Complex plasmas are composed of a weakly ionized gas and charged microparticles and represent the plasma state of soft matter. Complex plasmas have several remarkable features: dynamical time scales associated with microparticles are ‘stretched’ to tens of milliseconds, yet the microparticles themselves can be easily visualized individually. Furthermore, since the background gas is dilute, the particle dynamics in strongly coupled complex plasmas is virtually undamped, which provides a direct analogy to regular liquids and solids in terms of the atomistic dynamics. Finally, complex plasmas can be easily manipulated in different ways — also at the level of individual particles. Altogether, this gives us a unique opportunity to go beyond the limits of continuous media and study — at the kinetic level — various generic processes occurring in liquids or solids, in regimes ranging from the onset of cooperative phenomena to large strongly coupled systems.

In the first part of the talk I will highlight some of the basic and new physics which complex plasmas enable us to study, and in the second (major) part I focus on strong coupling phenomena in an interdisciplinary context.

I will emphasize the connections with complex fluids and address a number of generic liquid- and solid-state issues. Finally, I also briefly discuss application-oriented research.
Complex Plasmas

The Plasma State of Soft Matter

Acknowledgements: Thanks to
- the complex plasma groups in Moscow and Garching
- the Agencies DLR, ESA and ROSCOSMOS
- approx. 30 cosmonauts/astronauts
- the companies RSC-Energia and Kayser-Threde
Outline

- Introduction
  - Plasma
  - Complex (dusty) plasma
  - Soft matter
- 2-D complex plasma
- 3-D complex plasma
  - lab
  - space
- Summary
- Applications
What is a plasma?

| Crystal | Liquid | Gas | Plasma |

Plasma = (partially) ionized gas (4. state of matter)
99% of the visual matter in the universe is in the plasma state
Plasma

Sun
Plasma

Sun

Fusion

Neon-Light
Plasma

Sun

Fusion

Neon-Light

Star forming regions
Complex ("Dusty") Plasma

- 99% of the visible matter in the Universe is ‘plasma’
- A large fraction of this plasma is ‘dusty’:
  - Galaxies, interstellar clouds, star formation regions, planetary disks, comets, our atmosphere, planetary rings, all plasma processing devices, even plasma fusion reactors, etc.
Complex Plasmas

- 4th state of matter (99%)
- Most disordered state of matter
- Electrons & ions
- Charge on the particle
- ~10,000 e⁻ on a particle of 5 µm diameter
- Electric screening
Complex Plasmas

Coulomb interaction

- strong coupling

- "liquid" plasma
Complex Plasmas

- Coulomb interaction
  - strong coupling
  - Coulomb crystallisation
- Plasma Crystal

\[ \Delta \sim 0.2 \text{ mm} \]
New Physics

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

- Systems up to $10^9$ particles
- Particles individually visible
- Optically thin to 1000 lattices
- Atomistic dynamics virtually undamped
- Tunable interaction potential
- ‘Designed’ systems (2D, 3D)
- Full magnetisation possible
- Binary mixtures
Pierre-Gilles de Gennes* introduced this term to describe the class of materials that are:

- supramolecular, exhibit macroscopic softness, have metastable states and a sensitivity of their equilibrium to external conditions.

They typically have energies $kT$ of about room temperature, i.e. the physics is far above quantum states.

* Nobel Prize in Physics, 1991
Its a matter with **liquid** and **solid** properties!
The solid and liquid forms of complex plasmas are:

...´ supramolecular,

... exhibit macroscopic softness,

... have metastable states,

... sensitivity of their equilibrium to external conditions,

... and kT is far above quantum states´ ...

Pierre-Gilles de Gennes (Nobel Prize 1991)

→ plasma state of soft matter
The aim of the research is threefold:

1. to study this new form of matter and determine its properties,
2. to use these new systems as kinetic models for natural systems that cannot be observed in such detail,
3. to investigate possible technological applications.

Note: The visualisation of complex plasmas is equivalent to viewing an atomic system through a microscope that can identify atoms (0.1 nanometer) and resolve their motion (km/sec at room temperature)!
Complex Plasma Research

in the lab:
• 2-D - 2 ½-D systems
• 3-D systems under stress

under μg (space/ISS):
• large homogeneous 3-D systems

theory and simulation
Experiments in the Laboratory

- Re-crystallisation of a 2-D complex plasma
- Mach cones in 2-D and 3-D systems
- Onset of turbulence
2-D Set-up

GEC-RF Reference Cell

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Recrystallisation – grain boundary melting

→ scale invariant behaviour

Knapek et al. PRL 98, 015004 (2007)
Mach cones are V-shaped disturbances (shock waves) produced by a supersonic object moving through a medium.
Mach cones are V-shaped disturbances (shock waves) produced by a supersonic object moving through a medium.

\[ \sin \mu = \frac{C_s}{V} = \frac{1}{M} \]

Havnes et al. (J. Geophys. Res. 100, 1731, 1995) proposed to look for Mach cones in Saturn’s rings during the Cassini mission.

<table>
<thead>
<tr>
<th></th>
<th>Air</th>
<th>Water</th>
<th>Steel alloy</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_s ) (sound speed)</td>
<td>330 m/s</td>
<td>1500 m/s</td>
<td>6000 m/s</td>
</tr>
</tbody>
</table>
Mach cones in 2D systems

- laser excitation of monolayer plasma crystal
  - investigation of shock and wave propagation

\[ C_s (\text{sound speed}) \begin{array}{cccc}
\text{Air} & \text{Water} & \text{Steel alloy} & \text{Complex Plasma} \\
330 \text{ m/s} & 1500 \text{ m/s} & 6000 \text{ m/s} & \sim 1 \text{ cm/s}
\end{array} \]

- observation of Mach cones at microscopic level

\textit{Melzer et al. PRL, 2001, Samsonov et al. PRL, 2000}

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Mach cone in 3-D systems

PK-3 Plus Results from the ISS

Ke Jiang et al., EPL 85 (2009)
The Plasma Chamber

2D

3D
How to overcome gravity constraints and form real 3D systems?

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

- 6.8 μm
- 3.4 μm
- 1.28 μm

Microgravity
- Full 3D systems are possible
- Background plasma is more or less homogeneous
- Theoretical description gets easier
- Weaker forces like ion-drag now dominate the system
"Turbulence is the most important and fascinating outstanding problem in fluid physics" (Feynman).

Investigations at the kinetic (particle) level have not been possible so far, but they could hold the key to understanding this ubiquitous and generic phenomenon.


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Self-organisation in strongly coupled systems: liquid complex plasmas

Onset of turbulence (?) – first kinetic observations

Morfill et al. PRL (2004)
Momentum transfer in the interaction layer

• Three modes of momentum transfer:
  1. Binary collisions
  2. Penetrating particles
  3. Clump (eddy) detachment
If it were H$_2$O...
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>
</tbody>
</table>

(Images of rocket and parabolic flights are present on the page.)
Parabolic flights

we perform parabolic flights annually

Business is the salt of life.
TEXUS sounding rocket

1996 & 1998

Images: Wolfgang Engler (KT)

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In 1998: meeting with Vladimir Fortov (Minister for Science and Technology under President Jelzin at that time)

Let’s have a joint plasma experiment on MIR. It’s no problem...

This was the start for a long-standing cooperation with Russia!
Instead of the "Last" experiment on MIR it became the "First" on the young ISS

**Russian contribution**: launch, ISS resources, cosmonaut training and time, communication, download, etc.

**German contribution**: Development, manufacturing, tests, safety, documentation, etc.

http://www.heavens-above.com/
This joint research Lab, PKE, was installed as the first natural science experiment on the ISS by the first crew!
PKE-Nefedov

• Russian-German project, financed by ROSKOSMOS and DLR
• operational on ISS from March 2001 to July 2005
• 13 experimental missions (45 separate experimental runs) with > 65 h microgravity data
• first long term experiment on „complex plasmas“ in Space
• Result: > 30 publications in refereed journals (fundamental physics)
**PK-3 Plus**

- **Russian-German** project, financed by ROSKOSMOS and DLR, with ESA participation during Astrolab
- **second generation** lab on ISS
- new and more **advanced** hardware and software
- more and better **diagnostics**
- operational since Jan. 2006
- **14 missions** for exploring the new phase space and performing dedicated experiments (>60h µg time)
- > **20 publications** in refereed journals
Research topics under μg

• Crystallisation and melting of large 3-D plasma crystals
  – annealing
  – Including 3-D analysis
• Investigation of isotropic (void free) complex plasmas in the fluid regime at different $T_D$ and $n_D$
  – the critical point?
  – String fluids (with external excitation) in electrorheological plasmas
• Dynamics of lane formation
• Phase separation in binary mixtures
• Influence of gas cleanliness
• Crazy particles
• Shock wave propagation
• Boundaries between different particle sizes
  – Basic experiments with mixtures
• Instabilities occurring at high $n_D$ and low plasma power
  – Heart-beat
  – Filamentary mode
• Lanes form when two species of particles/objects are **driven against each other**.
• Lane formation is a **non equilibrium phase transition**.
• Like-driven particles form **stream lines**, where their mobility is enhanced.
• Lane formation depend on the details of **particle interaction and dynamics**.
• The formation of lanes in high density pedestrian dynamics [D. Helbig et al., Phys. Rev. Lett. 84, 1240(2000)]
• It is found in lots of different driven particle model system
  – colloids [e.g. J. Dzubiella et al., Phys. Rev. E 74, 011403(2006)]
Lane Formation using PK-3 Plus on ISS
experiments are complemented by particle resolved MD simulations
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.
Transition to string fluid

Thomas Reiter:
- ESA Astronaut
- DLR director
- ESA director

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Phase separation
Classical (one-component) fluids

In one-component systems, attraction in the binary interaction potential is the necessary condition for a fluid (liquid-vapor) phase transition.

Physics at the critical point is characterised by scale free behaviour of thermodynamic quantities and universal power-law relations. What is the kinetic origin?

SF$_6$ near critical point

Kenneth Wilson, Nobel Prize 1982
In multispecies systems, one can have a fluid phase transition (phase separation) even when the interaction is purely repulsive.

Example: Colloid-polymer mixtures.

Can we get phase separation in binary complex plasmas?
Microgravity experiments on ISS
Formation of a droplet

Side view: 3.4 μm particles injected in a cloud of 9.2 μm particles

Ivlev et al., EPL 85 (2009)

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Phase separation in complex plasma

- Yes!
  - although only repulsive interaction
  - due to the non-additivity of the interaction between particles 1, particles 2 and particles 1+2

→ investigation of the phase separation in general
→ investigation of the dynamical behavior at the critical point in CP

Ivlev et al., EPL 85 (2009)
μg-research in complex plasmas

PK-1

PK-2

PKE-Nefedov

PK-3 Plus

TEXUS

Discovery Plasma Crystal

1994

1996

1998

2000

2002

2004

2006

2008

2010

2012

μ-gravity experiments

TEXUS

PK-1 & PK-2

PK-3 Plus

PK-1

PKE-Nefedov

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Complex plasmas allow the investigation
- of scale invariant &
- generic processes
in fluid and solid systems at the most fundamental - the kinetic level
→ gain new insights into physics
→ pure fundamental physics
Application - Plasma Medicine

• experience with "cold plasmas" transferred into medicine sector:
  – Plasma sterilisation
  – Plasma medizin – fast growing field

*Methicillin-resistent Staph. aureus, MRSA (gram-positive)*
**Plasma Medicine**
Currently: investigations of plasma wound treatment and prurigo skin diseases
Long term: plasma (design) pharmacology for different diseases

**Plasma Microbiology**
Quantitative in vitro and in vivo investigation of bactericidal, virucidal and fungicidal effects of plasmas

**Plasma Dental Care**
Periodontitis prophylaxis, disinfection of dental cavities, general oral care, equipment disinfection

**Plasma Food Hygiene**
Disinfection of food containers, food surface disinfection, hygiene in food handling, preparation and packaging

**Plasma Hygiene**
Nosocomial and CA infection control (including multi-resistant germs – e.g. MRSA), prevention and containment of contagious diseases, disinfection of medical devices, surface treatment (heat and UV sensitive surfaces)

25th Anniversary Symposium of EPL, 3 & 4 May 2011
Thank you for your attention!