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# Collective effects in complex/dusty plasmas

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Collective effects occur when the interactions between particles lead to new phenomena that cannot be understood by considering only the individual particles. Instead, experimenters must take into account the whole ensemble – the sum is greater than the parts. Complex or dusty plasmas are very well suited to study collective effects. These plasmas consist of microparticles embedded in an electrically conducting gas. The microparticles acquire high charges and interact with each other, leading to a great variety of collective effects. Experimenters record the movement of the microparticles using high-speed cameras. Then, they trace the individual microparticles from frame to frame and study the detailed forces acting on the microparticles. This makes an investigation on the most fundamental level possible – the level of individual particles. In this review, I shortly introduce complex plasmas and then present examples of experiments on collective phenomena: droplets and clusters of microparticles, traveling waves, string and lane formation, and the Rayleigh-Taylor instability.

## I. INTRODUCTION

Let us for a moment imagine we wanted to study an experimental system, say a fluid in a container. If it were possible, we would watch individual atoms in the fluid move about, following their trajectories dictated by Brownian motion. The atoms would move in any direction, some up, some down, some left, some right. The task to bring order into such a chaotic system might seem like an attempt to herd cats. Yet if we zoomed out and considered a larger amount of atoms, it could suddenly become clear that the motion of the atoms was really correlated - for instance, they might be moving in large vortices, forming beautiful patterns, such as those in Rayleigh-Bénard convection (10). The pattern arises out of the interaction between the atoms - we cannot understand it by considering only the movement of a few individual atoms, but we have to take into account the whole system. This is what is meant by "collective effects". They can be achieved by feedback mechanisms and strong interactions between the constituents of the system (68). These collective effects are wide-spread in nature. For instance, chemical oscillators synchronize (37), animal swarms and human groups self-organize their movement (68), colloids form spatial structures (24), and even particles in quantum systems move collectively (15).

So what constitutes a good experimental system for studying collective phenomena? It is of course obvious that these phenomena must be present. But it is also desirable to use a system in which the motion of the individual particles is fully resolved. Then, we can study collective phenomena on the most basic level, namely that of individual particles. Indeed, we shall see that complex plasmas fulfill both of these requirements. In this article, I shall present some examples of collective effects in complex plasmas. Because of the limited space available, these examples are by no means comprehensive, and for details, the reader is referred to more extensive reviews on complex plasmas, e.g. (51). Before talking about concrete examples of collective effects in complex plasmas, I first introduce the system itself.

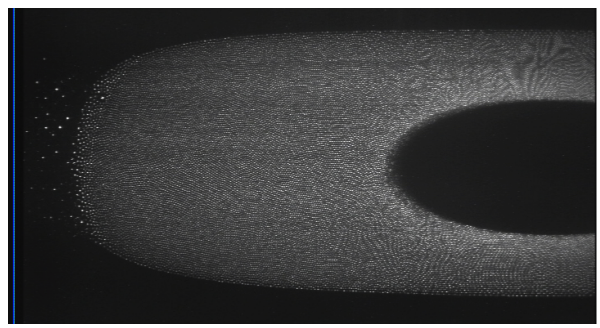

FIG. 1 Complex plasma under microgravity conditions. Approximately half of the midplane cut through the microparticle cloud is visible. The bright dots are microparticles that are illuminated by a laser. The central particle-free region is called "void". The patterns appear because the complex plasma is in the crystalline state. Field of view: 17 mm × 36 mm. Courtesy of the PK-3 Plus team (76).

## II. COMPLEX PLASMAS

Complex plasmas consist of nanometer or micrometer-sized particles that are suspended in an electrically conducting gas, a plasma. Commonly melamine-formaldehyde or silica particles are used. As these particles are of the same size as dust particles, complex plasmas are also called "dusty plasmas". Only microparticles, not nanoparticles, are discernable individually with an

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ordinary camera. The plasma around the microparticles consists of neutral atoms, ions, and electrons. All plasma particles constantly collide with the microparticles. As the mobility of the electrons is several orders of magnitude larger than that of the ions, the microparticles are hit by more electrons than ions and therefore acquire high negative charges. The charge is roughly proportional to the microparticle radius and is usually of the order of a few thousand electron charges per microparticle.

The ions and electrons in the plasma screen any electric fields, so the charged microparticles interact via a screened Coulomb (Yukawa) potential (51). A typical setup contains particle clouds with diameters of a few cm and interparticle distances of the order of 100 µm. The microparticles themselves always stay solid, but they can act like the atoms in ordinary systems in varying phases. A complex plasma in the crystalline phase is called "plasma crystal" (13; 26; 74). The system can also be in the liquid or gaseous state, which is characterized by less order (typically measured by the pair correlation function) and more movement of the microparticles.

The microparticles are also subject to forces from the surroundings: On Earth, *gravity* pulls the microparticles downwards and strongly disturbs the system. For this reason, experiments are often performed under microgravity conditions, for instance during parabolic flights (e.g., 38; 71; 73; 75), on sounding rockets (54) and on board space stations (22; 56; 57; 76). Figure 1 shows one half of the midplane of a complex plasma in the PK-3 Plus laboratory that is currently installed on the International Space Station. Two things are immediately obvious when looking at this picture: The particles do not fill the plasma chamber up to the edges, and there is a central, particle-free region. These two effects are caused by the two second-most important forces: The *electric force* in the plasma sheath and pre-sheath confines the negatively charged microparticles in the plasma chamber. It also accelerates the positively charged ions towards the edges of the plasma. When ions are streaming past microparticles, they drag the particles in the direction of the ion flow. This *ion drag force* generates the microparticle-free central region: the "void" (54), which can be observed when gravity can be neglected. Another force that acts on the microparticles occurs when they move with respect to the background gas: friction slows the microparticles down. This force on microparticles is called *Epstein damping* (18). Regardless, the rate of momentum and energy exchange through interactions between microparticles can significantly exceed the damping rate. Then, the internal dynamics of the microparticles is basically undamped (51). Other forces acting on the microparticles are the *thermophoresis* due to a gradient in the neutral gas temperature (32) and the forces due to *electron and ion temperature gradients* (36).

The interplay of forces can lead to instabilities. For instance, the void can become unstable in the so-called "heartbeat instability" (25), which manifests as a repeated contraction and expansion of the void. Most commonly, however, the microparticle cloud is stable, and other effects can be studied. The ion drag force also causes waves and strings made up of microparticles. But before we turn to these experimental observations, let us take a closer look at how complex plasma experiments are typically performed.

## III. EXPERIMENTAL PROCEDURES

Complex plasmas are produced by first igniting a low temperature plasma, usually either a radio-frequency (RF) or direct current (DC) plasma. Then, microparticles are introduced into the system, for instance by shaking a dispenser mounted into the chamber wall. After entering the plasma, the microparticles charge so fast that the electric field near the edge of the plasma confines them before they hit the ground. Once confined, the microparticles typically move with velocities of some cm/s or less. Therefore their dynamics can be resolved with high-speed cameras. The particles are most commonly visualized by illuminating them with a sheet of laser light. A camera in front of the plasma chamber focusses on the laser sheet. A filter on the camera lens filters out the light from the plasma itself, so that only the positions of the microparticles are recorded. The microparticles can then be traced from frame to frame (see, e.g., (19), and references therein), or particle image velocimetry can be used (78). A translation stage that moves the laser sheet through the system makes the three-dimensional structure of the system visible.

For small numbers of particles, experiments use three-dimensional diagnostics to follow the motion of particles even on complicated trajectories. For instance, a color gradient can code the particle positions (23), and holography (41) and stereoscopy (35) allow reconstructing the positions. Figure 2 shows a cluster that is studied with the color coding method. Once the particle dynamics is known, the complex plasma can be studied in detail.

## IV. COLLECTIVE EFFECTS

Complex plasmas display a wealth of collective effects. In the following, I shall present some collective effects of mesoscopic (consisting of few particles) and fluid complex plasmas, beginning with a phenomenon that the reader probably will associate with liquids: droplets.

### A. Droplets and clusters

Clusters of microparticles consist of a much smaller number than microparticle clouds, typically a few thousand particles or less (34; 39; 46). They are usually of more or less spherical shape. In order to make clusters, some additional force must be present to confine the particles – without it, the cluster would fall apart, as the highly charged particles strongly repel each other. One way to make clusters is to add an artificial confinement force. For instance, the experimenters can place a small glass box on the bottom electrode (5; 6). The glass box builds up an electric potential and repels the microparticles.

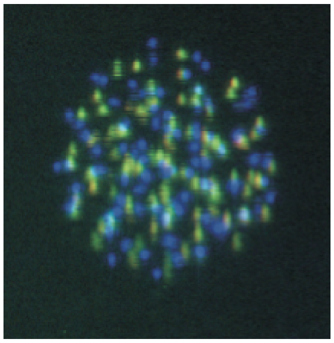

FIG. 2 A microparticle cluster consisting of about 60 particles. The cluster is illuminated by two different lasers with different colors to allow three-dimensional diagnostics. Courtesy of T. Antonova (2).

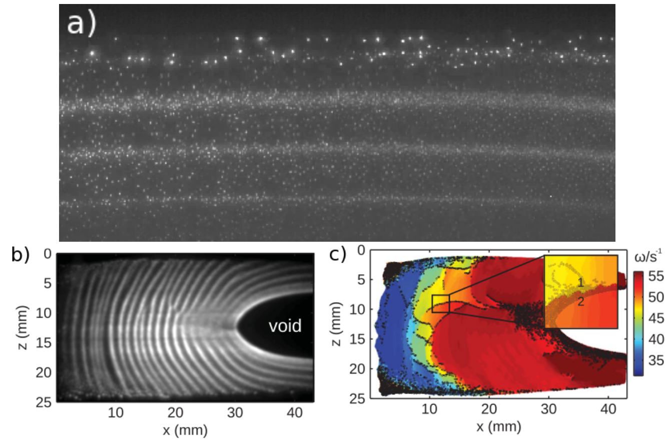


FIG. 3 (a) Zoom into dust-acoustic waves, travelling towards the top of the image. The brighter regions correspond to a higher microparticle density. (b) Smoothed view of waves under microgravity, and (c) corresponding frequency map with zoom into an interface between two frequency clusters. (b), (c): Courtesy of K. Menzel et al. (47), copyright (2011) by the American Physical Society.

Thermophoresis lifts the particles into regions of subsonic ion flow (5). The experimenters can also locally increase the plasma electric field with an electrode that is made up of small "pixels" that can be controlled individually (3). An example of such a cluster is shown in Fig. 2. If the cluster is produced with the segmented electrode, it is very easy to turn off the additional confinement and use the resulting breakup of the cluster to probe the plasma conditions at the local particle positions (4). The microparticles in clusters at higher pressures often arrange in a shell structure and can crystallize within the shells (11). The clusters are then called "Yukawa balls". The cluster properties depend on the number of particles in the cluster (there are some "magic numbers" of particles that have special properties (2)). Experimenters use clusters to study, for instance, cluster normal modes (28), laser heating and melting (63), and the rotation of the levitated clusters induced by electric fields (79).

The negatively charged microparticles can also spontaneously condense into droplets. This effect is surprising as the microparticles repel each other because of their negative charges. Nevertheless, it has been observed in cryogenic plasmas (1; 8), in a DC plasma (77) and in an RF plasma (65). Interestingly, the droplets can show phenomena that are very similar to droplets made of ordinary fluids. For example, they can break up by forming streams of particles, which is commonly seen in ordinary drops. Tracing the particle motion inside the droplets reveals that the particles move in vortices, just like water molecules in droplets falling in an airstream (65). The reader will wonder what might cause the condensation into droplets. The most promising hypothesis is that ions streaming towards the microparticles drag the microparticles towards the cluster center and causes an "effective surface tension" (65; 77). This hypothesis is unproven so far, but it is well known that ions have a profound impact on complex plasmas, as we shall see in the next section.

### B. Waves

When ions are streaming past microparticles with a sufficient velocity, they excite longitudinal acoustic waves in the microparticle fluid (9; 14; 61). This is a manifestation of the two-stream instability. These waves are called "dust-density waves" or "dust-acoustic waves" (DAWs), even though their dispersion relations are not necessarily acoustic-like ($\omega \propto k$) for all wave numbers (58; 60). They consist of travelling regions of higher and smaller microparticle densities, corresponding to the wave fronts and troughs. Figure 3 shows examples of DAWs.

DAWs get excited more easily when then microparticle number density is higher, when the damping due to the background gas is lower and when the ions move faster with respect to the microparticles (50; 62). Accordingly, self-excited waves appear when the pressure is lowered beneath a threshold (33; 48; 50; 66). As the sheath electric field pulls the ions towards the electrodes, their velocity increases the closer they get to the sheaths. The wave motion first appears near the edge of the cloud, with the fronts moving towards the edge. When the pressure is lowered even further, waves appear further away from the edges (64), until the whole microparticle cloud forms wave. Figure 3(b) shows this situation. Complex plasmas allow a detailed study of the frequency distribution within the cloud (see Fig. 3(c)) and the influence of nonlinearity on this distribution (47).

The wave amplitudes grow as the wave fronts move through the microparticle fluid (20). DAWs are often nonlinear, meaning that the variation in density is more steep than given by a sinusoidal curve (49; 67). By carefully controlling the external parameters such as the pressure, it is possible to adjust the degree of nonlinearity (21) – the lower the pressure, the more nonlinear the dust waves, until saturation occurs. Experimenters can trace the microparticle motion inside the waves (66; 72): Microparticles can be picked up by an approaching wave front and move with it. While moving with the wave-

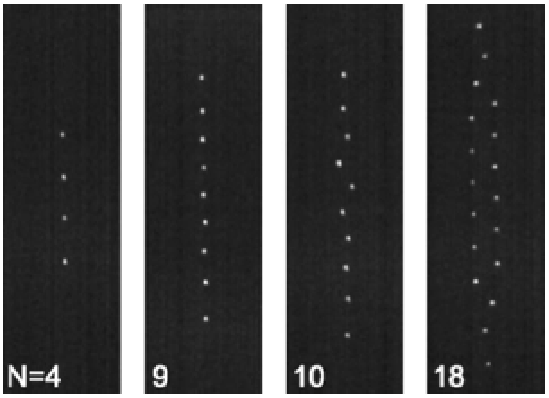


FIG. 4 Microparticle strings containing a varying number N of particles. The cluster with 10 particles undergoes the zig-zag transition. Courtesy of A. Melzer (45). Copyright (2006) by the American Physical Society.

front, the particles also move *within* the wavefront, until they "fall out" at the other end of the front and return to their original positions. The wave fronts can trap microparticles, but most of the particles have sufficient energy to escape the trapping (12; 30).

Even when the ion flow is not strong enough to excite waves, ions can have a profound impact on the microparticles: They force the microparticles to align in strings parallel to the direction of the ion flux.

### C. Particle strings

The electric field in the sheath and presheath regions of the plasma accelerates the ions towards the electrodes. While the ions are streaming past the microparticles, the negative charge on the microparticle surface attracts the ions and deflects them from their straight path. The ions form space-charge regions downstream of the microparticles. These regions attract other nearby microparticles and cause them to form chains or strings (55; 70). This effect can be important even for subsonic ion flows (7). Space charge regions form above and below the microparticles when the ions move alternately up and down. This is achieved with an electric field alternating with a frequency that the ions can follow but the microparticles cannot. Then, long microparticle strings in so-called "electrorheological plasmas" form (31).

It is also possible to form strings by using an additional confinement force, very similar as with the clusters that we talked about in the previous section. Glass boxes placed on the bottom electrode can force the microparticles into strings (40). A horizontal barrier on the lower electrode can lead to horizontal strings (29; 44). Whatever the mechanism by which they were produced, microparticle strings show many collective effects. For instance, they can be used to study the zig-zag transition from one to two parallel strings (45) (see Fig. 4). Waves and oscillations moving along the strings can be studied (e.g., 40; 43). The stability of strings made up of several particles is also of interest; the strings are subject to the hose instability, which can lead to their destruction (42). Next, we shall see what happens when, instead of ions flowing past microparticles, other microparticles do.

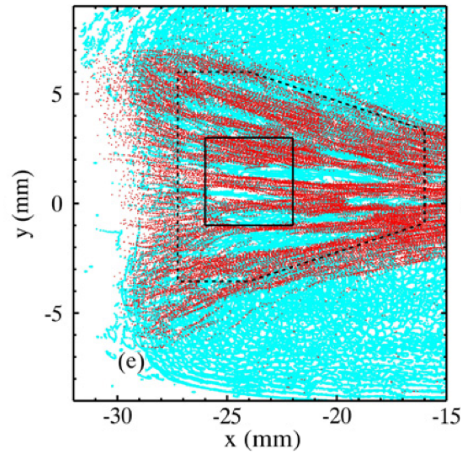


FIG. 5 Superposition of particle trajectories recorded during 5 s. Smaller microparticles (red) penetrate a cloud of larger microparticles (cyan). While moving to the center of the cloud, the smaller microparticles form lanes both in their own cloud and in the cloud of larger particles. Courtesy of C.-R. Du et al. (17).

### D. Lane formation

When two clouds with particles of different sizes stream past each other, the particles often form lanes. This effect occurs in diverse system, for instance colloids, pedestrians or lattice gases (see (69) and references therein). In complex plasmas, lanes form when smaller microparticles are injected into a complex plasma that already contains a cloud of larger particles (53; 69). The ratio of the electric and ion drag forces depends on the size of the microparticles. This leads to a sorting of the microparticles by size – the smaller ones are closer to the void. The small particles thus move through the cloud of larger ones, forming lanes. An example of this effect is shown in Fig. 5. Note that the lanes do not only form in the smaller particles, shown in red in the figure, but the larger particles are pushed together to form lanes as well. Another method to produce lanes is to use vortices that occur naturally in complex plasmas (16). The microparticles in the vortices are pushed into a cloud of stationary particles and form lanes there.

However they were produced, the lanes in the small particles form practically instantaneously. The larger particles are heavier and thus take longer to be pushed into lanes. Once they do form lanes, these lanes persist for a while after the small particles are gone. This means that there is a memory effect: if another cloud of small particles is injected before the larger particles have completely relaxed, the small particles move faster through the cloud. A universal order parameter describes the lane formation process. This can be used to predict optimal parameters for experiments on lane formation (17; 69).

Lane formation is a manifestation of the Rayleight-Taylor instability at low interfacial tension (80). In the next section, we shall see in which other experimental situations in complex plasmas this instability occurs.

### E. Rayleigh-Taylor Instability

The Rayleigh-Taylor instability occurs when a light fluid is accelerated into a heavy fluid. This instability is very common in nature, and its origin at the individual particle level is of great interest. It has been observed in complex plasmas in various circumstances: Firstly, as mentioned in the previous section, in the form of lane formation. Secondly, by accelerating the complex plasma below the void into the particle-free region above. The microparticle fluid then forms indentations in the microparticle cloud surface. These can be described as a Rayleigh-Taylor instability, and the surface tension calculated from the dispersion relation of the instability matches that measured during the experiment (65). The third circumstance in which the instability occurs is when a lower density microparticle fluid spontaneously penetrates into a higher density one (59). Then, the development of the instability is similar to that at the interface between two incompressible liquids.

The fourth mechanism to observe the Rayleigh-Taylor instability in complex plasmas is by shearing a vortex of microparticles against a stable microparticle cloud (27; 52). The particle in the vortex are centrifugally driven into the cloud, and the interface becomes unstable. A mixing layer between the flowing and the stable clouds forms. It is possible to study this mixing layer in great detail by tracing the microparticle movement. Figure 6 shows the velocity of the microparticles during the development of the mixing layer (27). The width of the mixing layer grows exponentially, and fingers of interpenetrating particle flows develop.

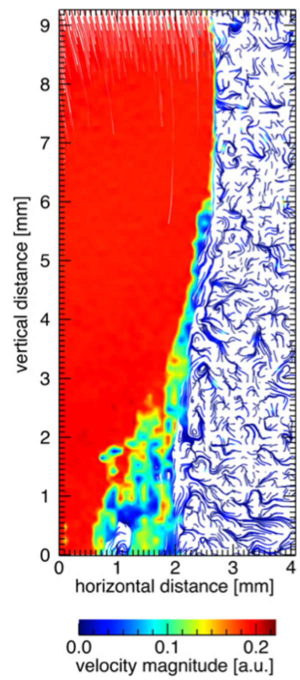


FIG. 6 Velocity map of the interface and mixing layer between downwards streaming (left) and resting (right) particles. The particles start to interpenetrate and form a growing mixing layer. Courtesy of R. Heidemann et al. (27).

## V. SUMMARY

In summary, I have given an introduction to complex plasmas and discussed some examples of collective effects in these systems. Complex plasmas are very well suited to study collective effects because the strong interaction between the microparticles gives rise to a wealth of these effects, and because it is possible to study the motion of individual particles. I have talked about droplets and clusters, which can be excited into different oscillation modes and show collective rotation and breakup mechanisms reminding of water drops. Experimenters can control the degree of nonlinearity of waves in complex plasmas and observe how particles are transported by the wave fronts. Particle strings contain phonons and are subject to instabilities. The Rayleigh-Taylor instability in complex plasmas manifests in various forms, for instance, in lane formation and in mixing layers at the interface of two microparticle clouds.

These are only a few examples of the collective phenomena that can be studied with complex plasmas; there are many other effects that I have not discussed or that have not even been investigated in detail yet.

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