Electric field driven aggregation of negatively and positively polarized particles in dilute suspensions

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Motivation

- Colloidal assembly provides the capability for scalable manufacturing of structured materials and devices for traditional and emerging industries.

- The rich variety of colloidal structures observed in numerous terrestrial experiments could also have been influenced by gravity effects, such as particle sedimentation, convection and jamming, which compete with electric forces during the slowly evolving structure formation.

Why microgravity?

- It is often assumed that time-average weightlessness simulated in a clinostat can reduce the effect of gravity on samples.

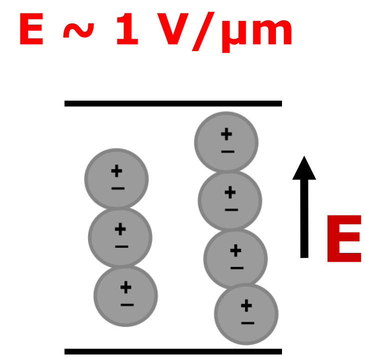
- Our low-gravity parabolic flight tests on a non-buoyancy matched suspension demonstrated that time-average weightlessness in a clinostat does not eliminate gravity effect on patterns in suspensions formed by an electric field (*Markarian, Yeksel, Khusid, Phys. Fluids 16, 2004*)

- The long-term microgravity experiment provides a unique opportunity to reveal the relationship between electric forces on the scale of individual particles and the suspension dynamics on the macroscopic scale.

Clinostat uses slow rotation to negate the gravity effects on plants and cell cultures https://en.wikipedia.org/wiki/Clinostat

Electro-rheological Fluids and Dipolar Suspensions

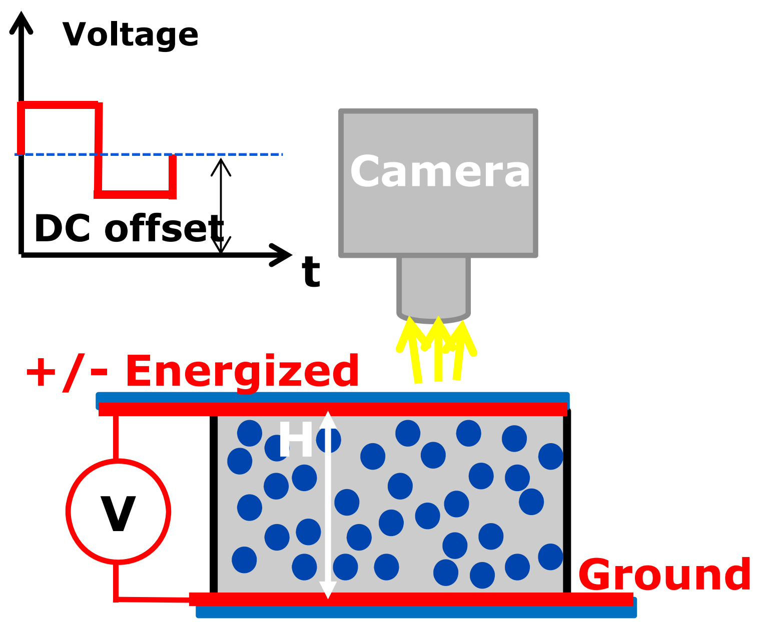
- ***Theories and MD simulations predict that long-range dipolar forces*** cause polarized particles to form chains that gradually crystallize in a three-dimensional body-centered tetragonal structure (*Tao, Sun, Phys Rev Lett, 67, 1991*)

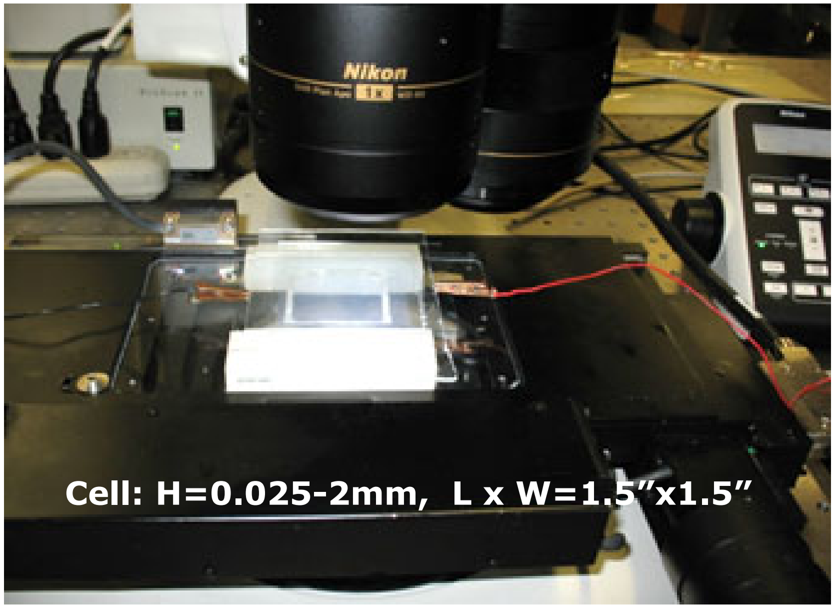


- Unexpected formation of a cellular pattern of particle-free domains (*black*) surrounded by particle-rich walls (*white*) in suspensions of neutrally buoyant negatively polarized particles was observed by *Kumar, Khusid, Qiu, Acrivos, Phys Rev Lett, 95, 2005* and then by by *Agarwal, Yethiraj, Phys Rev Lett 102, 2009*

- Formation of cellular structures was *never observed* in numerous MD simulations of dipolar colloids and experiments on electrorheological fluids and model suspensions.

Laboratory Setup





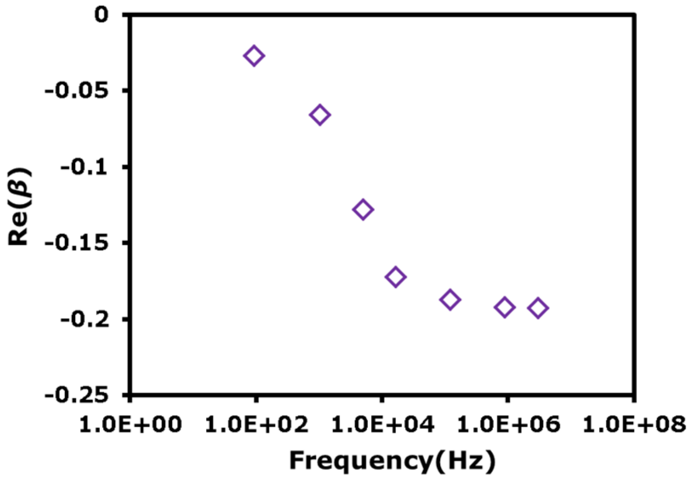
Illumination: Transmitted or reflected light

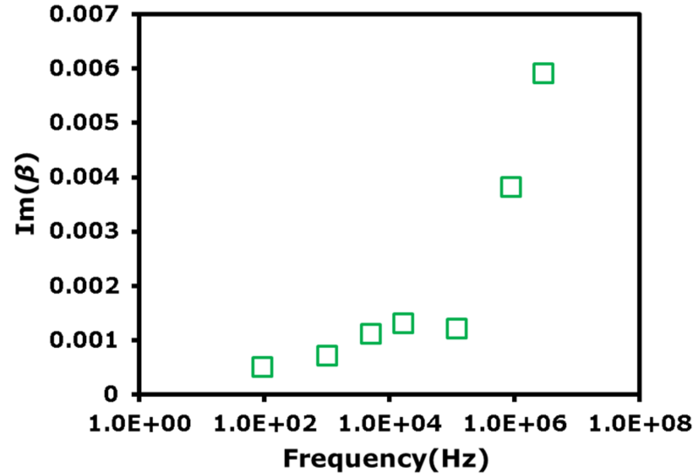
Field: Uniform; DC 0-0.2 V/μm
Sine or square Ac_{rms} 0.4 - 1 V/μm; 0.1-5kHz

Relative Particle Polarizability

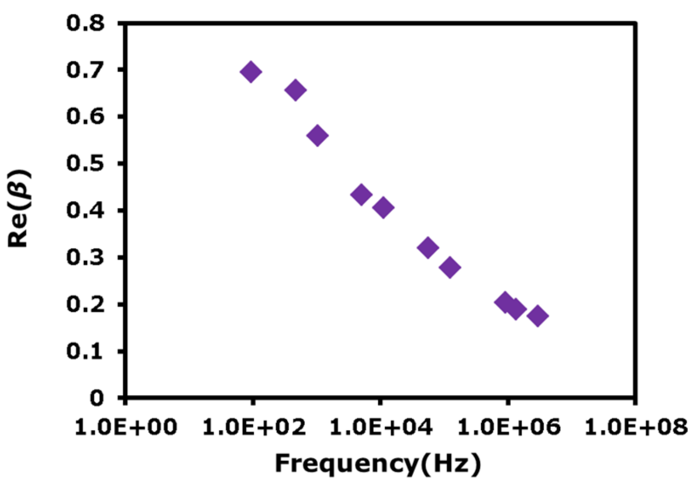
Maxwell-Wagner expression $\dfrac{\varepsilon_s^* - \varepsilon_f^*}{\varepsilon_s^* + 2\varepsilon_f^*} = c\beta(2\pi\nu)$

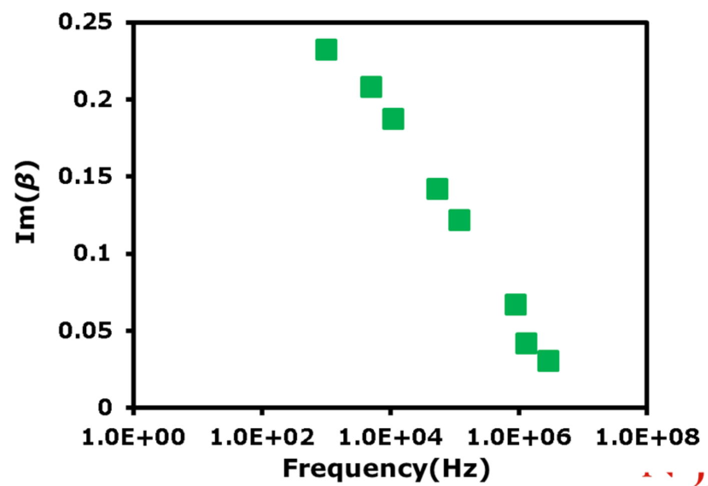
Negatively polarized micro-particles in Mazola oil





Positively polarized micro-particles in silicone oil



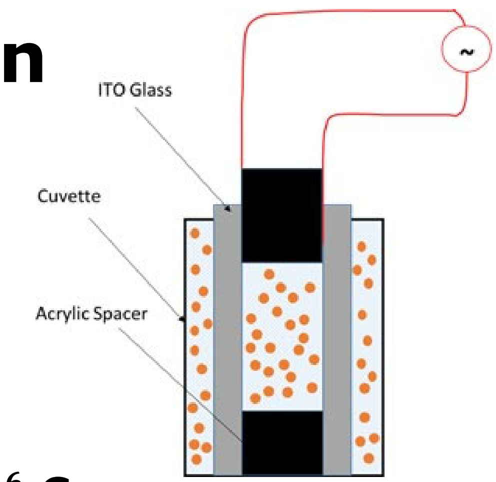


Particle Electrophoretic Mobility in AC field and DC field

Particle charge $\mu_p = Q_p / 6\pi\eta_f a$

$\mu_p = v_p / E$

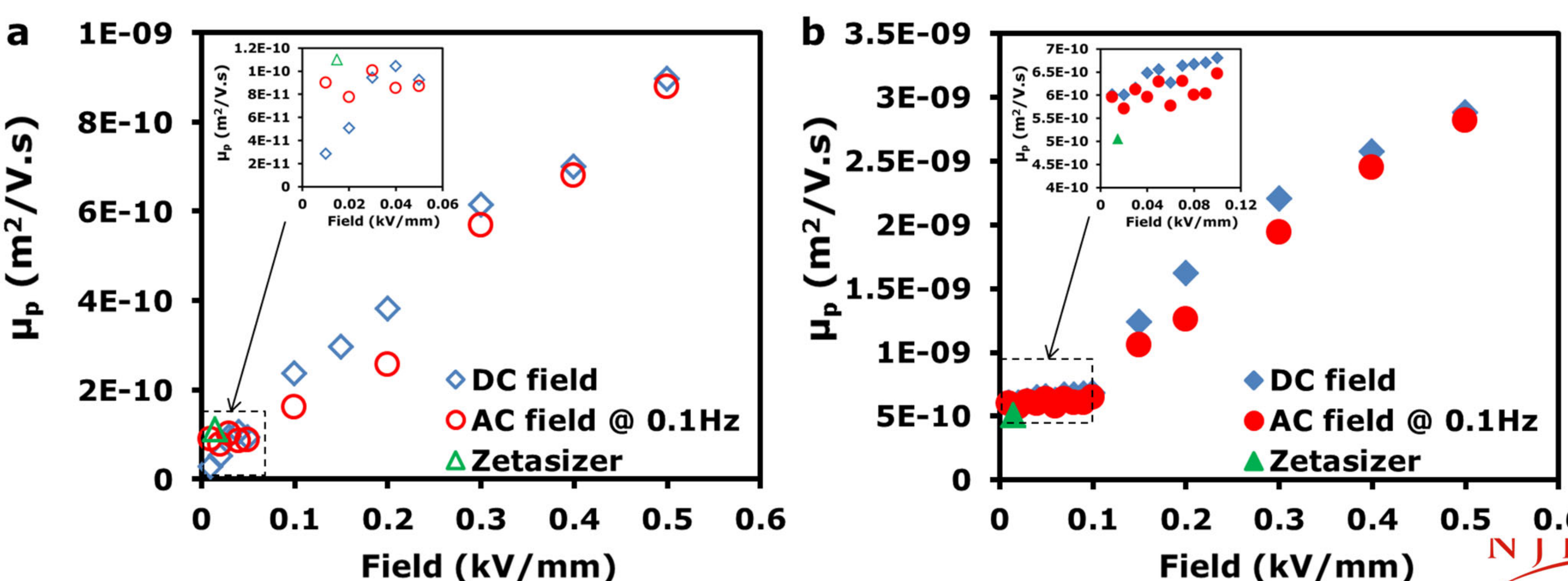
Strong field



(a) Negatively polarized particles in Mazola oil, $Q_p \approx \mathbf{-3.10} \cdot 10^{-16}$ **C**

(b) Positively polarized particle in silicone oil, $Q_p \approx \mathbf{-2.29} \cdot 10^{-16}$ **C**

Inset: $E \leq 0.1 kV/mm$ → **No electro-hydrodynamic flow**



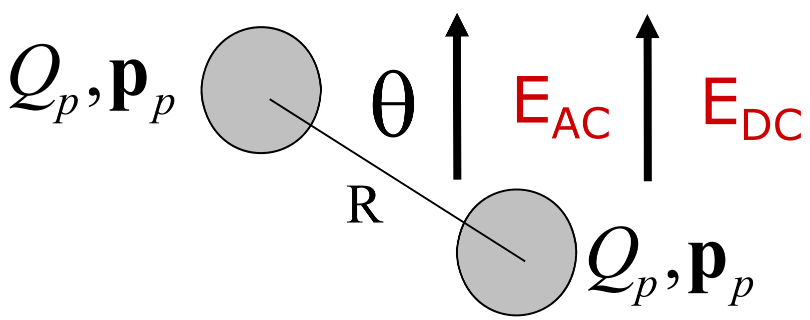
Cellular Pattern Formation

Electric field $\mathbf{E} = \mathbf{E}_{DC} + \mathbf{E}_{AC} \sin(2\pi\nu t)$

E_{DC}~ 0.02-0.05 V/μm

E_{AC} ~ 0.7-1.5 V/μm at frequency 0.1 Hz- 1 kHz

Charge relaxation time $\nu t_e = \nu\varepsilon_0\varepsilon_f / \sigma_f > 1$



Particle size 2a ~ 4 μm

Particle charge $Q_p \sim -3.4 \cdot 10^{-16} C$

Particle polarizability $\mathrm{Re}\,\beta \sim -0.13$

Field of a charged particle $E_p = \dfrac{Q_p}{4\pi\varepsilon_0\varepsilon_f a^2} \sim 0.3\mathrm{V}/\mu\mathrm{m}$ **< E_{AC}**

Coulomb DC force vs dipolar AC force $F_{DC} = Q_p E_{DC}$

$$\boxed{\frac{F_{DC}}{F_{dd}} \sim \frac{Q_p E_{DC}}{6\pi a^2 \varepsilon_0 \varepsilon_f \,\mathrm{Re}^2(\beta) E_{AC}^2} \sim 0.3}$$

Objectives & Proposed Advanced Colloids Experiments Electrically Controlled ACE-E

https://www1.grc.nasa.gov/space/iss-research/iss-fcf/fir/lmm/ace

- The appearance of **cellular patterns with particle-free domains surrounded by particle-rich walls** remains as **an open issue** and still awaits an explanation.

- Particles in ground-based experiments **move relative to one another on a particle scale in the course of structuring due to sedimentation**

- Long-term experiments in microgravity should reveal salient features of gravity effects.

- Colloidal assembly by the use of electric field gradients is a largely uncharted scientific area. Long-duration microgravity in the ISS is necessary to study the effects of field gradients since the particles and the suspending liquid have a substantial density difference.

- COTS equipment can be used for the fabrication of ACE-E hardware.