Four-Phase Flow in Dusty Plasma

Simultaneous existence of SOLID-LIQUID-GAS-PLASMA in a medium subject to flow*

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Dusty plasma, comprised of **free electrons**, **free ions**, **neutral atoms**, and **fine particles**, behaves in ways that have opened up a new line of research.

SOLID: The fine particles can form a 2- or 3-dimensional lattice, a *plasma crystal*
*LIQUID: The crystal can melt, transforming to a liquid state via a phase transition
GAS: The liquid state can evaporate, transforming to a gaseous state

SOLID: Fine particles, each having diameter sub-nanometer up to ten micrometers
*LIQUID: Water, biological tissue, blood, ionic fluid
GAS: Air, inert gas, fuel and combustion products,
PLASMA: ionized gas of electrons and ions (positive and negative)

Outline

Plasma is the fourth state of matter

(solid, liquid, gas, plasma)

Three states of Dusty Plasma

(crystal, liquid, gas)

Growing nanoparticles in liquid in contact with plasma

Dusty Plasma characteristics

Solar System applications of Dusty Plasma

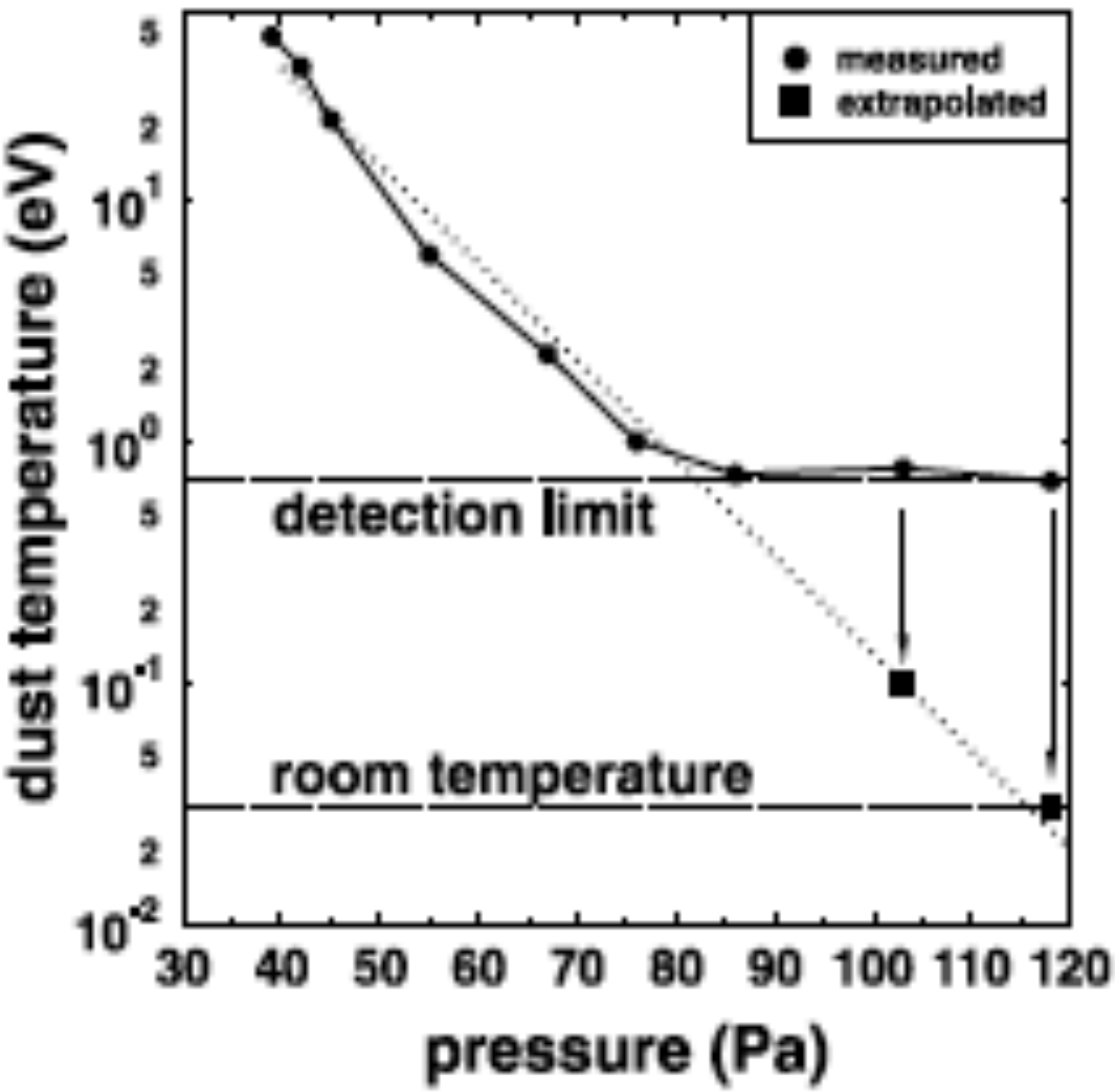
Strongly Coupled Systems and Plasma Crystallization

Charged-particle systems are described by the Coulomb coupling parameter which is defined as the ratio of the electrostatic energy of neighboring particles and their thermal energy.

A system is strongly coupled when the electrostatic interaction exceeds the thermal energy, i.e. when $\Gamma > 1$.

The simplest case is a system of point charges with pure Coulomb interaction, the so-called one-component plasma (OCP). From simulations it is found that crystallization of the charges occurs when Γ exceeds the critical value of $\Gamma_c = 168$. A system with $1 < \Gamma < \Gamma_c$ is in the liquid state, but still strongly coupled.

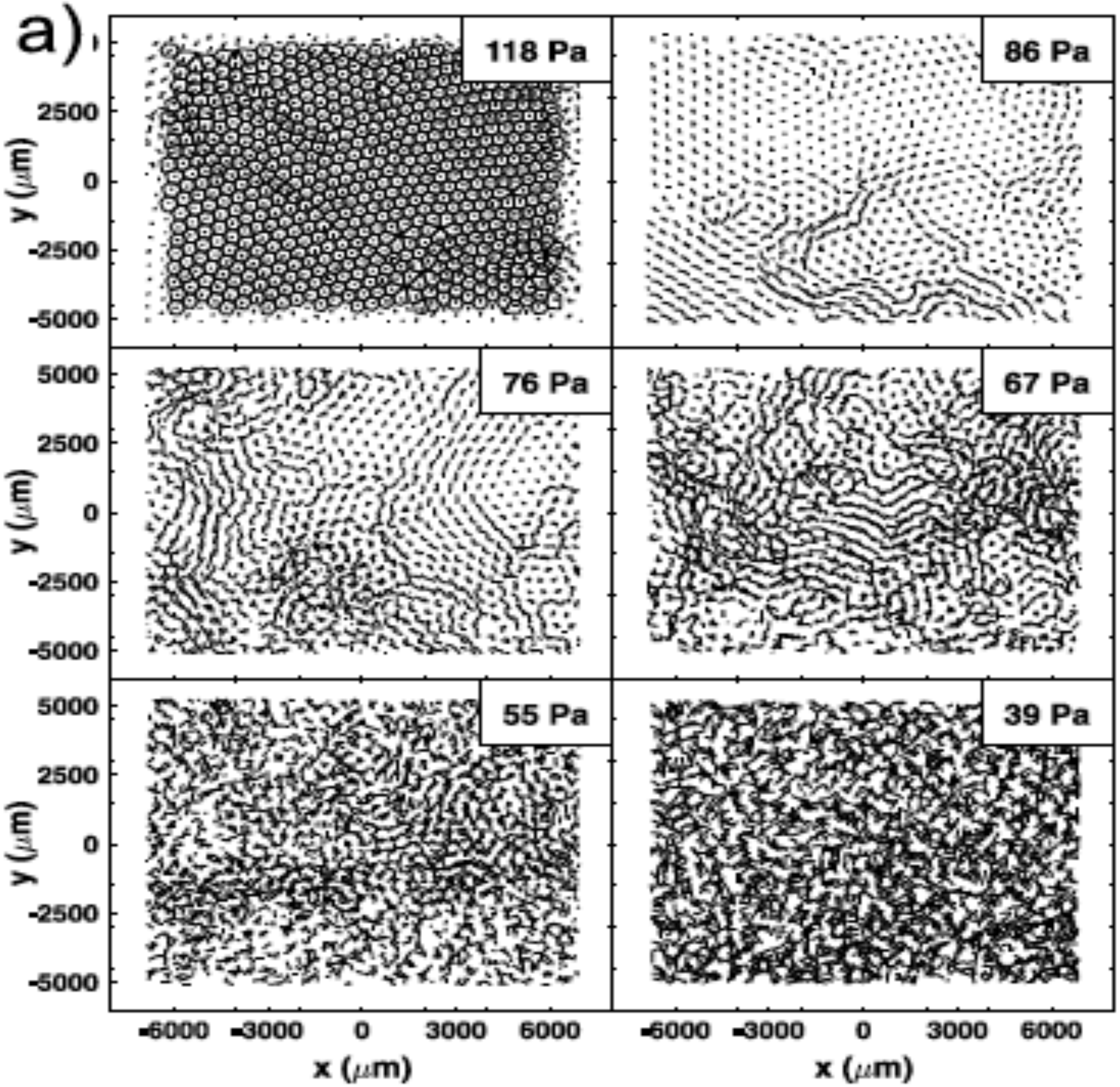
Reducing the neutral-gas pressure increases the fine-particle kinetic energy (dust temp)



… and the dusty-plasma crystal undergoes a phase transition to a dusty-plasma liquid and then to a dusty-plasma gas …

Three states of Dusty Plasma

The four phases of matter can manifest within plasma as three phases of Dusty Plasma, plus the plasma itself

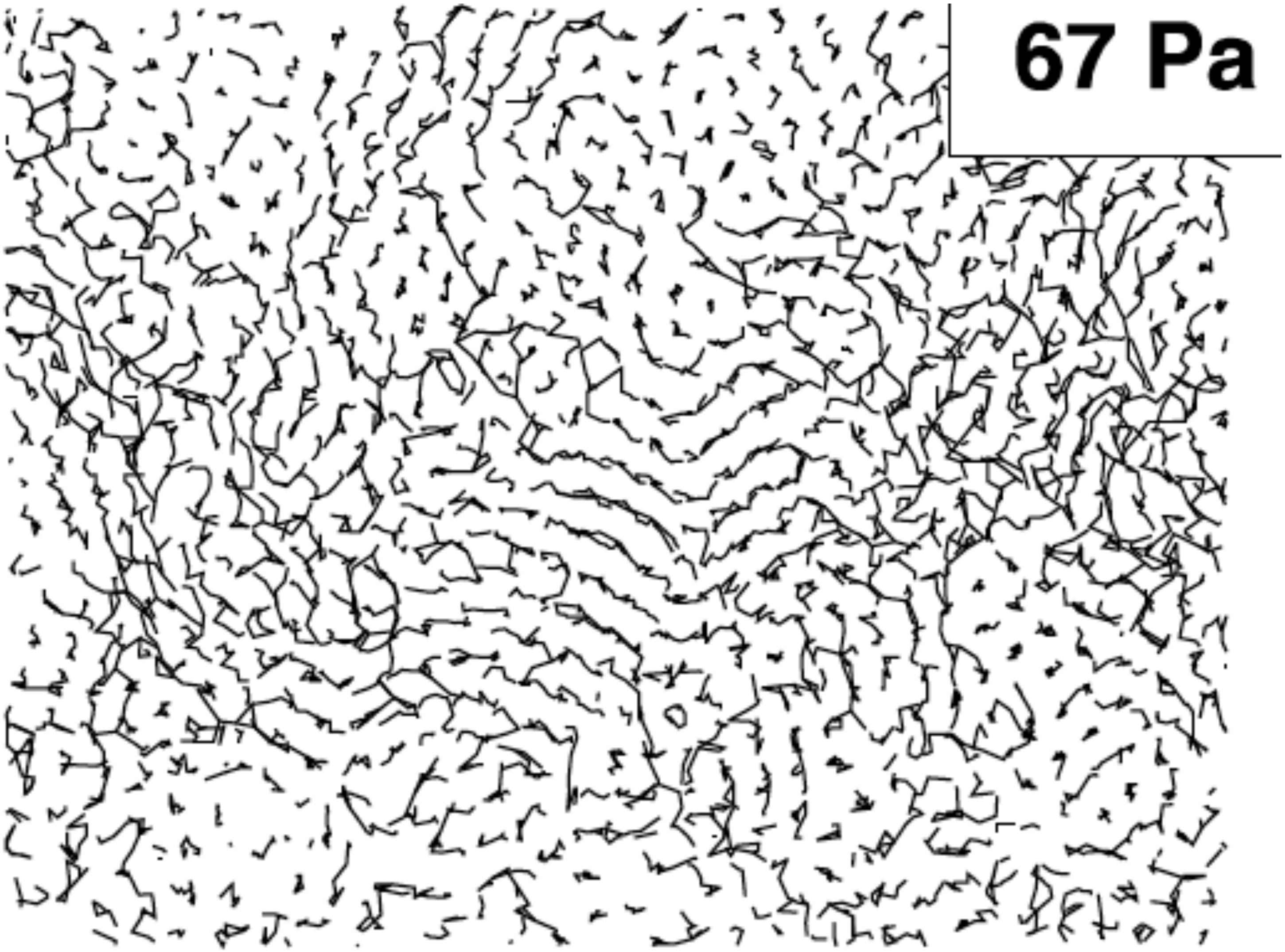


Solid: Fixed-point trajectores

Liquid: Direction-correlated trajectories

Gas: Loss of particle-particle correlation

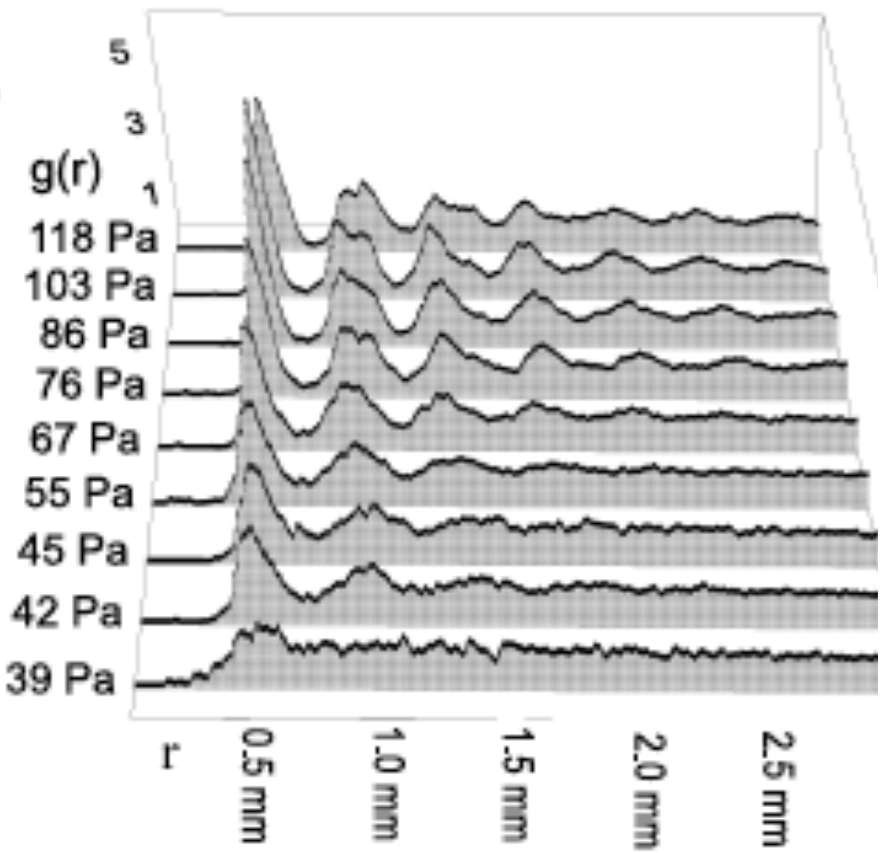
Fluid flow characterizes the dusty-plasma liquid state

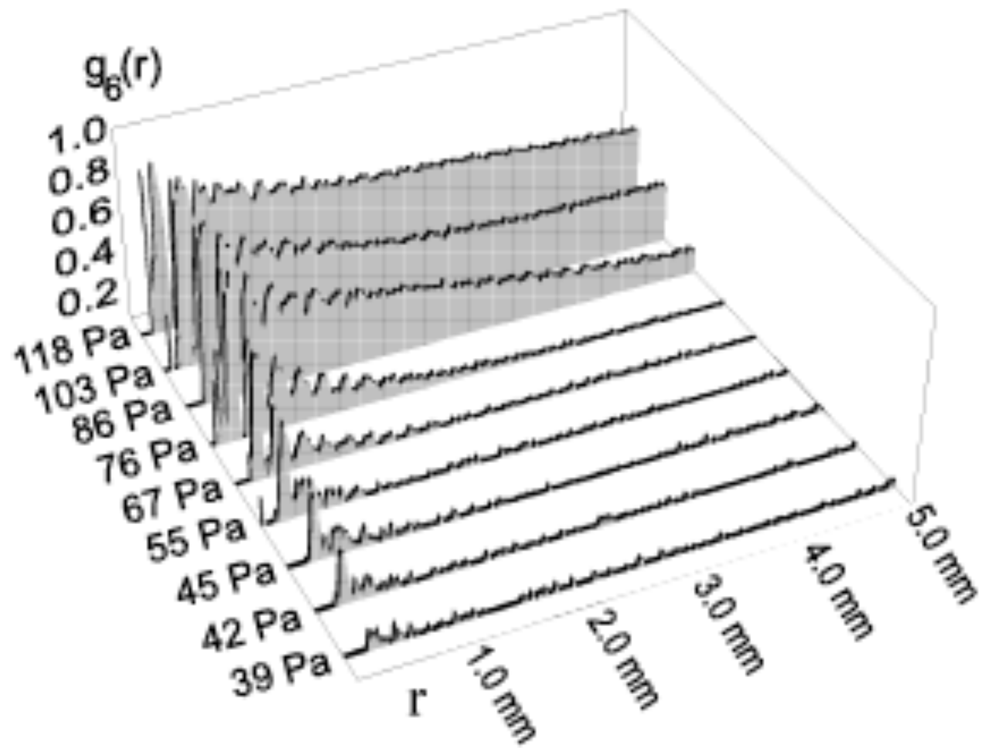


Regionally direction-correlated trajectories are indicated from imaging diagnostics.

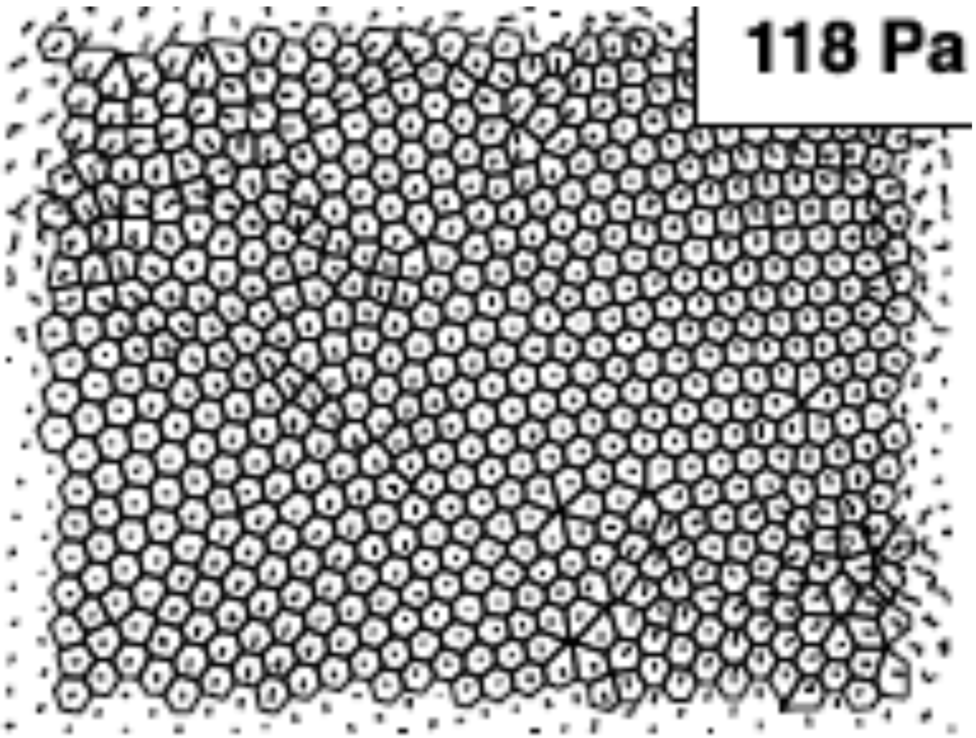
Strongly Coupled Systems and Plasma Crystallization

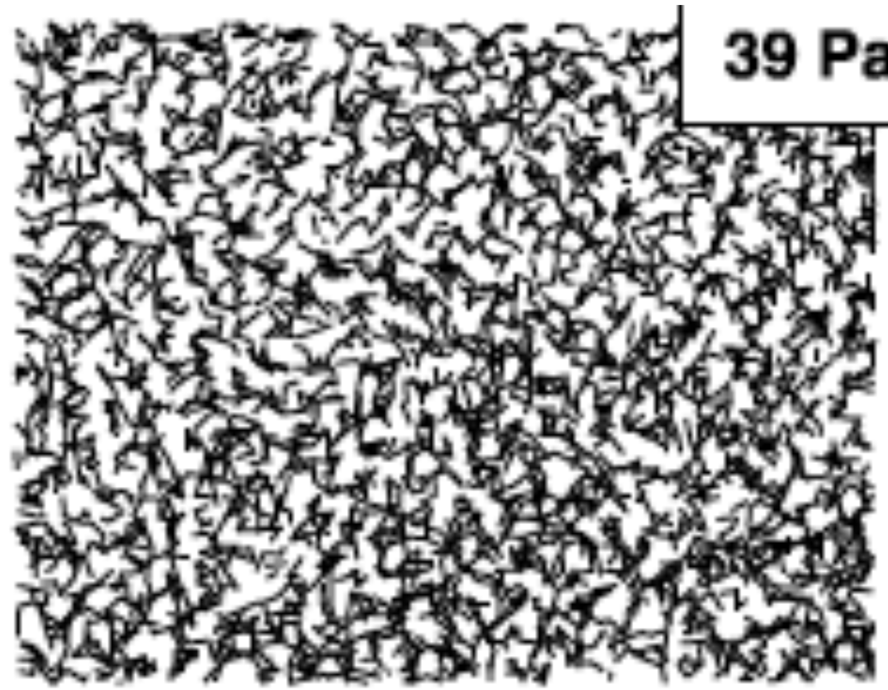
Particle-particle correlation decreases w/ decreasing pressure, indicating transitioning phase.



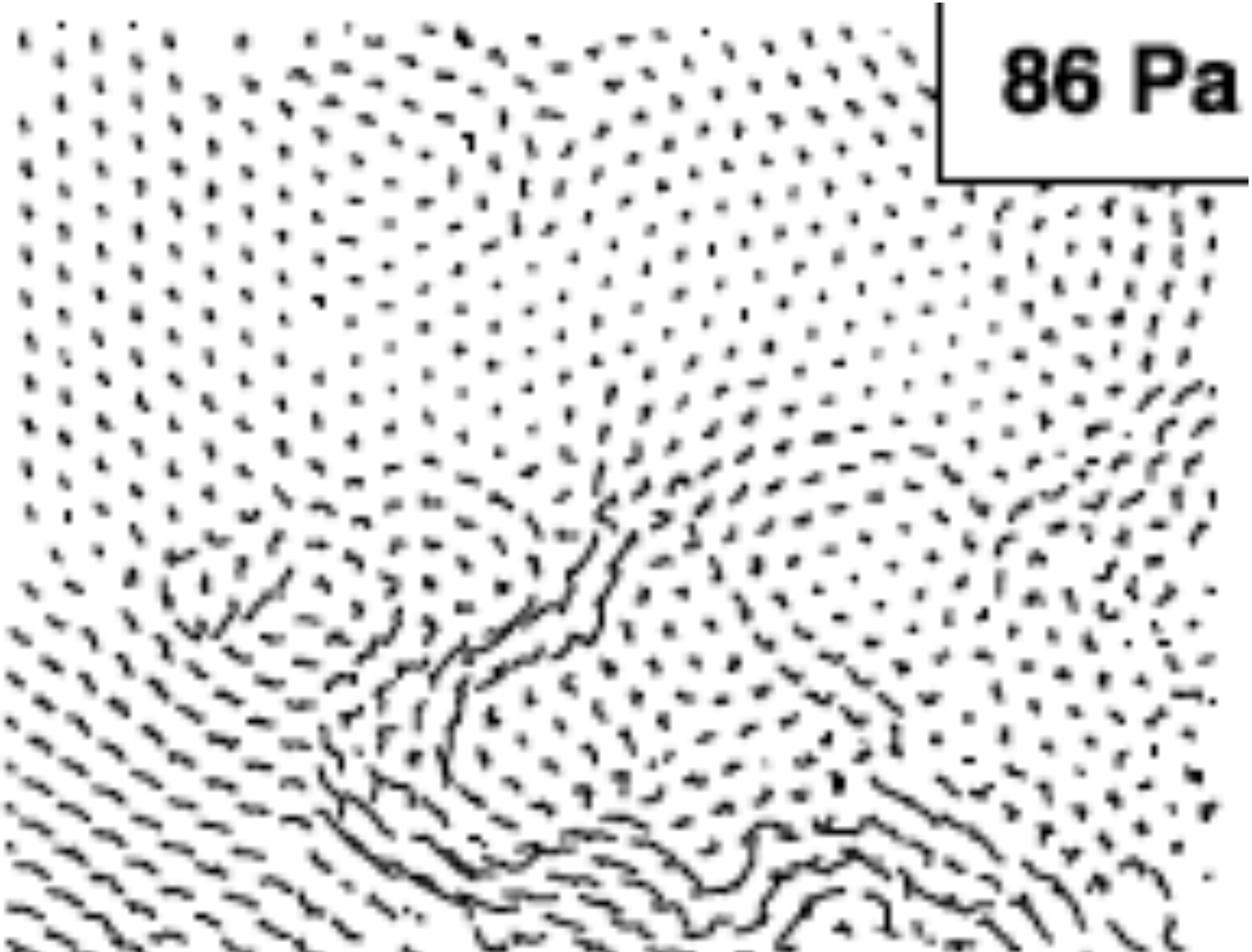


Gas-Solid Flow

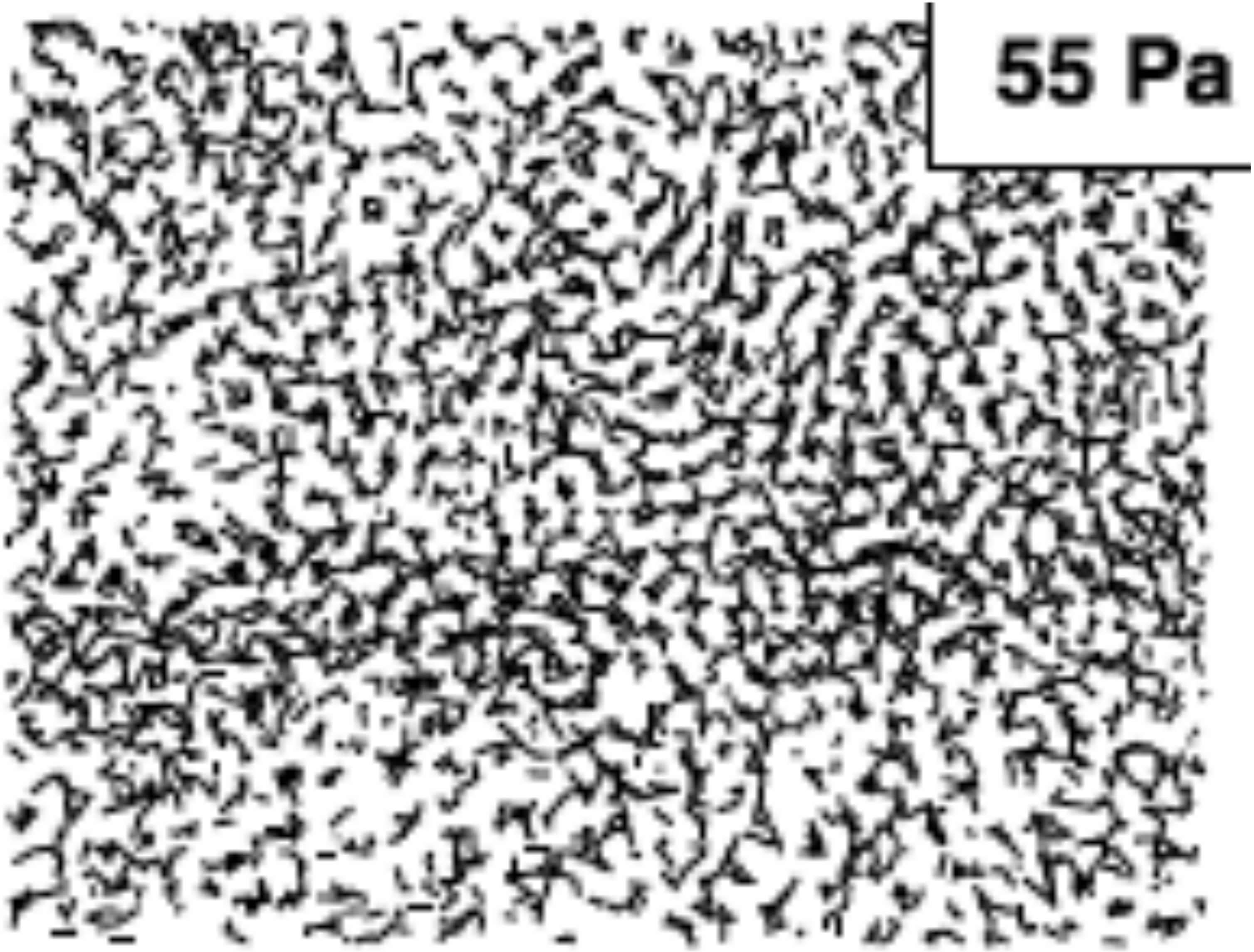




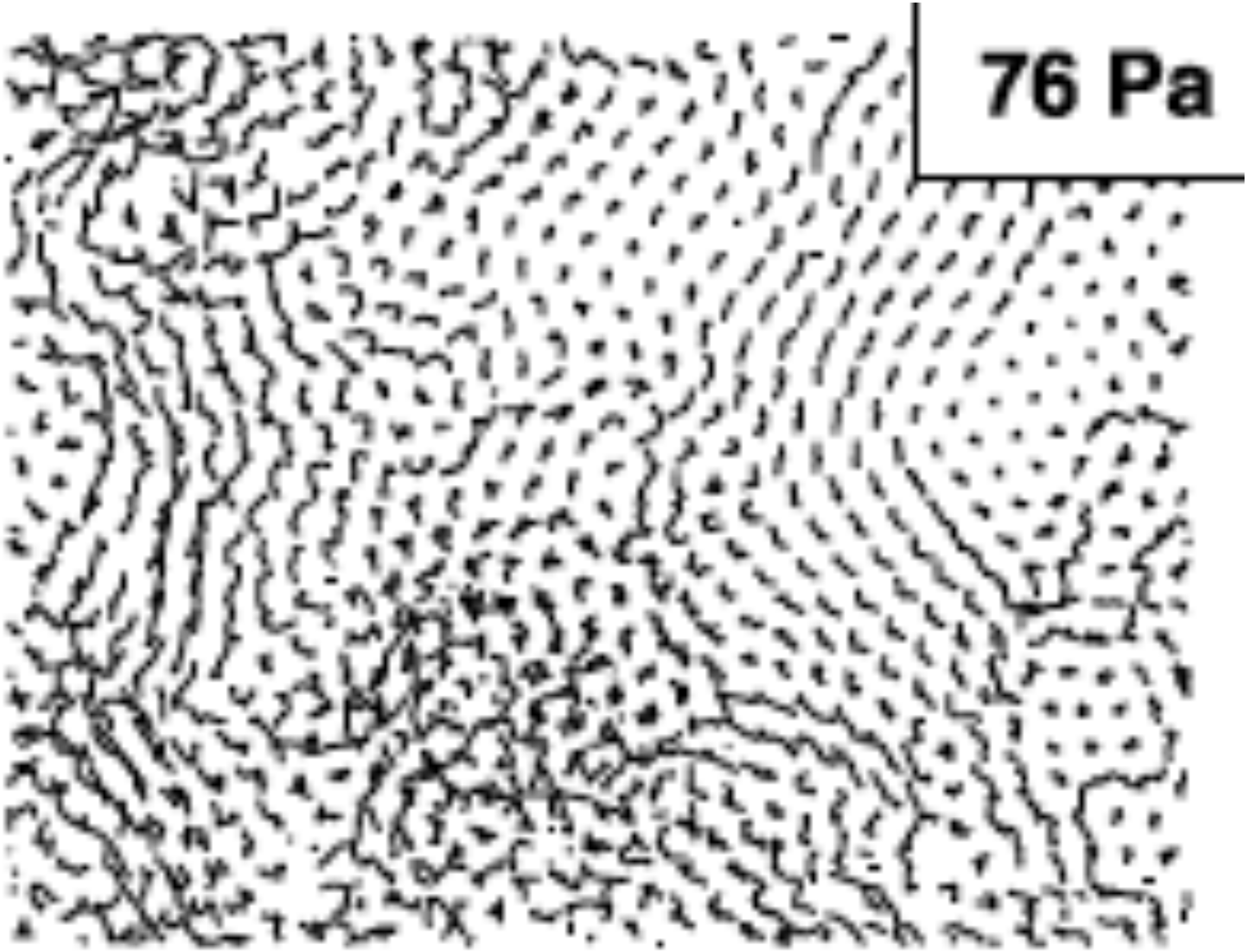
Liquid-Solid Flow



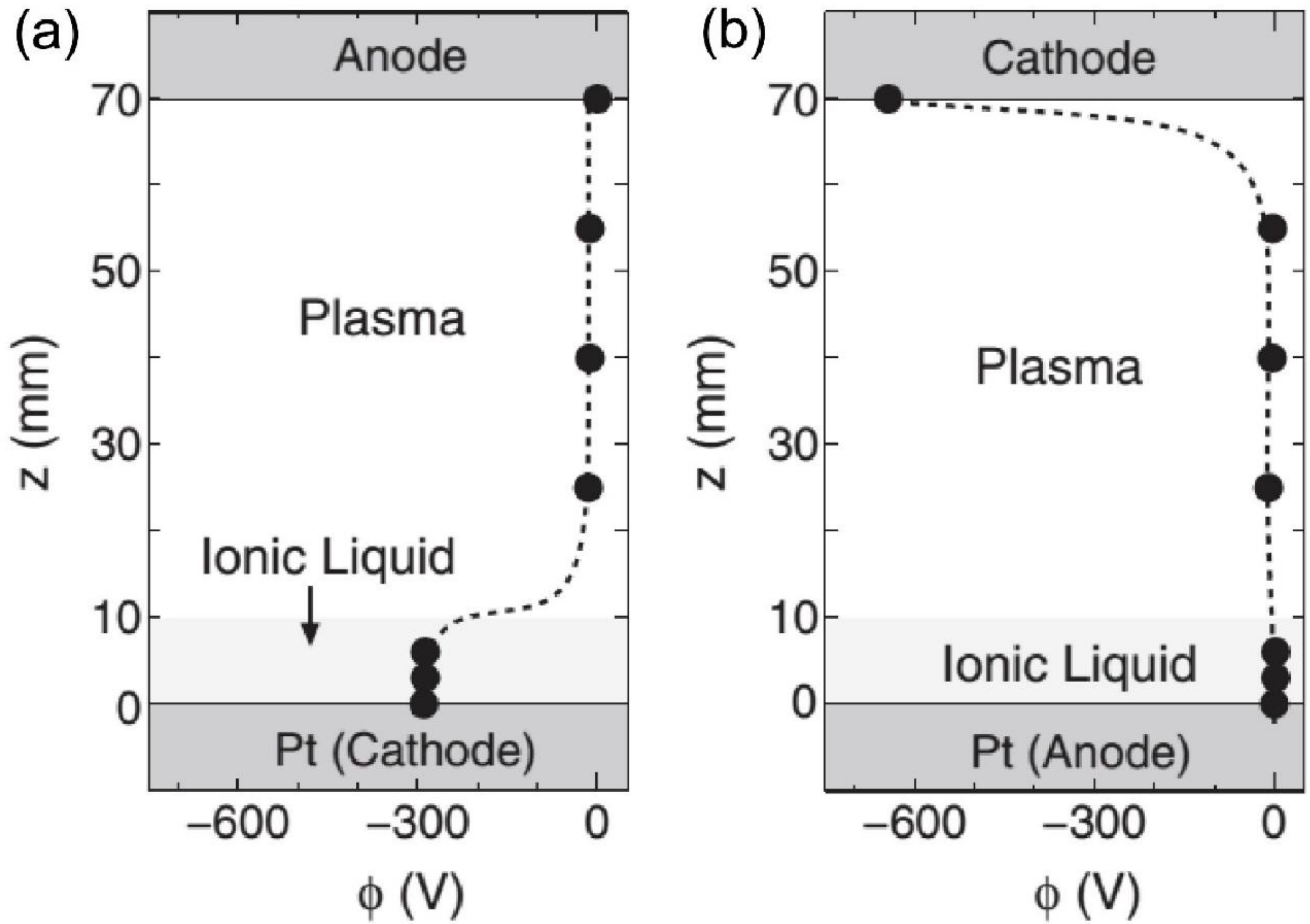
Gas-Liquid Flow



Gas-Solid-Liquid Flow



Plasma potential distributions along the axis of the electrodes for liquid as (a) cathode, and (b) anode



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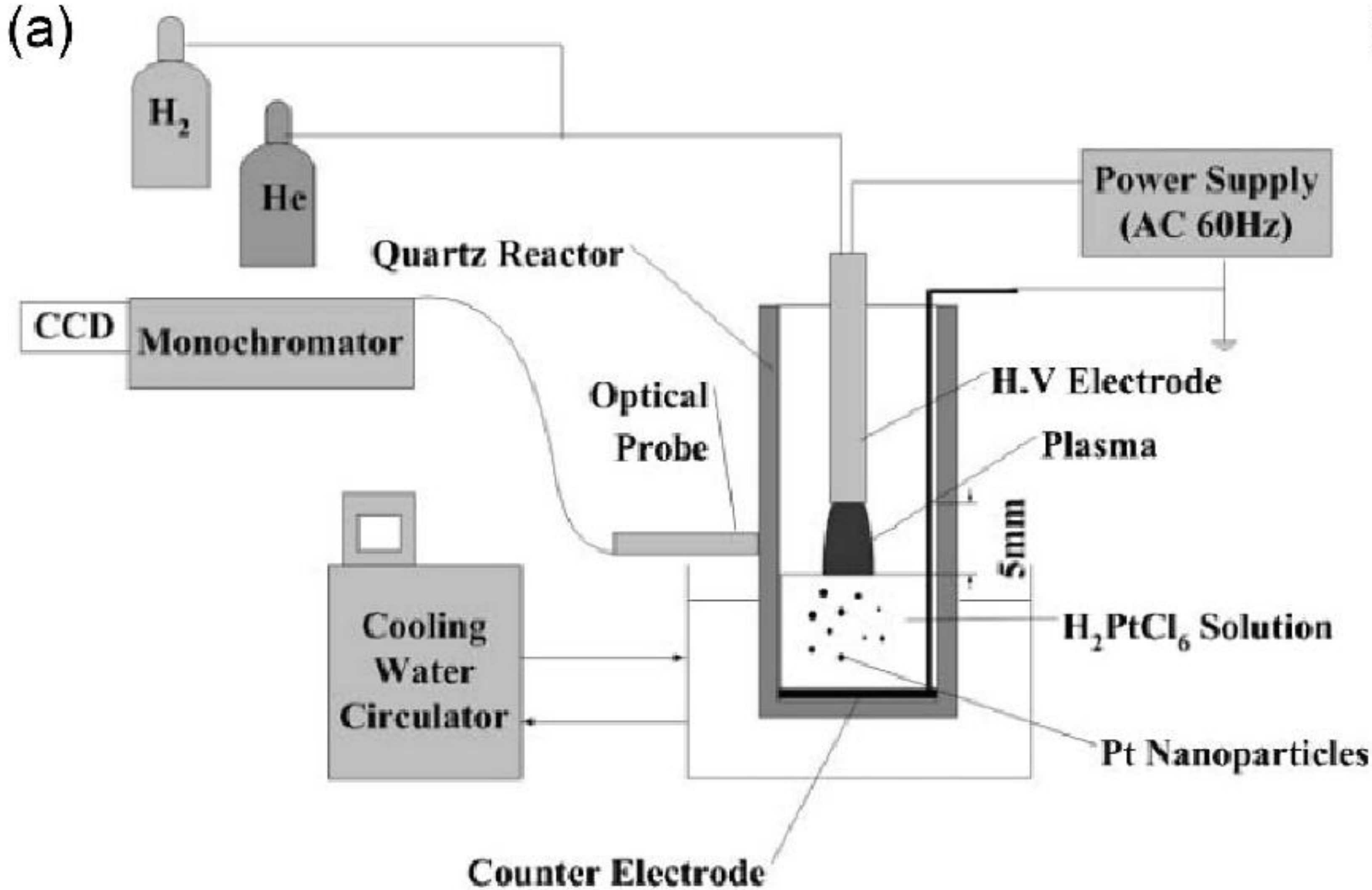
Setup for plasma-liquid synthesis of Pt nanoparticles



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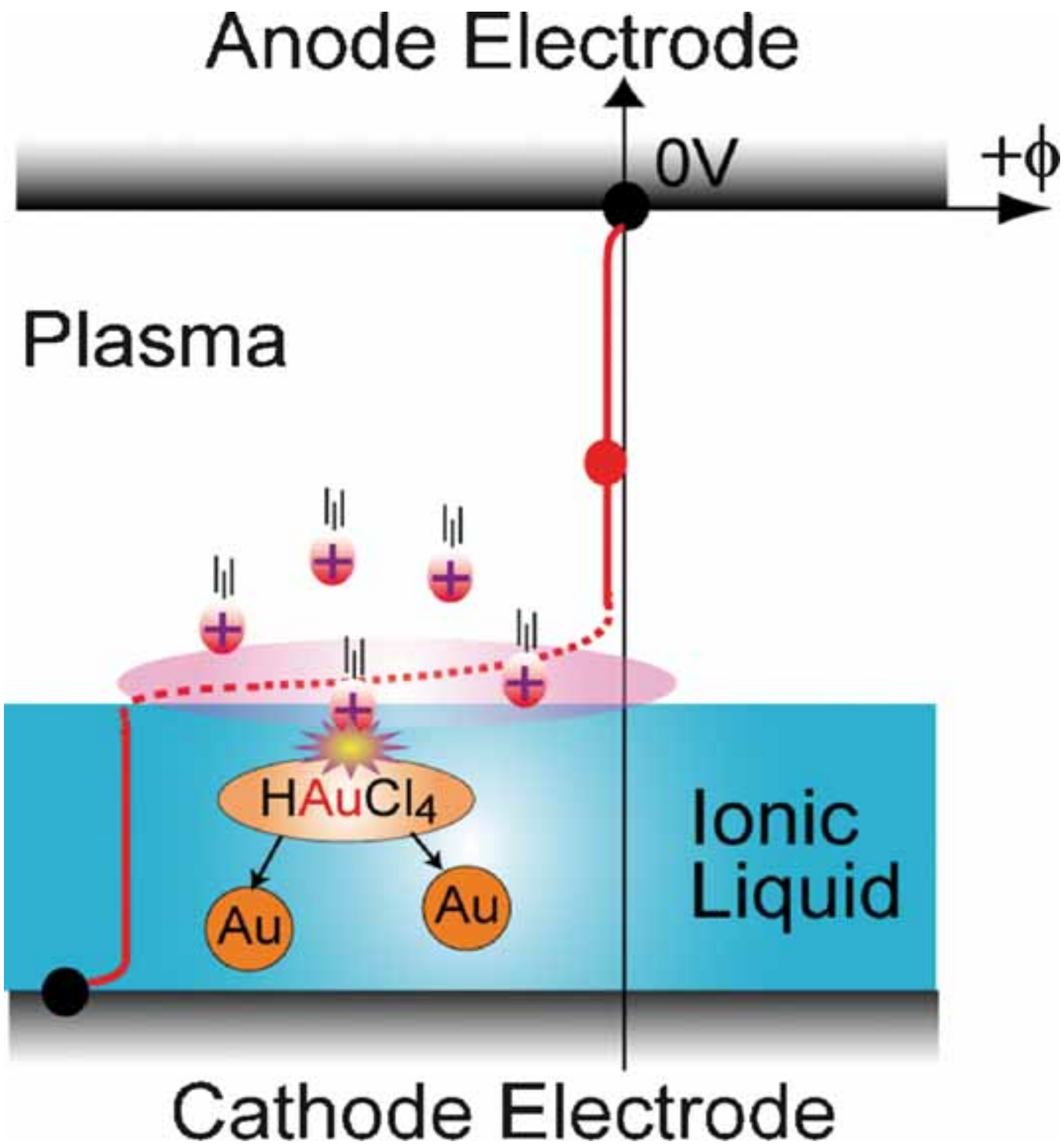
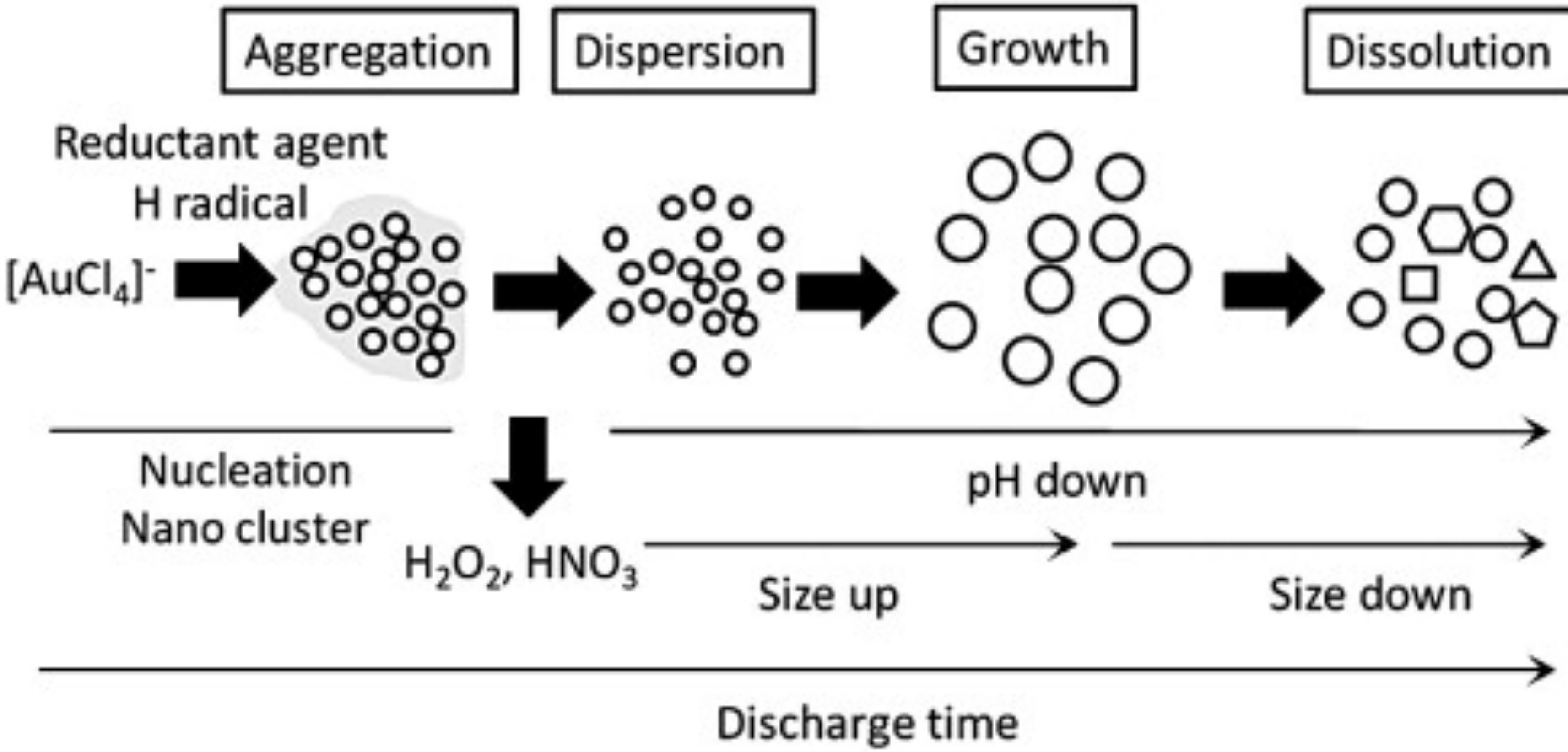
Liquid in contact with plasma

Setup for plasma-liquid synthesis of Gold nanoparticles



Liquid in contact with plasma

Dynamic process of Gold nanoparticle synthesis from plasma in liquid



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Liquid in contact with plasma

Particle Charging

A particle capacitively charges until its surface potential ϕ_s repels enough electrons and attracts enough ions that net current is zero.

Theory and experiment estimate particle charge within a factor of two. The "orbit-motion-limited" (OML) theory assumes collisionless ions. The Gotti-Kortshagen and ABR models assume collisional ions. In OML theory, the currents are calculated by assuming that the electrons and ions are collected if their collisionless orbits intersect the probe's surface.

Surface potential ϕ_s depends on the plasma temperatures and is independent of the particle's size.
Surface charge is proportional to the particle's radius.
A sphere in a non-flowing hydrogen plasma with $T_e = T_i$ has the Spitzer potential

$$\phi_s = -\,2.50 k_B T_e / e.$$

A spherical assumption introduces only a small error,as long as the particle is small.

Reduction of the charge due to high particle density

When $P > 1$, the charge and floating potential are significantly diminished while, for $P << 1$, the charge and floating potentials approach the values for an isolated particle. In practical units,

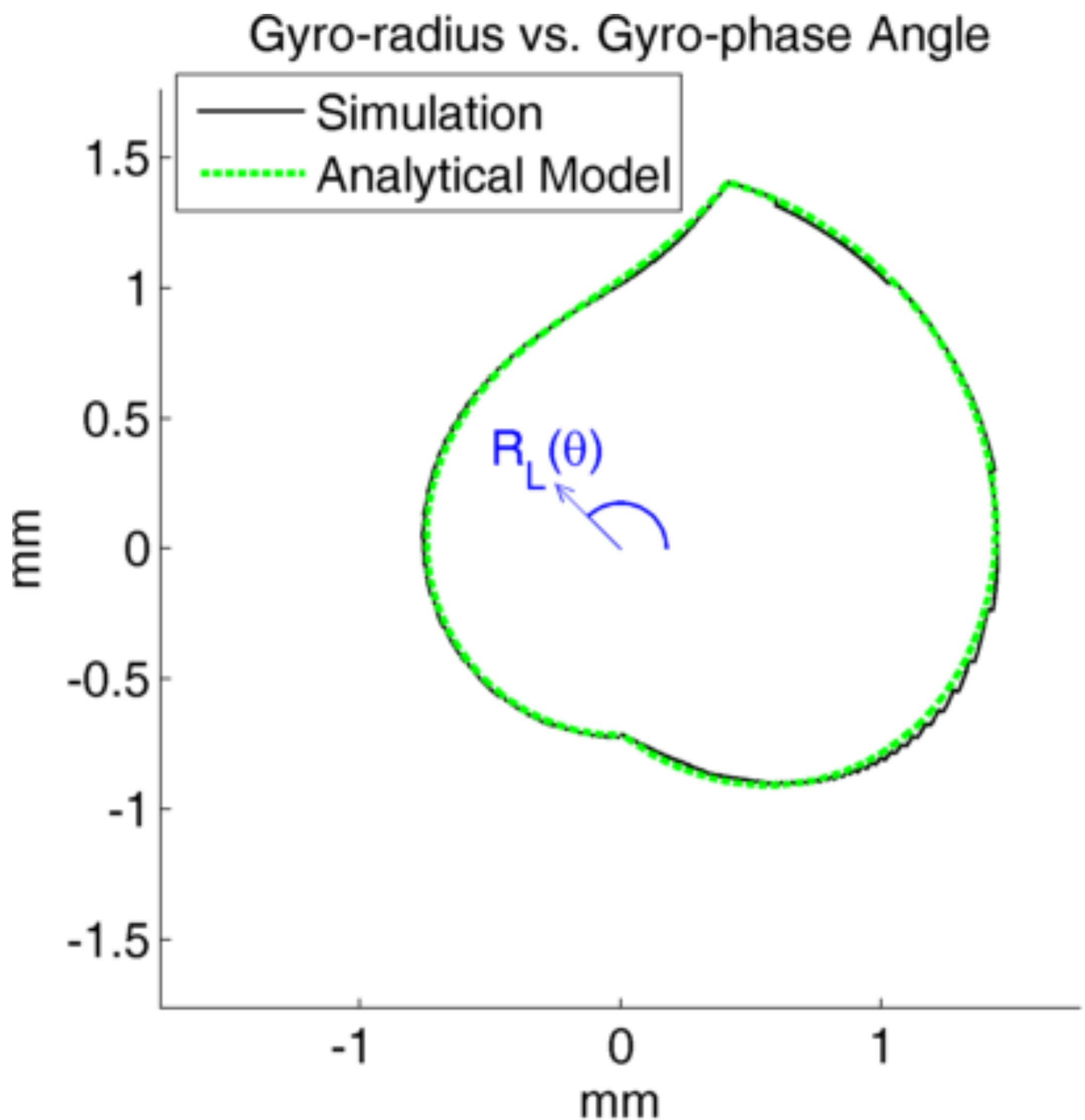
$$P = 695\, T_{eV}\, a_{\mu m}\, n_{d,cm-3}/n_{i,cm-3}\,,$$

where n_d and n_i are the dust and ion number densities, respectively, and the various parameters are in the units indicated by the subscripts.

Consider a silane rf discharge in which particles have grown to radius a = 115 nm and dust density is $n_d = 10^8$ cm^{-3}, while the ion density is $n_i = 5\text{x}10^9$ cm^{-3}. For T_e = 2 eV, which is probably accurate to a factor of three, P is estimated to be 3.2 (accurate to the same factor of three), corresponding to a 45 % reduction in the particle's charge.

Charging models typically neglect discreteness in the currents collected by the particle

- The fractional fluctuation is strongest for smallest particles.
- The power spectrum of the fluctuations is dominated by very low frequencies, with half the spectral power lying at frequencies below 2.4% of the inverse charging time, implying that grains have time to achieve real-time equilibrium charge.
- At higher frequencies, the spectral power diminishes as the second power of frequency.



Forces on Particles

Electric Force   Gravity   Ion Drag Force   Neutral Drag Force

Thermophoresis

Arises from a temperature gradient in the neutral gas. Neutral gas atoms from the “hotter” side that hit the dust grain transfer a larger momentum to the dust than atoms from the “colder” side. The force points towards regions of colder gas.

Radiation Pressure

Arises from the momentum transfer when a photon reflects, transmits, or absorbs at a particle surface. All three processes contribute to the radiation pressure.

Particle Interaction Force

Particles in isotropic plasma:

The interaction can be precisely determined experimentally from the dispersion of waves and from analysis of collision dynamics between dust particles. The interaction is a purely repulsive Yukawa potential with a screening length that is compatible with the electron kinetic shielding distance.

Particles in a Plasma Sheath

Often, the dust particles are trapped in the strongly non-neutral, non-equilibrium plasma sheath where strong electric fields and a directed ion motion towards the electrode prevail. An obvious sign is the unexpected vertical alignment of dust particles in the sheath

Detailed simulations and experiments have revealed that the force between dust particles in the sheath is a very peculiar nonreciprocal, attractive force:

Dust grains located lower in the sheath are attracted by higher-up grains, but the upper grains experience a repulsive force from the lower. The origin of this non-reciprocal attraction lies in the ion streaming motion in the sheath region between the plasma and an electrode

Experimental Methods – Particle Confinement

Dusty plasmas are usually confined in **radio-frequency (RF) discharges** between parallel electrodes that easily tolerate impurities. RF discharges for dusty plasma research are typically operated at 13.56 MHz at relatively low RF powers (usually <10 W) and gas pressures in the range between 1 and 100 Pa.

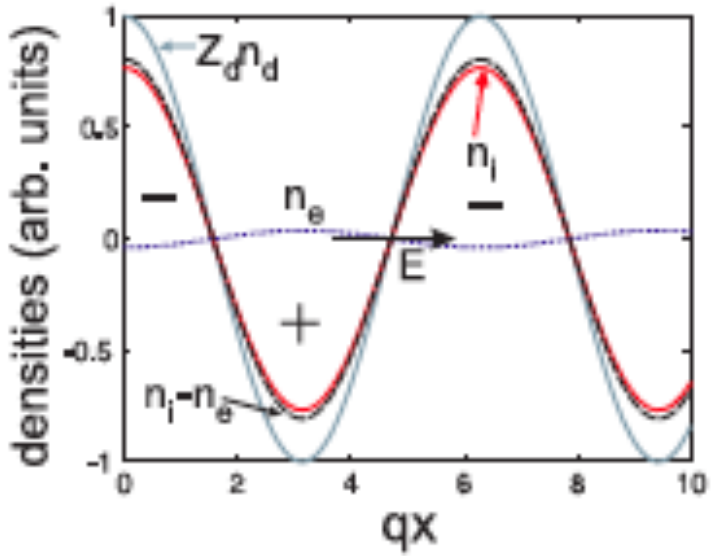
Dusty plasmas are also studied in **DC glow discharges and thermionic discharges**, with the former usually operated between 10 and 500 Pa at discharge currents between 0.1 to 10 mA.

Nanometer-dusty plasma exhibit large regions from which the dust is expelled. These so-called “voids” have well-defined boundaries defined by the force balance between the ion drag and electric field force.

Experimental Methods – Measurement

- Charge measurement
  - Potential well
  - Linear resonances
  - Nonlinear oscillations
- Particle imaging and tracking

Waves in Dusty Plasmas



One category of waves does not require strong coupling of the dust particles and a second category (lattice waves) does.

A wave-like disturbance in the negatively-charged-dust density leads to an enhanced negative space charge that is immediately shielded by the ambient plasma ions and (to a lesser extent) electrons. The shielding is incomplete, as $\Delta n_d Z_d > \Delta(n_i - n_e.)$ and this is enough to form negative and positive space charge regions.

Solar System Applications

Dust Complex onboard the ExoMars-2018 lander for investigations of Martian dust dynamics

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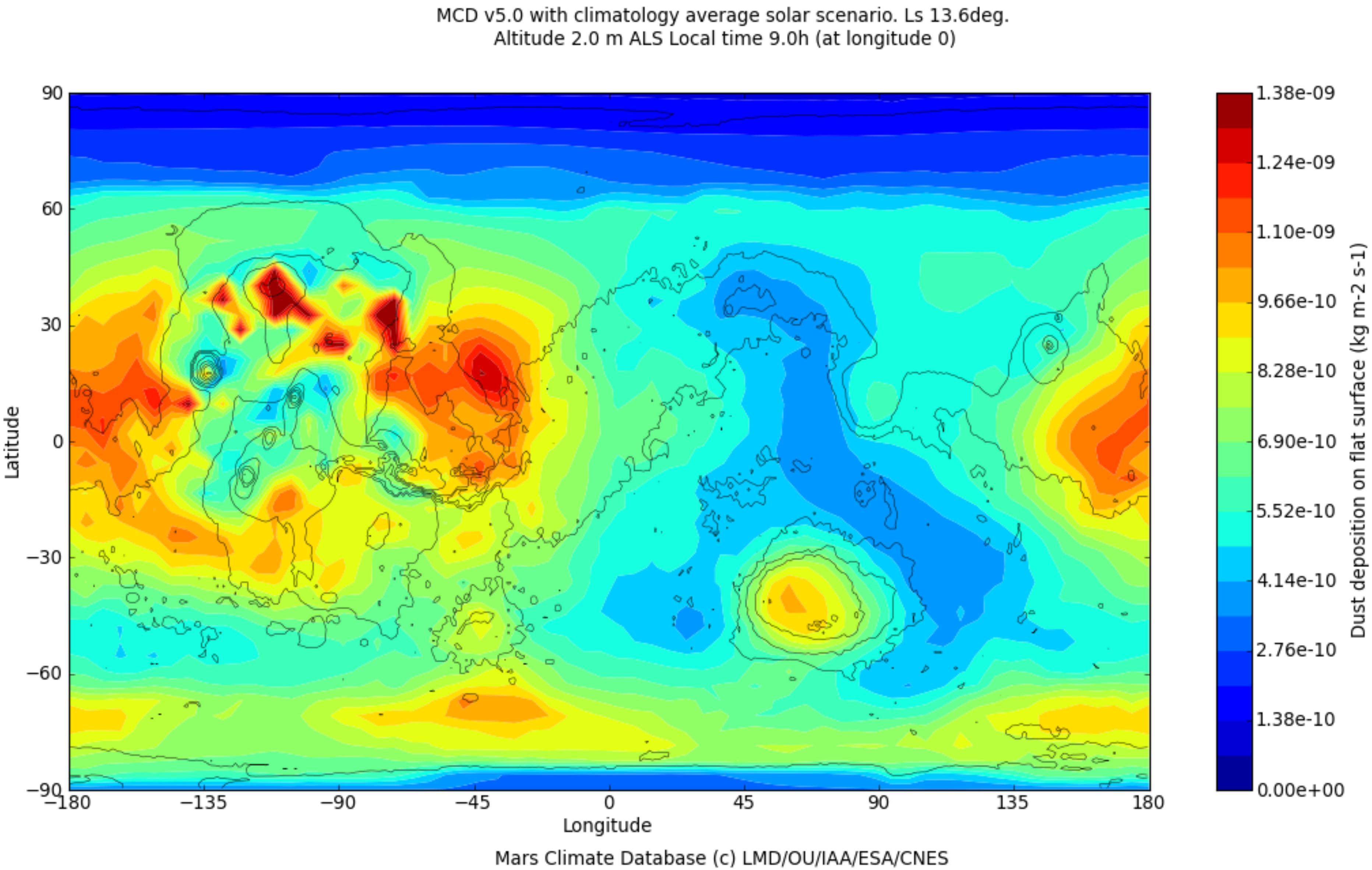
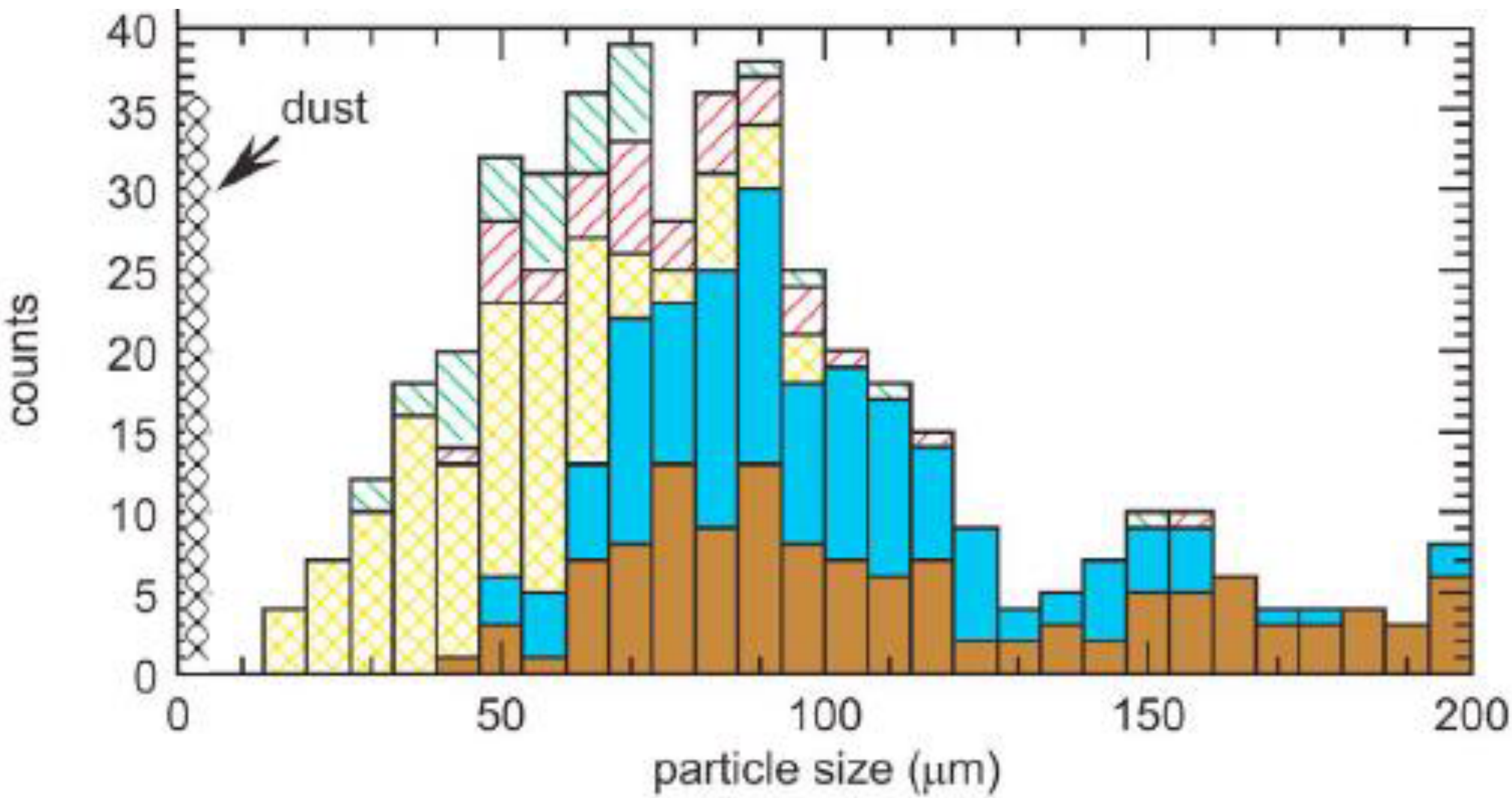
Surface flux and grain-size distribution will be measured



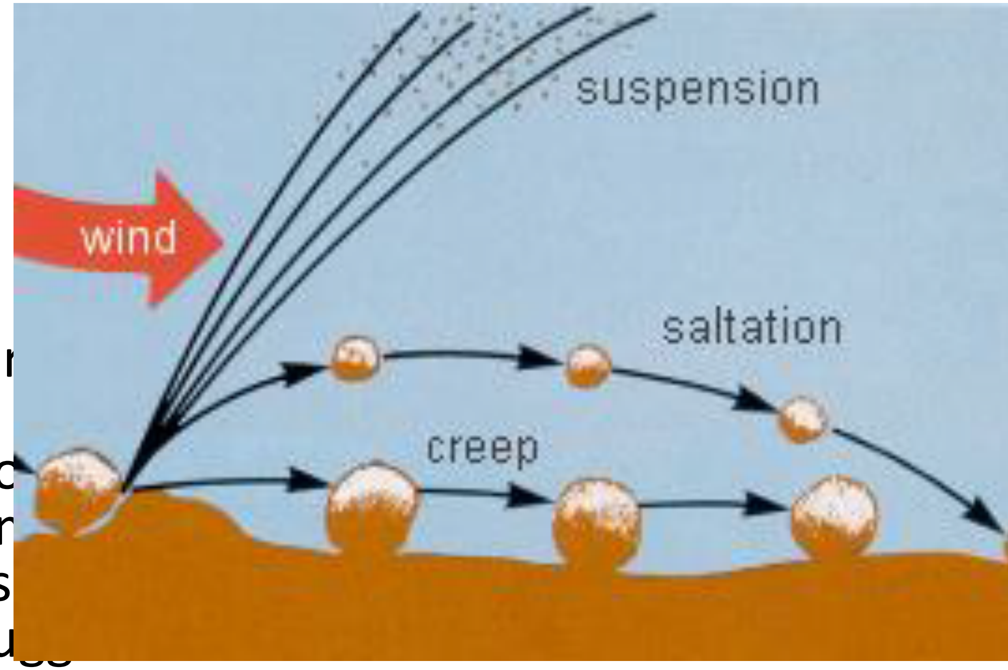
Wind mobilized particles on Mars range in size from less than 1 µm, for suspended dust, to as large as 1 cm.



Background for understanding Martian dust dynamics

- **Martian atmosphere contains a significant load of suspended dust**.
- The dust cycle and the resulting feedback on atmospheric circulation are still poorly known for Mars.
- Airborne dust contributes to determine the dynamic and thermodynamic evolution of the atmosphere, including large-scale circulation processes, on diurnal, seasonal and annual timescales. It plays a key role in determining the current climate of Mars and probably influenced the past climatic conditions and surface evolution. Moreover, wind and windblown dust are the most important currently active surface modifying agents on Mars. They are responsible for erosion, surface-dust redistribution, and weathering.
- The study of atmospheric Martian dust is relevant in the context of analyzing hazard connected to the contamination/failure of payloads in space missions (e.g., solar panels, mechanisms, optical systems) and to the environmental risks for human exploration, due to dust deposition, impacts and electrification.
- ExoMars 2018 mission will offer an unique opportunity to study these processes by monitoring dust dynamics for one Martian year. This will allow us, for the first time on Mars, to span from periods of relatively clear sky to the statistical dust storm season, where an important load of dust is expected to be injected into the atmosphere.

Mechanisms of Aeolian Sand Transport

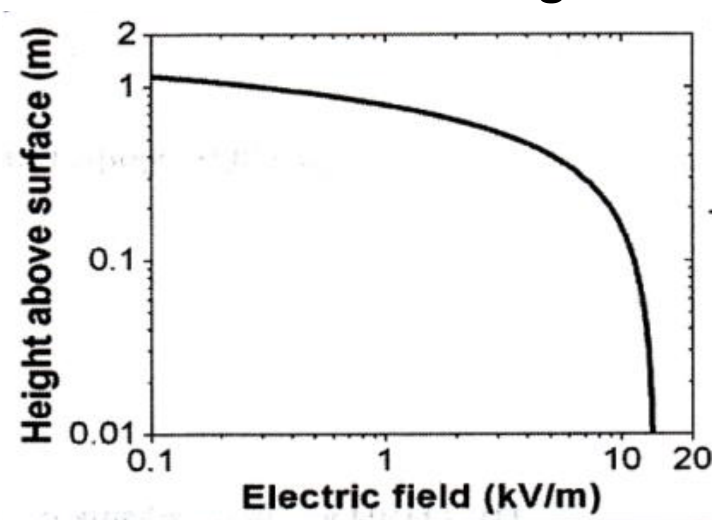


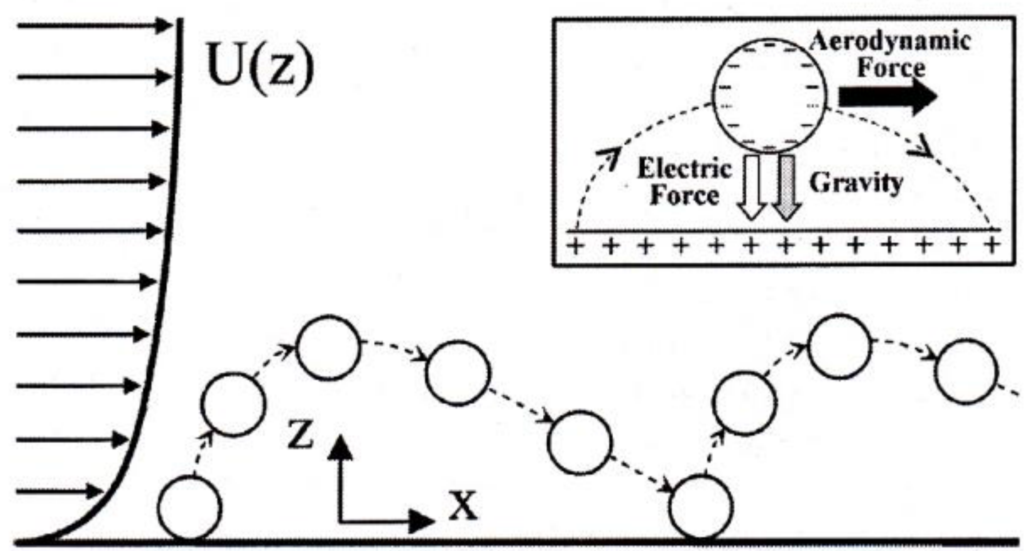
Dust devils and dust storms are ver
mon events on Mars and saltation
sidered the main mechanism respo
for rising dust during these phenor
although other plausible dust emis
mechanisms have recently been su

A first model for dust injection required sandblasting, where saltating sand-size particles are responsible for dust entrainment via impacts (saltation). Martian saltation process has been widely studied due to the observations of the very extended dune fields on the surface of Mars (generated as on the Earth by saltating sand grains), and is now considered an important mechanism actually acting on Mars after the observation of recent movements of Martian dunes and some MER observations.

Dust Complex will measure flux and fields (E, B) as well as particle size distribution

The dust complex will measure **dust vertical flux** and **granulometry** with the MicroMED sensor, while monitoring the sand saltation mechanism (**horizontal flux**) (probably responsible for dust lifting) with the Impact Sensor. The role of Electric Field (E-field) in accounting for a major dust lifting mechanism has been hypothesized, but has never been addressed observationally. The Dust Complex shall fill this gap by measuring **E-fields** near the surface where they are expected to be stronger. There is a possibility of detecting micro-discharges at the low altitudes of atmosphere due to accumulation of electric charges, or even particles, at the different layers. **Electromagnetic activity sensor** (EMA) is intended to observe these discharges.





Dust Complex will characterize climate cause and effect

This instrument, if used in synergy with meteorological sensors (in particular pressure, temperature, wind sensors) will be able to completely characterize aeolian processes and correlation them with environmental conditions on Mars.

The information that can be obtained with the Dust Complex instrument, by *in situ* measurements over different time spans (days, seasons, years), represents a key input into different areas of research:

• in the context of search of life on Mars

-to determine present climatic conditions at Mars surface

-to determine physical parameters impacting on life presence on Mars

-to derive information about past history of Mars climate

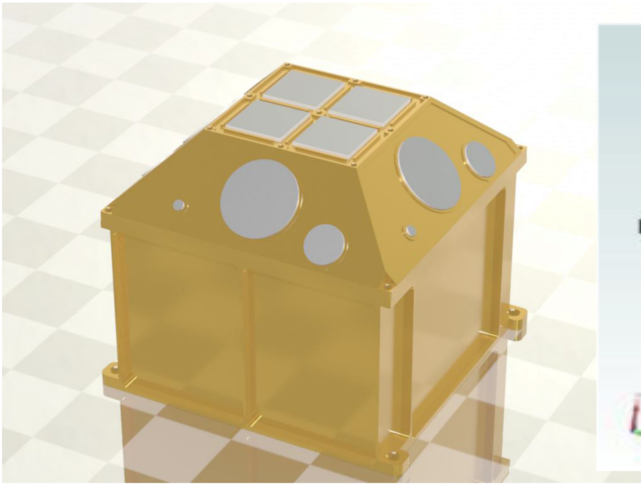
-to provide ground-truth for validation of data coming from orbiter observations

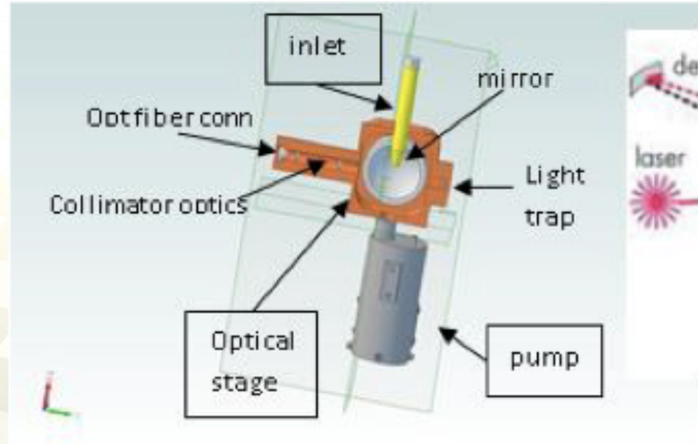
• in Mars operations

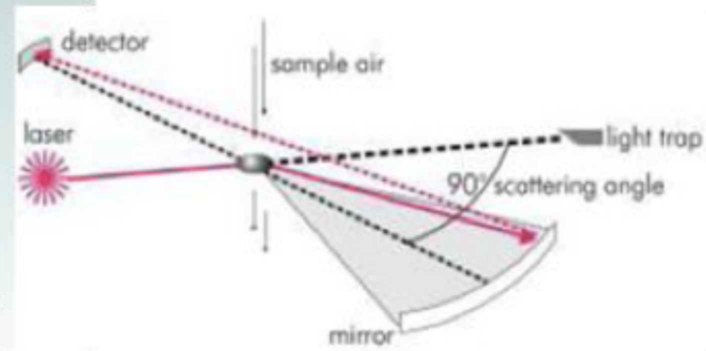
-to evaluate hazardous conditions due to Martian environment

-to place constraints on operative conditions on surface of Mars

-to support definition of future Mars exploration missions.







The Dust Complex is a suite of 4 sensors devoted to the study of Aeolian processes on Mars

- an **Impact Sensor**, for the measurement of the saltating sand grain flux, has 4 sides to measure horizontal and vertical dust flux and to measure momentum for grains 2.5 µm in diameter and larger.
- a **particle counter sensor**, MicroMED, for the measurement of airborne dust size distribution and number density of entering dust grains from 0.2 to 10 µm radius. It consists of an Optical Particle Counter, analyzing light scattered from individual dust particles.
- an **Electric Probe**, for measuring the electric field at the surface of Mars.
- an **Electomagnetic Field sensor** for registering EM-discharges

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COSPAR 2014 Poster

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