Magnetized Dusty Plasma Experiment: A user facility for complex plasma research

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Thanks: To many students and the world-wide dusty plasma community

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Outline

• Introduction to dusty plasmas
• Role of magnetic fields
• Experiments with magnetic fields
  – Early experiments
  – Current experiments
• Magnetized Dusty Plasma Experiment (MDPX)
• Summary
Dusty (complex, fine particle, colloidal) plasmas

• Complex plasmas - four component plasma system
  – Ions
  – Electrons
  – Neutral atoms
  – Charged microparticles

• Plasma and charged microparticles - coupled via collection of ions and electrons from the background plasma.

• Presence of microparticles:
  – Modifies density and charge distribution
  – Modifies plasma instabilities
  – Introduces new dust-driven waves

• Measurements of dust particles:
  – Forces
  – Electrostatic potential
  – Velocity distributions
Because dusty plasmas are a topic of **UNIVERSAL** interest.

Dusty plasmas cover a wide range of phenomena:

- **plasma processing**: $10^{-2}$ m
- **fusion**: $10^1$ m
- **planetary rings**: $10^8$ m
- **nebula**: $10^{17}$ m
Plasmas exist over a wide parameter space

What are the parameters of a dusty plasma?
Key physics: Charging - $Q_d$ is a new dynamic variable

- A dynamic equilibrium is established as the grain electrically floats in the plasma: $I_{total} = I_{electron} + I_{ion} + I_{see} + I_{thermionic} + I_{hv} = f(n_j, T_j, \varphi; r, t)$
- Implication: $dQ_d/dt \neq \text{constant}$
- Grain charge ($Q_d = Z_d e$) is a new dynamic variable
- In the laboratory, $Q_d$ is negative. In space, $Q_d$ can be positive or negative
Key physics: Mass - large $m_d$ extends plasma timescale

- Fundamental time scale for plasma oscillations - plasma frequency

$$\omega^2 = \sum \omega_{ps}^2 = \omega_{pe}^2 + \omega_{pi}^2 + \omega_{pd}^2$$

where: $$\omega_{ps}^2 = \frac{q_s n_{0s}}{\varepsilon_0 m_s}$$

- For typical lab plasma parameters: $f_{ps} = \frac{\omega_{ps}}{2\pi}$
  
  $n_{i0} = n_{e0} \sim 10^{14} \text{ m}^{-3}, n_{d0} \sim 10^{10} \text{ m}^{-3}$, argon plasma, $Z_d \sim 4600$, $a \sim 1.5 \mu\text{m}$

- $f_{pe} = 90 \text{ MHz}$, $f_{pi} = 330 \text{ kHz}$, $f_{pd} = 23 \text{ Hz}$

Parameters:

- $s$ – ion, elec, dust (i, e, d)
- $a$ – dust radius
- $q_s$ – charge; $q_d = -Z_d e$
- $n_s$ – density
- $m_s$ – mass
Key physics: Coupling Parameter - $\Gamma$ controls self-organization

- $\Gamma$ (coupling parameter) is indicative of the self-organizing, emergent properties of dusty plasmas.
- A dusty plasma can be used as a model system to investigate problems in soft-matter physics.
- Assume dust particles interact via a screened Coulomb interaction (Yukawa, Debye-Hückel):
  \[ \varphi \sim \frac{\exp\left(-r / \lambda_d\right)}{r} \]

\[ \Gamma = \frac{\text{electrostatic potential energy}}{\text{thermal energy}} = \frac{Q_d^2}{4\pi\epsilon_0 k T_d \Delta} \]

\[ \Delta = \text{Wigner-Seitz radius} = \left(\frac{4\pi n_d}{3}\right)^{-1/3} \]
• Plasma and charged microparticles are coupled
Dusty Plasmas and Magnetic Fields

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- Coupling gives rise to dynamical processes
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- Magnetic field – modifies the coupling
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- Coupling gives rise to dynamical processes
- Magnetic field – modifies the coupling
- Magnetic field – modifies the dusty plasma dynamics
Dusty Plasmas and Magnetic Fields

- Magnetized plasma and charged dust may contribute to:
  - Fusion experiments
  - Astrophysical systems
Magnetic field effects

L. Mestel and L. Spitzer, Jr

(Received 1956 July 27)*

Summary

The paper deals with the problem of gravitational condensation in the presence of a magnetic field. It is shown that as long as the field is frozen into the contracting cloud the magnetic pressure sets a lower limit to the mass that can remain gravitationally bound: if the field is taken as $10^{-6}$ gauss in regions of density $10^4$ H atoms/cm$^3$, this lower limit is $\approx 5 \times 10^8 \odot$. However, if the bulk of the cloud is obscured from galactic starlight by dust grains, the plasma density within the cloud will decline rapidly, as ions and electrons attach themselves to the grains. When the plasma density is low enough the frictional coupling between plasma and neutral gas will be so small that the distorted magnetic field will be able to straighten itself, dragging the remains of the plasma with it, while the bulk of the cloud contracts across the field. With the magnetic energy so reduced to a small fraction of the gravitational energy, the cloud is able to break up into stars.

• Most often, the role of the magnetic field in incorporated in the dynamics of the charged dust.

• This has been particularly important for interpreting phenomena within the solar system.

• One example are the dust streams emanating from Jupiter due to volcanic activity at Io.

\[
m \frac{d\vec{v}}{dt} = q_d \left( \vec{E} + \vec{v} \times \vec{B} \right) + \vec{F}_G + \vec{F}_d + \vec{F}_r
\]

Modification of a comet’s tail: an astrophysical example

- December, 2011: Comet Lovejoy passes near the Sun
- The dust tail modified by plasma flowing along magnetic field lines

Enhancing microparticle confinement by extending the anode spot region.

(R. Merlino, Univ. of Iowa)

Early laboratory studies at low magnetic field

- Low magnetic field - indirect influence on dust particles

- Modification of:
  - Ion flows
  - Inter-particle forces
  - 2D/3D structures

- The majority of these studies used magnetic field strengths, \( B \leq 100 \text{ mT} \) (1 kG)
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Rotation of a microparticle cloud due to $E \times B$ drift.
Early laboratory studies at low magnetic field

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  - Inter-particle forces
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Toroidal rotation of a dusty plasma cloud – Kiel Univ.
Magnetizing a dusty plasma

- Magnetization criterion
  - Magnetic forces will be comparable to the other forces acting upon the grain

- Challenges:
  - Dust grains charge, \( Z_d \sim 1000 \)
  - Dust grain mass, \( m_d > 10^8 m_{ion} \)

- That is: \( q_d/m_d << e/m_{ion} << e/m_{elec} \)

- Key parameters:
  - Gyroradius to exp. size: \( \frac{\rho}{L} \sim \frac{a^2v_d}{BL} \ll 1 \)
  - Gyrofreq. to collision freq.: \( \frac{\omega_c}{\nu_{dn}} \sim \frac{B}{aP} > 1 \)
  - Magnetic to gravitational force: \( \frac{F_m}{F_g} = \frac{Q_d v_d B}{m_d g} \sim \frac{v_d B}{a^2} \geq 1 \)

Key Result: Maximize \( B/a \)
Magnetizing a dusty plasma

Gyro-orbit size vs. B

Assumptions:
• Uniform size melamine particles
• Charge from OML
• Velocity, \( v \sim 10 \text{ mm/s} \)
• Critical radius, \( r = L/10 \sim 1.5 \text{ cm} \)

![Graph showing the relationship between gyroradius and magnetic field strength](image-url)
High magnetic field experiments: Max Planck Institute

- Magnetic field: 4 Tesla
- Inner diameter: 40 cm (dia.)
- Vacuum chamber: 20 x 20 cm
- Orientation: Rotatable
- Particles: 1 - 5 µm

Images courtesy of U. Konopka, P. Bandyopadhyay, MPE
High magnetic field experiments: Kiel University

- Magnetic field: >4 Tesla
- Inner diameter: 30 cm (dia.)
- Vacuum chamber: ~10 cm x 1m
- Orientation: Rotatable
- Particles: 0.1 – 0.2 μm

Images courtesy of F. Greiner, Kiel University
Magnetized Dusty Plasma Experiment (MDPX)

• MDPX project:
  – Develop a fully magnetized dusty plasma
  – Develop flexible, multi-configuration magnetic geometry
  – Operate as a multi-user facility

• Two primary scientific questions:
  – As a dusty plasma becomes magnetized - how do the structural, thermal, charging, and collective properties of the system evolve?
  – If a dusty plasma has magnetic particles - how does the system evolve in the presence of uniform and non-uniform magnetic fields?
Dusty plasma experiments with high magnetic fields have been built around the world.

<table>
<thead>
<tr>
<th>Device*</th>
<th>$B_{\text{max}}$ (T)</th>
<th>Diameter (cm)</th>
<th>Axial (cm)</th>
<th>Plasma Source</th>
<th>Dust diameter (μm)</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>JIHT</td>
<td>0.25</td>
<td>3.6</td>
<td>60</td>
<td>DC</td>
<td>5.5</td>
<td>24</td>
</tr>
<tr>
<td>DUSTWHEEL (Kiel)</td>
<td>0.5</td>
<td>15</td>
<td>67</td>
<td>RF</td>
<td>-</td>
<td>28</td>
</tr>
<tr>
<td>Tohoku</td>
<td>4</td>
<td>10</td>
<td>2</td>
<td>DC, RF</td>
<td>5 - 10</td>
<td>25</td>
</tr>
<tr>
<td>MPE</td>
<td>4</td>
<td>20</td>
<td>20</td>
<td>RF</td>
<td>2 - 9</td>
<td>26</td>
</tr>
<tr>
<td>Suleiman (Kiel)</td>
<td>&gt; 4</td>
<td>5</td>
<td>100</td>
<td>RF</td>
<td>0.1 - 0.2</td>
<td>29</td>
</tr>
<tr>
<td>MDPX</td>
<td>&gt; 4</td>
<td>35</td>
<td>200</td>
<td>RF, DC</td>
<td>0.5 - 10</td>
<td>30</td>
</tr>
</tbody>
</table>

*JIHT – Joint Institute for High Temperatures, Moscow, Russia; Kiel – Kiel University, Germany, Tohoku – Tohoku University, Sendai, Japan, MPE – Max Planck Institute for Extraterrestrial Physics, Garching, Germany.

The MDPX experiment based at Auburn University will be the latest experiment in this series.
**Parameters:**

- **Magnetic field:** > 4 T (uniform)
- **Magnetic field gradient:** 1 - 2 T/m
- **Magnets:** 50 cm ID / 125 cm OD
- **Magnet material:** NbTi superconductor
- **Experiment volume:** 45 cm dia. x 175 cm axial
- **Uniform region:** 20 cm dia. x 20 cm axial
- **Project cost:** $2.1 million
- **Project start:** Sept., 2011
- **Construction time:** 2 years

**New capabilities:**

- **Magnetic field:** Variable configuration
- **Plasma chamber:** Large plasma volume
- **Microparticle imaging:** \( r > 0.3 \mu m \)
- **Data storage:** Robust database and storage capabilities

E. Thomas, Jr., et al., PPCF, **54**, 124034 (2012)
E. Thomas, Jr., et al., IEEE TPS, **41**, 811 (2013)
A key feature of the MDPX design is the use of independently controlled magnetic field coils. This enables a variety of magnetic field configurations to be used.

**MDPX configurations**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Uniform field</td>
</tr>
<tr>
<td>2</td>
<td>Linear gradient</td>
</tr>
<tr>
<td>3</td>
<td>Quadrupole</td>
</tr>
</tbody>
</table>
MDPX capabilities: Flexible magnetic configuration

- Uniform
- Linear gradient
- Quadrupole
MDPX capabilities: confinement of charged dust

Preliminary simulations of dust particle trajectories in MDPX

Simulations using DEMON
MDPX: Vacuum Chamber

Main chamber:
- Octagonal frame
- 14 inch (35.56 cm) inner diameter
- 8 ports, 6.5 in x 7 in (16.5 cm x 17.8 cm)

Extensions:
- Cylindrical
- 5.5 inch (14 cm) inner diameter
- 18 inch (45.7 cm) long

Diagnostics:
- LIF
- PIV
- High speed imaging
- Probes
- Spectroscopy
Upcoming studies in the area of magnetized dusty plasmas

• Fundamental studies:
  – Dust transport
  – New dust waves, dust-modified plasma waves
  – Dust $\mathbf{g} \times \mathbf{B}$ drift
  – Wakes structure formation
  – Charge equilibrium and variable charging*
  – Anisotropic Coulomb shielding
  – Dust cyclotron motion
  – Dynamics of non-spherical dust grains*

• Strongly-coupled phenomena:
  – Plasma crystal formation*
  – Modified lattice waves
  – Phonon propagation
  – Dust string formation*

* Studies proposed by collaborators/users
Upcoming studies in the area of magnetized dusty plasmas

• Magnetic field gradients:
  – Behavior of paramagnetic, super-paramagnetic particles
  – Dust grad-$\mathbf{B}$ drifts
  – Phase transition experiments*

• Studies beyond dusty plasmas (via collaborations/users):
  – Physics of highly magnetized, steady-state plasmas
  – Plasma filamentation
  – Plasma source development*
  – Particle imaging [high speed, plenoptic,* Mie ellipsometry*]
  – Plasma-surface interactions in large magnetic fields*
  – Development of novel MRI-based diagnostics*
  – Technology of steady-state superconducting magnet systems
  – Development of cyber-infrastructure systems

* Studies proposed by collaborators/users
Technical challenge: filamentation in rf generated plasmas

The observed plasma glow (rings/spirals/filaments)

With increasing field the plasma more and more develops inhomogeneous plasma structures.

§ Schwabe et al., PRL 106,215004(2011)
MDPX Laboratory Construction
MDPX: Laboratory Facility

To: CTH stellarator lab

AUPSL Magnet Lab
Leach Annex

Black line: calculated 5 Gauss line

Zone 1: green (limited access) \([B < 50 \text{ G}]\)
Zone 2: blue (restricted access) \([B \text{ to } 100 \text{ G}]\)
Zone 3: red (restricted access) \([B > 100 \text{ G}]\)

Microgravity Complex
Plasma Lab (Konopka)

Control Room

AUPSL High Bay Area

To: CTH stellarator lab
MDPX status: magnets under construction

From: Superconducting Systems, Inc. and MIT Fusion Engineering Group
MDPX status: magnets under construction

From: Superconducting Systems, Inc. and MIT Fusion Engineering Group
MDPX status: dust cloud formation

April, 2012

April, 2013 (Chamber v2)

October, 2012
8 µm diameter silica particles in 22 mTorr, 3 W, argon plasma

Preliminary tests of dusty plasma confinement
MDPX status: diagnostic development is in progress
Status: magnets in final assembly, chamber is being tested
Initial research plans for MDPX

MDPX Research Program

Goal 1: Magnetization in uniform fields
- Phase 1: Dust particles in magnetized plasmas
  - Rigid body rotation
  - Dust gyromotion
- Phase 2: Magnetized dusty plasmas in uniform fields
  - Grain charging
  - Inter-dust forces
  - Plasma waves and dust waves

Goal 2: Magnetization in non-uniform fields
- Phase 3: Magnetized dusty plasma in field gradients
  - Gradients on magnetic particles
  - Strongly coupled effects
Summary

- Charged dust, magnetic fields, and plasmas co-exist in many laboratory, fusion, and astrophysical environments.

- The technical expertise is now available to develop a new, flexible, multi-user experimental facility for the study of magnetized dusty plasmas.

- The MDPX facility is under development at Auburn University.
  - Vacuum vessel (V1 and V2) have been built and tested.
  - Magnet construction is ongoing, expect delivery in late Fall, 2013.
  - Diagnostic development is ongoing.
  - Begin magnetic field operations before end of 2013.

- The modular design of MDPX enables a variety of scientific investigations beyond dusty plasmas: properties of magnetic materials, highly magnetized plasmas, etc.

- Open invitation to collaborators/users
  - Seeking proposals for a broad range of plasma and/or dusty plasma experiments that can make use of steady-state, high magnetic fields.
  - Begin first collaborative experiments by Summer/Fall, 2014.
The people who did the work!

**MDPX team:** Dr. Ross Fisher (post-doc), Mr. Darrick Artis (technician / master of all)  
Stephen Adams, Spencer LeBlanc, Brian Lynch, Keith Wood (graduate students)

And a small army of undergraduates:
Matt Gill, Kevin Gilmore, Joseph Shaw, Robert Sutherland,
Taylor Hall, Shane Moorhead, Christian Polka, Daniel Robinson, James Schloss

Magnet design and construction:
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LANL, NRL, PPPL
Kiel Univ., Univ. of Delhi, IPR (India), Max Planck Inst./DLR