Complex/Dusty Plasma Physics – from Laboratory to Space

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Outlook

Introduction Plasma and Dusty Plasma
History of Dusty Plasma Research
Experiments in the Laboratory
Experiments in Space
Conclusion and Outlook
What is a Plasma?

Plasma:
- fourth state of matter
- most disordered state of matter
- 99% of the visible Universe is Plasma
What is a Dusty Plasma?

- Gas
- (partly) ionised plasma
- Dust
- Friction
- Charge
- Liquid
- Solid
What is a Dusty Plasma?

Dusty Plasma

gas → Dusty Plasma → plasma

dust

liquid

solid
The first observations of dust in a laboratory plasma were made by Langmuir. He reported these observations on September 18, 1924 at the Centenary of the Franklin Institute in Philadelphia.


“... we have observed some phenomena of remarkable beauty which may prove to be of theoretical interest.”
Dusty Plasma History – Space

• “plasma” is everywhere in the Universe
• a fraction of this plasma is “dusty“:
  • Galaxies, interstellar clouds, star forming regions, planetary discs, comets, our atmosphere, planetary rings
Dust in processing plasmas

Unexpected dust problems in plasma-surface processing: pioneering works
-e.g. etching (SiO\(_2\)): G. Selwyn & al, J. Vac. Sci. Techn. A 7, 2758, 1989.


Images from Gary Selwyn: The original discovery that RF plasmas (etching/deposition) can be appropriate medium for particle growth in the gas phase and particle levitation.
Dust Particles

• **sizes** from large molecules via clusters to mm, typical size µm
• **shape**: spherical, elipsoidal, rod like, fractal, flake
Coulomb solid of small particles in plasmas

H. Ikezi
GA Technologies Inc., P. O. Box 85608, San Diego, California 92138
(Received 11 December 1985; accepted 11 March 1986)

Small particles in plasmas can form a coulomb lattice. The conditions for solidification in a laboratory plasma are discussed.
1994: Discovery of Plasma Crystals in the Lab

Plasma Crystal: Coulomb Crystallization in a Dusty Plasma

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DLR, Institut für Raumfahrttechnik, 51140 Köln, Germany
(Received 25 January 1994)

A macroscopic Coulomb crystal of solid particles in a plasma has been observed. Images of a cloud of 7-μm “dust” particles, which are charged and levitated in a weakly ionized argon plasma, reveal a hexagonal crystal structure. The crystal is visible to the unaided eye. The particles are cooled by neutral gas to 310 K, and their charge is >900 e, corresponding to a Coulomb coupling parameter \( g > 20/700 \). For such a large \( g \) value, strongly coupled plasma theory predicts that the particles should oscillate in a Coulomb crystal in agreement with experimental findings.

25 years of Plasma Crystals

Independent discovery in 1994 by 4 groups:

Dusty $\rightarrow$ Complex Plasma?

Complex Plasma

- gas
- cold plasma
- microparticles
- liquid
- solid
Complex Plasmas

Complex plasmas provide a new experimental approach for fundamental studies of strong coupling phenomena – “fully resolved dynamics at the individual particle level”.

- Particles individually visible
- Atomistic dynamics virtually undamped
- Systems up to $10^9$ particles
- Classical system for liquids
- Classical system for crystals
- Binary mixtures

... but gravity disturbs fundamental investigations
## Multi-scale research approach

<table>
<thead>
<tr>
<th>“Microscopic” scale</th>
<th>“Macroscopic” scale</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Plasma-particle interactions</strong></td>
<td><strong>Particle-particle interactions</strong></td>
</tr>
<tr>
<td>• Particle charging</td>
<td>• Collective effects</td>
</tr>
<tr>
<td>• Plasma screening</td>
<td>• Plasma mediated (wakes, shadowing) interactions</td>
</tr>
<tr>
<td>• Plasma absorption on the particles</td>
<td>• Thermodynamic properties</td>
</tr>
<tr>
<td>• Charge fluctuations</td>
<td>• Phase transitions</td>
</tr>
<tr>
<td>• Surface physics/chemistry</td>
<td>• Critical phenomena</td>
</tr>
<tr>
<td>• Plasma flows and resulting forces</td>
<td>• Transport properties</td>
</tr>
<tr>
<td>• Other forces (thermophoresis, polarization, radiation)</td>
<td>• Wave phenomena</td>
</tr>
<tr>
<td>• etc.</td>
<td>• etc.</td>
</tr>
</tbody>
</table>

- Plasma physics, astrophysical plasmas, fusion research, technological applications
- Strongly coupled systems, soft condensed matter, material science, phase transitions
Experiments in the Laboratory
2-D Set-up (Earth Laboratory)

(a) 2-D plasma crystal (>> 5000 particles)

HeNe laser horizontal sheet
CCD camera (top view)
lower electrode
diode laser vertical sheet
micro lens
microspheres
video camera (side view)

RF

QE

mg

particle

sheath

lower electrode

height

potential

GEC-RF Reference Cell
Experiments on 2-D systems

- Phonons excited by particle thermal motion

- Dislocations generated by excessive shear stress

- Recrystallization of a 2D Plasma Crystal

- Mach cones caused by extra particles beneath the lattice or laser excitation

- Mode-coupling instability due to plasma wakes
Science Question: Limiting speed of dislocations

- **Controversial subject**: The common wisdom was that a gliding edge dislocation cannot surpass the sound speed of shear waves $C_T$, as the energy radiated by a dislocation becomes infinite at $C_T$.

- **However**, this was never before observed experimentally.

- **Eshelby** predicted (Eshelby, Proc. R. Soc. London 1949) that an edge dislocation can glide at a particular speed of $\sqrt{2} C_T$ without any radiation at all.

- **Supersonic dislocations** moving at $1.3 C_T - 1.6 C_T$ were obtained in atomistic computer simulations (Gumbsch and Gao, Science 1999).
“Gliding dislocations” in 2D plasma crystals

Stress on the plasma crystal was introduced through a slow rotation.
Dislocations observed at kinetic level

- triangulation
- bond-orientation
- vorticity

$v > \text{sound speed} \quad \rightarrow \quad \text{Mach cone}$

3-D Set-up (Earth and Space Lab)
Dust Agglomeration in Waves

MF particles, 1.28 µm diameter

Schwabe, et al., PRL 2007
Dust Agglomeration in Waves

Du, et al., NJP 2010
Dust Agglomeration in Waves
Ice particle growth in D$_2$-O$_2$ plasma

Shimitsu al., JGR 2010
Ice particle growth in plasma with H$_2$O

Chai et al., APJ 2015
Gravity

- Well-defined 2D systems can be formed and investigated at the kinetic level (phase transitions, defect propagation, etc.)
- Force-free 3D systems are not achievable

Gravity

- Microgravity is possible
- Full 3D systems are possible
- Background plasma is more or less homogeneous
- Weaker forces like ion drag now dominate the system
### How to overcome gravity?

<table>
<thead>
<tr>
<th>Method</th>
<th>μ-g Time</th>
<th>μ-g Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drop Tower</td>
<td>~ 4-9 s</td>
<td>very good</td>
</tr>
<tr>
<td>Parabolic Flights</td>
<td>20-25 s</td>
<td>ok</td>
</tr>
<tr>
<td>Rocket Experiments</td>
<td>6 – 20 min</td>
<td>very good</td>
</tr>
<tr>
<td>Space Experiments</td>
<td>Days or Month</td>
<td>very good</td>
</tr>
</tbody>
</table>
Russian-German/European Labs on ISS

Past:
• PKE-Nefedov: 2001 – 2005
• PK-3 Plus: 2006 - 2013

Current:
• PK-4
  • Scientific operation since Oct. 2015
  • Research on fluid and flowing systems

Future:
• Ekoplasma
  • Development of the next generation lab
  • Expanding the accessible parameter range by orders of magnitudes
PK-4 – dc plasma chamber
Results from µg experiments

- electrorheological plasmas
- phase separation in binary mixtures
Electrorheological (ER) fluids

- Electro/magnetorheological (ER/MR) fluids are suspensions of microparticles in a non-conducting liquid or gas.
- Interparticle interaction and hence structures formed by microparticles in ER/MR fluids is governed by external electric/magnetic fields.
- ER/MR fluids represent a broad class of viscoelastic media: At low fields they are “normal” fluids. Above a critical field, at low shear stresses ER/MR fluids behave like elastic solids and at high stresses – as viscous liquids.
Electrorheology in Complex Plasmas

- interaction different compared to colloidal fluids
- charge plays an important role
- need for an alternating field

\[ U_0 = 26 \text{ V} \]

\[ U_0 = 66 \text{ V} \]

(Ivlev et al., PRL 2008)
Outlook: Phase diagram of ER media

ER media exhibit rich variety of phase states, depending on the packing fraction of particle $\eta$ and electric field $E$.

Of particular interest are the bco-bct second-order transition in solids (Yethiraj & van Blaaderen, Nature 2003) and the isotropic-to-string transition in fluids at low $\eta$ and $E$ (Ivlev et al., PRL 2008).

(Hynninen & Dijkstra, PRL 2005)
PK-4 - Formation of ordered structures in ER-Plasmas

Side view of the suspension

Cross-sectional view

Structure factor of the cross-sectional view

argon, 0.2 mbar pressure, symmetric polarity-switching with 0.5 mA current, 500 Hz frequency
Two-component fluids

Phase separation

• the "oil-water problem" investigated at the level of individual particles.

• How small can the system be and still separate?
• What is the transition to thermodynamics at the smallness limit?
• What is the role of the interaction potential?
Two component fluids - complex plasmas

First kinetic studies of phase separation

This makes binary complex plasmas unique for modeling the phase separation at the atomistic level – no other known system can provide this!
Nonadditivity in pair interactions

Equilibrium of binary mixtures is characterized by generalized Berthelot mixing rule,

\[ W_{12} = (1 + \delta) \sqrt{W_{11} W_{22}} \]

where \( W_{ij}(r) \) is the pair interaction energy \((i,j = 1,2)\) and \( \delta \) is the nonadditivity parameter:

- For \( \delta > 0 \) particles 1 and 2 tend to “avoid” each other \( \Rightarrow \) phase separation.
- For \( \delta < 0 \) particles 1 and 2 tend to stay close to each other \( \Rightarrow \) mixing.

**In complex plasmas, \( \delta \) is always positive!**
Spinodal line

The spinodal line in the \((\Gamma_1 \kappa^{-2}; x_1)\) space is

\[
\frac{\Gamma_1}{\kappa^2} \approx \frac{1}{48\delta} \left( \frac{1}{x_1} + \frac{1}{\tilde{Z}^2} \right)
\]

Here \(\Gamma_1 = e^2 Z_1^2 / T \Delta\) is the coupling parameter, and \(x_1 = n_1 / \langle n \rangle\) is the concentration of (smaller) particles 1. Also, \(\tilde{Z} = Z_\gamma / Z\).

For the "droplet formation" experiment mentioned above (with \(\kappa = 4 - 5\)), the critical point is located at \(\Gamma_1 \approx 50\) and \(x_1 \approx 0.8\).

Ivlev et al., EPL 2010

Future perspective: this allows controlled studies of critical point phenomena at the individual particle level for the first time.
PK-4 on the ISS

ESA Columbus Modul

EPM Facility on ISS

PK-4 Experiment

PK-4 in EPM
PK-4 on the ISS

Laser excited shear flow – experiment from 14.2.2017

- Investigation of a many-body system on the microscopic and kinetic level
- How many particles are needed for collectivity?
- How do macroscopic quantities (e.g. viscosity) develop?
Density waves

Negative polarity

Positive polarity

Jaiswal, PoP 2018
Summary

• complex/dusty plasma is an interdisciplinary research field combining all four states of matter
• complex plasma is a new state of soft matter
• where does it belong to? fundamental physics, fluid physics, material physics, soft matter physics, space physics
  → it covers all - allows a broad range of basic/fundamental studies
Conclusion - Research under μg conditions

• complements the research on ground
• allows „pure“ investigations in the bulk plasma and new insights into:
  • Plasma-particle interaction
  • Particle-particle interaction
  • Start of collective behaviour
• Opened new research topics:
  • Electrorheological plasmas
  • Phase separation in binary mixtures
→ continue research of plasma state of soft matter
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