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Topical: Superparamagnetic Dusty Plasma Experiments in Microgravity

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1. Background: Complex plasma and the need for microgravity

A dusty plasma is a plasma containing nanometer to micron-sized solid particles (dust) that aquire an electrical charge Q_d due to the interaction with the plasma environment. The charging process can be rather complicated. However, in the case of a low temperature (LT) plasma, taking into account only electron and ion currents, the dust net charge can be estimated by Orbit Motion Limited (OML) theory, and depends only on the particle radius R and the electron temperature T_e (typically $k_B T_e \approx 2 - 3\ eV$). A rule-of-thumb is $Q_d \approx -1700e\ R[\mu m] k_B T_e[eV]$ for these environments. Due to their charge, the dust can be levitated in plasma regions with a sufficiently high electric field E_0, where the dust weight $m_d g$ is balanced by the electrostatic force, thus $Q_d E_0 \approx m_d g$. For particles that are larger than a few μm, these condition is usually only satisfied in the plasma sheath while particles of sub-micron size can even be levitated in the pre-sheath. Unfortunately, the latter are much harder to study and, further, do not show the undamped dynamics of systems with larger particles that are of fundamental interest and that make dusty plasma so unique. *To study the behavior of large, three-dimensional dusty plasma systems that are based on particles in the micrometer-sized range and beyond, the gravitational influence has to be reduced and experiments need to be performed under free-fall ("microgravity") conditions.* As a result, a wide "microgravity" research program has been established in dusty plasma research over the last decades, supported by multiple, international operating space agencies from Europe, Russia and the US.

2. Study limits of dust-dust interaction types: Known and newly proposed

In the majority of ground-based and space-based experiments on the physics of dusty plasmas, investigations have focused on magnetic-free environments and dust-dust interactions that are based on screened Coulomb (Yukawa-type) potentials. Other than initial studies decades ago and several recent detailed experiments on dusty plasma behavior in ground-based high magnetic field setups, magnetic interactions within the dust species have barely been addressed. Similarly, the study of non-Yukawa type interactions have so far been restricted to electrically induced modifications to the screened Coulomb potential. Some detailed studies addressing changes to the dust interaction potential as a result of ion streaming (the ion wake-effect) have been performed in ground-based laboratories and particularly in the space experiments PK-3 Plus and PK-4. Still, the study of mixed, user controlled dust-dust interactions is not yet sufficiently developed.

A new area in the next decade of research in dusty plasmas is expected to start with the detailed study of systems of dust particles that interact with both screened Coulomb (Yukawa) and dipole interactions. Dipole interactions that have been discussed to date include (i) an electric dipole interaction that can be induced by an external alternating electric field that polarizes the screening cloud around a dust particle leading to the so-called electrorheological plasma [1, 2], and (ii) a magnetic dipole interaction between superparamagnetic dust particles that acquire a magnetic moment in an external magnetic field $\mathbf{B}$ [3, 4]. Both of these could lead to new kinds of dusty plasma liquids and crystals whose structure and interparticle spacings could be tuned by external means. *More importantly both approaches* *have the potential to give the experimenter some form of user control on the particles interaction itself, a feature that can finally make complex/dusty plasma the universal tool to study multi-particle systems and their collective behavior for many equivalent representations across other physical sub-disciplines.*

3. Comparing Yukawa and magnetic dipole interaction strength

While electrorheological dusty plasmas have been observed under microgravity conditions (see [1]), superparamagnetic dusty plasmas have been studied only under laboratory conditions where a relatively large magnetic field (roughly ~ 0.1 T) is required in order for the magnetic dipole interaction between micron-sized superparamagnetic particles to be comparable to the Yukawa interaction (see [3]). *Microgravity conditions could provide a unique opportunity to study superparamagnetic systems at much lower magnetic field strengths, owing to the possibility of using larger dust particles while only minimally influencing the plasma itself.* A paramagnetic dust particle acquires a magnetic moment $\mathbf{M}$ aligned along $\mathbf{B}$ that is proportional to R^3B. While the electrostatic force between charged dust scales as $Q_d^2 \propto R^2$, the magnetic dipole force between paramagnetic dust varries as $M^2 \propto R^6B^2$. Thus the ratio of the magnetic dipole to electrostatic forces scale as R^4B^2: this implies that as R increases, a lower B would be required for magnetic tuning of the dust interaction. It should be noted that there is precedent for successfully distributing large dust particles of sizes tens of microns in microgravity experiments (see e.g., [5]).

To examine the scaling of the dust interactions in more detail, consider a plasma containing superparamagnetic dust particles with uniform radius R, immersed in a magnetic field $\mathbf{B}$. We assume that the dust interacts via the electrostatic screened Coulomb (Yukawa) force and a magnetic dipole force. The Yukawa force between two dust particles with charge Q separated by a distance d is $F_E = (Q^2/d^2)(1 + d/\lambda_D)\exp(-d/\lambda_D)$, where λ_D is the plasma Debye screening length. The magnetic dipole force between two dust particles can be repulsive or attractive depending on their relative positions. When the magnetic dipole force is attractive and larger in magnitude than the Yukawa force, there would likely be agglomeration of the dust. To avoid agglomeration and still allow magnetic tuning of the dust interaction, one could arrange parameters such that the ratio of the Yukawa force to the magnetic dipole force is larger than unity but not so large that the magnetic force plays little role, as described in the following quantitative estimates.

The maximum magnitude of the attractive magnetic dipole force between two superparamagnetic dust particles occurs when the particles are aligned along $\mathbf{B}$. With a separation distance d along $\mathbf{B}$, the maximum magnitude of the attractive force is given by [4] $F_{M,max} = 6M^2/d^4$, where $M = R^3B(\mu - 1)/(\mu + 2)$ with μ being the magnetic permeability of the dust material. This yields the ratio

$$\frac{F_E}{F_{M,max}} = \frac{1}{6\eta^2}x^2(1 + x)e^{-x}\,, \tag{1}$$

where $x = d/\lambda_D$ and the parameter η, which characterizes the strength of the magnetic dipole to electrostatic interaction, is $\eta = M/(Q\lambda_D)$. The ratio of the magnitudes of the

Yukawa to the maximum attractive magnetic dipole force (viz. eq. 1) is plotted in Figure 1 as a function of dust particle separation x for several different values of η that label the curves. From Fig. 1, it can be seen that for these η values, the ratio $F_E/F_{M,max}$ can be larger than unity for $x > 1$, and remains larger than unity for larger dust separations which may be possible in microgravity.

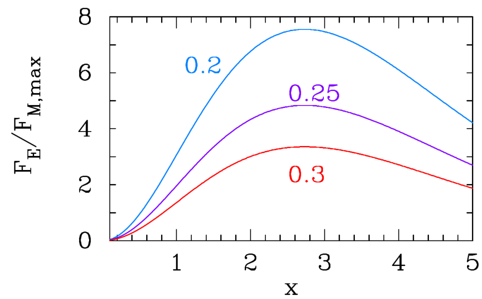

Figure 1: Plot of $F_E/F_{M,max}$ as a function of $x = d/\lambda_D$ for different values of η that label the curves.

The parameter η is roughly (e.g., [6])

$$\eta \approx 0.03 \, \frac{R^2(\mu m)B(G)}{|\phi_s(V)|\lambda_D(\mu m)} \left(\frac{\mu - 1}{\mu + 2}\right) , \tag{2}$$

where ϕ_s is the surface potential of the dust particle. *Because η scales as R^2B, larger dust sizes, such as those expected to be possible to confine in microgravity, could reduce the requirement on B to enable magnetic tuning of the dust interactions while reducing the overall influence of the magnetic field on the plasma itself.* Another effect which could lower the requirement on the magnitude of B is a smaller $|\phi_s|$, which implies a lower electron temperature T_e (since $|\phi_s| \propto T_e$), possible electron depletion effects (e.g.[7]) and/or collisional effects on dust charging (e.g., [8]).

4. Estimating realistic experiment parameters for a space based experiment, such as the Complex Plasma Facility – COMPACT, proposed for the ISS

As a ball-park example of nominal parameters, consider the following nominal low temperature argon plasma parameters: electron temperature $T_e \sim 2$ eV, ion temperature $T_i \sim 0.03$ eV, ion density $n_i = 1 \times 10^8$ cm^{-3}. We assume that the dust particles are in the bulk of the low temperature plasma, so that $\lambda_D \approx \lambda_{Di}$. With these parameters, the ion Debye length $\lambda_{Di} \sim 130$ μm. Estimating the dust surface potential using orbit-motion-limited (OML) theory yields $\phi_s \sim -4$ V. We consider superparamagnetic dust particles with $\mu = 4$. Taking $R \sim 30$ μm, we have from eq. (2) that $\eta = 0.25$ for $B \sim 10$ G. Note that there is a limit on the dust density n_d due to the overall charge neutrality condition $Z_d n_d \lesssim n_i$, where Z_d is the negative charge state of the dust, given roughly as $Z_d \sim 695\, R(\mu m)|\phi_s(V)|$. For this example, we estimate roughly $Z_d \sim 8 \times 10^4$ and $n_d \lesssim 1.2 \times 10^3$ cm^{-3}.

As a different example of nominal plasma parameters, consider a thermal plasma with lower T_e: $T_e \sim T_i \sim 0.2$ eV, $n_i \sim 1 \times 10^9$ cm^{-3}. This gives the linearized plasma screening length as $\lambda_D \sim 70$ μm. We assume OML theory applicability, which yields $\phi_s \sim -0.8$ eV. Again considering superparamagnetic dust particles with $\mu = 4$, and taking $R =\sim 20$ μm, eq. (2) implies that $\eta \sim 0.3$ for $B \sim 3$ G. Estimating the dust charge state as $Z_d \sim 1 \times 10^4$, the limit on dust density for this case is roughly $n_d \lesssim 1 \times 10^5$ cm^{-3}.

How can these experiments be realized? One of the most important requirements is that particles of a sufficient size must be levitated and confined in the plasma volume. This implies that the influence of the particle weight has to be reduced as much as possible. *Experiments, performed under free-fall or "microgravity" conditions would fulfill this requirement and allow new experimental scenarios not possible on ground.* A variety of particle sizes could be used in this case, applying the same background magnetic field, and thus keeping the plasma conditions about the same while only changing the particle interaction. Such experiments would be highly preferable as they are comparable to each other.

A potential experimental setup that could be utilized for the proposed experiments is COMPACT (the Complex Plasma Facility) that is being developed as a potential International Space Station (ISS) based experiment. Follow-up experiments or lunar surface based experiments would also work, but are still in the conceptual development phase, while COMPACT is already at a high technical readiness level (TRL). COMPACT is currently designed to be operated without a magnetic field. However, only a minor change would be necessary to allow operation of COMPACT with the required low magnetic fields (≈ 10 Gauss). The requirements for integration of a single Helmholtz coil pair as sketched in figure (2), would also require additional power of around 10 Watt for the coils, and additional mass of around 1.5 kg (if copper is used for the coil wires). This value is estimated from the following equation [11]

$$B = \left(\frac{4}{5}\right)^{3/2} \frac{\mu_0}{4\pi a^2} \sqrt{\frac{mP}{\rho_R \rho_m}}, \tag{3}$$

where B is the achieved magnetic field in the center of the coil pair (10 Gauss), $a \approx 0.15$ m is the coil radius, $P \approx 10$ W is the assumed available power, m is the mass of the conducting wires, ρ_R and ρ_m are the specific resistivity and the mass density of the conducting material (here $\rho_R = 1.67 \times 10^{-8}$ Ωm and $\rho_m = 8960$ kg/m^3 for copper). If more copper is used the power requirement can be reduced accordingly.

5. Experimental scenarios and further outlook

There are many types of research experiments that could be contemplated in these systems where the interaction potential between the charged, superparamagnetic dust particles is anisotropic. While the electrostatic Yukawa force is repulsive and isotropic, the magnetic dipole force between the dust can be repulsive or attractive depending on the relative positions of the dust particles (see e.g., [3, 4, 9]). Because the maximum attraction between two paramagnetic dust particles occurs when they are aligned along $\mathbf{B}$, one expects a ten-

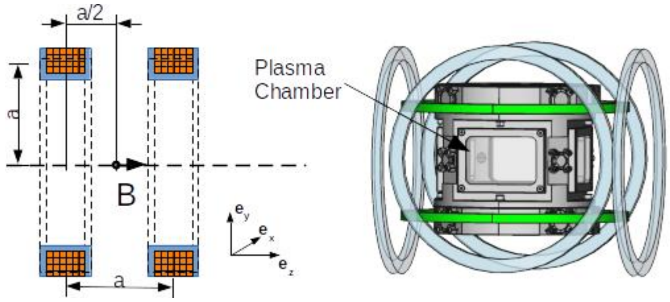

Figure 2: Left: Sketch of a Helmholtz coil pair. Right: Adaptation of a coil pair for a 1-dimensional additive magnetic field (green) that is directed normal to the electrode surfaces. Alternatively, if possible, a full set of three coil pairs would allow to user to define the orientation of the magnetic field (green+cyan). However, this might produce some challenges for the design modification while the one additional coil (green) should be straight forward to implement.

dency for the formation of chains of dust along the magnetic field whose inter-dust spacings could be tuned by varying B. This could lead to new research on the formation of dust structures, the propagation and excitation of dust waves, and interaction of electromagnetic waves with the dust structures. For example, the dispersion relation of dust acoustic waves would depend on the direction of propagation with respect to $\mathbf{B}$. As another example, chains of dust with regular spacings might be able to diffract electromagnetic waves of wavelength comparable to the inter-dust spacing, which would be in the terahertz or far-infrared regime. (We note that the diffraction of visible light and tunable photonic crystal behavior by chains of charged, superparamagnetic colloids in a magnetic field has recently been reported [10]).

The anisotropic dust interaction in a superparamagnetic dusty plasma in a magnetic field is complementary to another type of anisotropic dust interaction that has been studied under microgravity conditions in electrorheological (ER) plasmas. In ER plasmas, an external alternating uniaxial electric field induces ion flows that generate ion wake fields on opposite sides of the shielding cloud surrounding a dust particle, resulting in a dipole interaction (see [1, 2]). This leads to the formation of chains of dust particles aligned along the direction of the external electric field. It could be interesting to combine the anisotropic interactions due to magnetic effects with those due to electrorheological effects to further manipulate the formation of dust structures. For the latter experiment scenarios, it would be preferable for the orientation of the magnetic field vector to be user-defined with an arbitrary angle respect to the electrode surface normal.

Other experiments that might be contemplated include studies of the magnetic packing force, $\mathbf{M} \cdot \nabla \mathbf{B}$, in the case that the magnetic field has a gradient (the Helmholtz coils would be driven individually to add magnetic field gradients). This force could move dust into the region of increasing magnetic field (see [3]), perhaps altering the dust configuration. Furthermore, because there are generally electric fields in a plasma that can induce ion flows, the interplay of ion wake field effects and magnetic effects could be studied. Introducing magnetic fields and superparamagnetic particles will highly increase the variety of complex plasma experiments and add a new quality via a new form of particle interaction control.

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[11] Equation derivation can be requested from the author U. Konopka. It was omitted to keep the 5 page limit.