29th EPS Conference on Plasma Phys. and Contr. Fusion Montreux, 17-21 June 2002 ECA Vol. **26B**, O-4.29 (2002)

MOVEMENT OF NON-SPHERICAL PARTICLES IN COMPLEX PLASMA

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Abstract

Motion of non-spherical dust particles suspended in a plasma is studied. We observe oscillations and rotations (*spinning*) of fibre-like particles trapped in a low-pressure radio-frequency plasma. We show that interactions of particles with positive ions with inhomogeneous drift velocity can cause motions in the plane perpendicular to the ion flow. Besides a general description, two concrete cases with and without net transfer of momentum (in average) are considered. A torque induced on asymmetric objects, leads to their spinning with frequencies up to a few tens of Hz, typical for the experimental conditions.

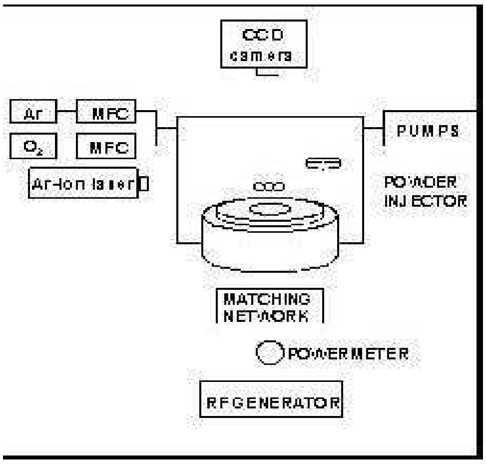
1. Introduction

The interactions of mesoscopic dust particles with plasmas are an important topic in astrophysics and atmospheric science [1]. Behaviour of isolated dust particles and particle clouds in plasmas has been extensively studied in laboratory reactors on Earth [2]. This resulted not only in a better fundamental understanding of complex plasmas, but also in various applications of dust particles in material science [3]. Recently, experiments have been performed under micro-gravity conditions using parabolic flights, rockets and the international space station [4,5]. The vast majority of these studies concern the behaviour of spherical particles in plasmas. However, microscopic particles encountered in the atmosphere (ice crystals), in the interplanetary space (comet debris) and also in plasma reactors (flakes) often have a non-spherical or even asymmetric shape [6]. The exact description of non-spherical particle dynamics is a complex task. Several efforts have been undertaken to analyse the behaviour of elongated objects, like cylindrical rods or thread-like polymers [7-9]. We also would like to mention that there is big experience in experimental and theoretical study (especially on interparticle interactions) of the rod-likes in charged colloidal suspensions [10]. Naturally physical specificity and properties of the rod-likes in plasmas and colloidal suspensions are rather different.

Particles immersed in plasmas acquire a negative charge. The position of any particle in the plasma is roughly determined by the global force balance: interactions with the electric field (Coulomb force), the gravitation force and forces related to the momentum transfer from plasma species to particles (ion and neutral drag, thermophoretic force).

2. The experimental conditions and some experimental observations

In typical low-pressure laboratory conditions, micrometer sized particles are suspended above the lower planar electrode at the edge of the plasma sheath, while smaller particles



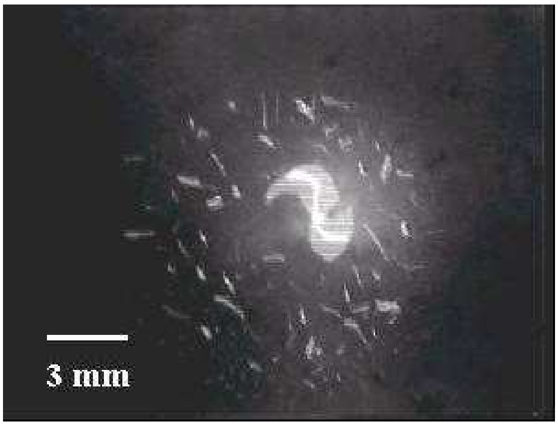


Figure1 (left). Sketch of the experimental set-up. The plasma is a 13.56 MHz capacitively coupled rf discharge. We inject particles through a sieve and they are trapped in the plasma sheath above the circular groove in the electrode. The dust cloud is illuminated by a horizontal laser sheet and imaged at 90° from the top by a video camera at 25 frames/s.

Figure 2 (right). A big particle spinning in a cloud of smaller spherical ones. Due to particle speed and the finite exposure time the spherical particles appear as stripes and the elongated spinning particle as the “spiral arms of a galaxy”.

form clouds in the plasma glow. Even though the Coulomb force results in efficient trapping of particles, they still retain some freedom of motion. Generally, the electric fields in the radial (parallel to the electrode) direction are weak, which allows for particle displacement in the horizontal plane. Moreover, non-spherical objects can also perform oscillations and rotations in their centre of mass system.

In this work we address the movement of charged non-spherical particles suspended in a low-pressure plasma. The experimental setup is depicted in Figure 1. Fibre-like cellulose particles with typical dimensions of 2 μm width and 20 μm length are suspended in an argon plasma at a pressure of 100 mTorr. Radial confinement is achieved by a 3 cm wide and 3 mm deep cylindrical groove in the powered electrode. Within this potential trap particles can move freely in the radial direction. Gas inlet is distant from the particle site, so that the flow does not influence the particle motion.

We have observed particle motion in its centre of mass, with a typical frequency of a few to a few tens of Hz. Based on the images, this motion may be either rotation or an oscillation around the horizontal axis; both movements will be referred to as spinning. In Figure 2 a video frame is shown, depicting the particle spinning. These motions were observed for particles of various shapes, from simple strings, through boomerang-like object to asymmetric twisted fibres. We shall discuss in this work the role of ion collection drag force, which may be responsible for this effect.

3. Spinning of the rod-likes under influence of the ion drag force

To explain spinning we will use the local collecting cross-section, which was applied to determine the rotational temperature of the spherical grains [11]. Here we assume on basis [12], that the orbit part of the ion drag force is not essential for net changes in the angular momentum. Particles of arbitrary shape can be modelled, but here we focus on cylindrical rod-like particles with length L and diameter 2a. The collecting local cross-section $d\sigma$ and respective total angular momentum **K** of asymmetrical grain due to collisions with particles of a sort α can be written as:

$$d\sigma = -\,\theta\,(-\,\mathbf{n_v}\,\mathbf{s_r}\,)\,\mathbf{n_v}\,d\mathbf{s_r}\,,\quad \mathbf{K}_\alpha = m_\alpha \iint d\mathbf{v}\,d\sigma\,[\mathbf{r}\times\mathbf{v}]\,|\mathbf{v}|\,n_\alpha(\mathbf{r})\,f_\alpha\,[\mathbf{v}-\mathbf{u}_\alpha(\mathbf{r})]\,,\quad (1)$$

where θ is the Heaviside function (1 if particle is hit by the coming ion and 0 if it passes by), $\mathbf{n_v}$, $\mathbf{s_r}$ are the unit vectors for relative velocity **v** of small particles (ions, atoms) and grain and the normal to the grain surface in a point **r** respectively. The function f_α is the distribution function of the small particles of type α having a local density n_α (**r**) and drift velocity $\mathbf{u}_\alpha$ (**r**). To find the total momentum transfer it is necessary to summarize over all species α. In case of a homogeneous flow, one can easily see that there is no (even instantaneous) transfer of momentum **K** that can result in the observed spinning effects.

Here we consider the effects of *two concrete cases of gradients* of the drift ion velocity: a) a gradient directed *along* the ion velocity **u** (e.g. ions accelerated in the sheath region) and b) a gradient *perpendicular* to **u** (e.g. radially inhomogeneous plasma). Note that only in the latter case there is a net time averaged transfer of angular momentum to the rod. Assuming for the first case, that the ion velocity is dominated by a collisionless acceleration in the sheath field $u \gg v_{Ti}$, where $v_{Ti} = (T_i/m_i)^{1/2}$ is the ion thermal velocity, the distribution function reduces to a normalized delta-function $f_\alpha \sim \delta\,[\mathbf{v}-\mathbf{u}_\alpha(\mathbf{r})]$. As well known from the case of spherical particles (see e.g. [12]) the collecting cross-section (for the usual case of a high grain charge, when the parameter $\Gamma = Ze^2/RT_i > 1$, where R and Z are the radius and charge number of the grain) is higher than geometrical square of the particle, due to collecting of the ions with bigger than the radius R impact parameters. The same situation is valid, naturally, for the elongated particles. In this report, for estimation, we consider the simplest case of very fast ions, where this effect is negligible. We consider $\mathbf{u}_i(z)$ parallel to the electric field **E** directed against z axis and du(z)/dz < 0, where $u(z) = |\mathbf{u}(z)| = -\,\mathbf{u}_z(z) \equiv -\,u_z$. For particles spinning around y-axis, we find from (1) the non-zero component of **K**:

$$\mathbf{K}_y = m_i\,|\sin\theta|\,\sin\theta\;2a\int_{-L/2}^{L/2} dl\,l\;n_i(l\cos\theta)\,u_z(l\cos\theta)\,|u_z(l\cos\theta)|\,. \qquad (2)$$

Here θ is the angle between z direction and the instantaneous direction of the long axis of the rod-like particle. If we use the continuity equation for ions (without ion source of ionisation: $n_i(z)u(z) = j_+$) and suggest a small relative change of the ion drift velocity on the scale L, the momentum equation of motion takes a form:

$$I\,d^2\theta/dt^2 = (1/12)\,a m_i j_+ L^3 \sin\theta\cos\theta\,|\sin\theta|\,(du(z)/dz)|_{z=0} \qquad (3)$$

The moment of inertia I of a rod in (3) is $I \approx (1/12)\,ML^2$. Particle mass is given by $M = \pi a^2 L\rho$, ρ is the particle material density. In the sheath region the ion velocity increases approximately linearly with decreasing distance to the electrode. A realistic value is $(du(z)/dz)|_{z=0} = 5\times10^6\ s^{-1}$. Substituting this in eq. (3) yields:

$$d^2\theta/dt^2 = -\,(5\times10^6\ m_i j_+/\pi a\rho)\,\sin\theta\cos\theta\,|\sin\theta| \qquad (4)$$

This equation of motion can describe two kinds of particle motion: oscillations and rotations. The vertical alignment ($\theta = 0$) is a stable equilibrium position around which the rod can oscillate. Even though this is not a harmonic oscillator, it is tempting to consider the θ-independent multiplication factor on the right hand side as $-\,\Omega_0^2$, and to evaluate the characteristic frequency of particle vibrations. This frequency is of the order of a few Hz for a particle with the size of order 10 μm, which is comparable to the experimentally observed values. According to (3) the oscillation frequency increases with increasing ion flux and velocity and decreases with increasing the particle radius. Note that it is independent of the particle length. The second type of motion occurs when a particle has sufficient kinetic energy, so that it can "flip over" the horizontal alignment ($\Theta = \pi/2$), which is an unstable equilibrium position. In this case the particle will keep on rotating in the plane vertical to the electrode. Since there are two degrees of freedom in which the particles can move, both rotations and oscillations are two-dimensional and they may look alike when viewed from the top. We found the characteristic spinning – oscillations and rotations with typical for the experiments characteristic frequencies. We want to point out that the characteristic spinning – oscillations and rotations frequencies of a few to a few tens of Hz typically observed in the experiments are also found this approach. While the typical frequencies for oscillations of the rod-likes due to the presence of a permanent dipole moment are in the order of several kHz [8], clearly in disagreement with our experiments.

For simplicity we neglected friction with the atomic gas in a plasma. However, it is obvious that the above model using a gradient in the ion drag force parallel to the ion current cannot drive stationary oscillations in presence of friction. It only describes the movement given a certain initial angular momentum.

However, the same derivation repeated for a gradient in the direction perpendicular to the ion drift velocity (the second case mentioned above) can provide the net transfer of the angular momentum averaged in time and the respective equation of motion, which follows also by use eq. (1), can lead to rotations of the rod-likes as well to oscillations. Which kind of the stable regime in that case is realised depends by the parameters of the discharge.

More complicated cases for spinning and also translational motion of the particles, due to the reactive force, created by surface recombination of the ions and evaporation atoms to the plasma, will be studied in future using the same approach.

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