that must be satisfied for a charged particle in a plasma to be considered *magnetized*: First, the radius of its gyromotion in the magnetic field must be much smaller than the typical dimension of the volume in which it is contained. Secondly, since laboratory plasmas are created typically by ionizing a neutral gas, the gas pressure should be low enough that the charged particle can perform a least a few gyrations before it collides with the neutral atom. These criteria lead to two quantitative conditions: (i) he charge-to-mass ratio of the particle should be large, and (ii) the neutral gas pressure should be low. This is very challenging because a typical charge-to-mass ratio of a dust particle is roughly twelve orders of magnitude smaller than the corresponding value for an electron; and there is a lower limit on the pressure required to form a plasma. Since the mass and charge of a dust particle both depend on its radius, the bottom line is that the parameter, aP/B, where a is the radius of the dust particle, P is the neutral gas pressure, and B is the magnetic field strength, must be much less than 1. This requires that small particles and large magnetic fields be used. A further consideration, is that in order to be able to image the particles in visible light, the diameter cannot be much smaller than the wavelength of the laser used to illuminate them. Fortunately, a set of operational parameters which satisfy the necessary magnetization criteria were found.

How is the magnetization of the dust particles demonstrated? Ideally, magnetization of a dust particle would be observed by imaging the gyromotion of a single particle. Unfortunately, under the typical operating parameters of the MDPX, a dust particle large enough to be imaged, would not execute a full gyro-orbit in the plasma. (A possible method of indirectly observing dust magnetization for very small particles that cannot be imaged will be discussed below.)

Observation of dust magnetization in MDPX relied on the fact that a charged particle in a plasma in which the magnetic field was oriented in the direction perpendicular to the acceleration of gravity, **g**, is subject to a **g** × **B** force in the direction perpendicular to **g** and **B**. The MDPX was specifically designed to allow for rotation of the magnet system so to operated with **g** ⊥ **B**, in anticipation of the performance of this measurement. With **g** ⊥ **B**, dust particle falling through the plasma would then experience a force resulting in a deflection of its trajectory from the vertical direction. **Observation of dust particle deflection provides direct evidence of the effect of the magnetic field on the charged dust particles, i.e., dust magnetization**. This experiment was performed as part of the Ph.D. thesis of B. Lynch and under the direction of the full collaboration: E. Thomas, Jr., U. Konopka, R. L. Merlino, and M. Rosenberg. A full description of the experiment and the results are contained in an article which is presently in the final stages of preparation for submission to the Journal Physics of Plasmas.

Unmistakable evidence of the deflection of the dust particles due to the **g** × **B** force was obtained by the acquisition and analysis of the images of the trajectories of several thousand dust particles inserted into and falling through the plasma. In addition to the basic observation of dust magnetization, the quantitative analysis of the dust particle trajectories provides a method for estimating the charge on the dust particles, and ascertaining the effect of the magnetic field on the dust charge. **A scientifically significant conclusion of this investigation was that the dust**

charge was significantly reduced relative to the value expected for dust in an unmagnetized plasma, the so-called OML value. (OML, or orbital motion limited theory is the widely used approach for computing the charge on a dust particle.) The results of this experiment point to the need for the development of new theoretical and numerical methods of computing the charge on dust particles under conditions of strong plasma magnetization. This issue is of a more general nature, since it also arises in situations in which objects may be charged by plasma collection in a magnetized plasma, e. g., Langmuir probes in magnetized plasmas, or charging of surfaces in tokamaks.

(c) *Dust acoustic waves (DA) in the MDPX device*

A plasma can support of large number of electrostatic waves. Electrostatic waves produce fluctuations in the plasma density and space potential. The effect of charged dust on plasma waves falls into two categories:

(i) The dispersion relations for the plasma waves can be modified due to the effect on the charge neutrality condition (Part of the negative charge in the plasma resides on massive dust particles.) These modifications occur even for plasma waves of such a frequency that the dust particles do not participate directly in the wave motion. The presence of dust can change both the propagation characteristics of the waves, as well as the conditions under which the waves are excited.

(ii) The presence of the relatively massive charged particle component in the plasma (the dust) leads to the presence of new low-frequency wave modes which directly involve the motion of the dust particles – these are usually referred to a dust waves. The most common example of a dust wave mode is the dust acoustic (DA) wave, which is essentially an longitudinal dust sound wave that propagated through the dust suspension. This mode is unique in that it can be observed visually by laser light illumination and video imaging techniques. This mode has been observed and investigated in detail in *unmagnetized* dusty plasmas.

Ed Thomas and I began a study of dust acoustic waves in the MDPX in 2015 and worked on and off on this for two years. We observed the DA mode in MDPX and tried to characterize how the magnetic field affected it. One interesting issue was that although the wave propagated generally in the direction of the ion drift, as in the unmagnetized case, the situation in the magnetized case was considerably more complicated. As the magnetic field was increased, the wavefronts evolved from planar to V-shaped. Part of the complication was related to the fact that the discharge was filamented at high magnetic fields and this greatly affected the wave propagation. The results of these investigations were reported in a paper published in Physics of Plasmas in 2016. Our experiments demonstrated for the first time that the DA wave could be excited in a magnetized dusty plasma. The DA wave is of potential importance in astrophysical plasmas as a potential mechanism for triggering condensation of dust grains into larger objects. Since these regions also involve magnetic fields, the role of the magnetic field in modifying the DA wave needs to be explored.

(d) *Observation of the electrostatic dust-cyclotron mode (EDC)*

Experiments on MDPX aimed at observation of the EDC mode were a major component of the proposed work during this reporting period. There was considerable discussion among the principal collaborators (Thomas, Konopka, Merlino, Rosenberg) on how to carry out this task.

Theoretical predictions of the properties of the EDC waves under possible MDPX conditions were performed by M. Rosenberg. It was clear that observation of the EDC mode required the dust grains to be capable of executing multiple gyro-orbits in the dusty plasma. This meant that very small dust grains must be used, with the consequence that optical imaging would not be possible. To operate with very small grains (VSG), we adopted the plan of using grains grown directly within the plasma. This is accomplished by suitable has mixtures, e. g. methane and argon, which under plasma-chemical processes are known to form nanometer sized grains, by agglomeration and accretion. The detection of the EDC wave would be carried out by observing either density or potential fluctuations on probes inserted near the edge of the plasma. Unfortunately, the Covid-19 pandemic interfered with these plans, and the EDC experiments could not be carried out. However, observation of the EDC mode (it has not been observed previously) would be an important milestone in dusty plasma physics studies and will remain a priority in the future. Experiments were conducted on the MDPX that showed clearly that dust grains could be grown through plasma-chemical processes at high magnetic field.

RESEARCH ACTIVITIES AT THE UNIVERSITY OF IOWA

Experiments were conducted at the University of Iowa that were complementary to work performed at the MDPX. The University of Iowa has a linear magnetized plasma device (Q machine) that is capable of producing fully ionized plasmas with magnetized electrons and ions. The magnetic field in this device can operated up to 0.4 T. Although this device did not contain dust particles, experiments could be performed to investigate the effect of the magnetic field on the collection of currents due to electrons and ions. Thus it was possible to investigate some of the processes that simulate the collection of currents to dust particles. Specifically experiments were performed to study the effect of changing the direction of the magnetic field relative to the surface normal of the probe. Unfortunately, the ability to continue these experiments was impacted by the pandemic so that new planned experiments could not be performed. Previously these experiments were carried out by the PI at the University of Iowa with an undergraduate physics major who eventually attended Auburn University and worked on the MDPX device under Professor Thomas.

SYNERGISTIC AND OUTREACH ACTIVITIES

The PI at the University of Iowa has participated in the Adopt-a-Physicist program sponsored by the AIP, SPS, APS, and AAPT. Adopt-a-Physicist connects high school physics students to real physics graduates who are eager to share their stories. Working in areas ranging from particle physics research to freelance writing, the participating physicists embody a huge range of careers, backgrounds, interests, and educational levels. This is an effective program which allows high school students interested in STEM careers to speak directly to a working physicist about their life experiences in science and especially to inform them about their career path. This provides enthusiastic students with important information that they might not otherwise be able to obtain from high school counsellors.

PERSONNEL SUPPORTED ON THIS GRANT

1. R. L. Merlino (PI)
2. M. Miller (Engineer)

MAJOR COLLABORATORS

1. E. Thomas, Jr. (Auburn University)
2. U. Konopka (Auburn University)
3. M. Rosenberg (UCSD)
4. Avinash Khare (Sikkim University, India)

PATENTS GRANTED OR APPLIED FOR

None

INVITED TALKS

12th International Workshop on Non-neutral Plasmas, 10 – 13 July, 2017, Lawrence University, Appleton, WI USA. (see paper 3 below).

PUBLICATIONS RELATED TO THIS GRANT

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3. Merlino, R. & Thomas, E. & Lynch, B. & LeBlanc, S. & Hall, T. & Konopka, U. & Rosenberg, M.. (2018). The magnetized dusty plasma experiment (MDPX). AIP Conference Proceedings. 1928. 020011. DOI: 10.1063/1.5021576.
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8. E. Thomas Jr., U. Konopka, D. Artic, B. Lynch, S. LeBlanc, S. Adams, R. L. Merlino, M. Rosenberg J. The magnetized dusty plasma experiment (MDPX). Plasma Physics 81, 345810206 (2015) DOI: 10.1017/S0022377815000148

MANUSCRIPTS ACCEPTED FOR PUBLICATION

Robert L. Merlino, Dusty Plasmas: From Saturn's Rings to Semiconductor Processing Devices, Advances in Physics X. Final manuscript submitted May 27, 2021. This is a 90 page articled commissioned by APX and reviewing 25 years of research in dusty plasmas.

MANUSCRIPT IN PREPARATION FOR SUBMISSION

1. Observations of Dust Grain **g**×**B** Deflection in the Magnetized Dusty Plasma Experiment (MDPX), B. Lynch, U. Konopka, R. Merlino, M. Rosenberg, and E. Thomas.
2. Electron and Ion Currents to a Planar Probe Oriented at an Arbitrary Angle to the Magnetic Field in a Cesium Q Machine Plasma, Michael J. McKinlay and Robert L. Merlino.