Experimental Investigations of Dusty Plasmas

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Abstract. This paper highlights some of the history of laboratory experiments in dusty plasmas, beginning with an early unexpected discovery of Langmuir. Although there was a great deal of theoretical work on dusty plasmas long before dedicated laboratory experiments were initiated, the experimental work is catching–up and new discoveries in the laboratory are motivating further theoretical work.

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INTRODUCTION

On September 18, 1924, Irving Langmuir in an address marking the Centenary of the Franklin Institute in Philadelphia described what was possibly the first laboratory observation of a dusty plasma [1]. Langmuir was investigating a discharge in a glass tube containing 2–4 Torr of argon gas. The discharge took place between a heated tungsten filament located at the end of a 10 cm diameter pyrex tube and a disk shaped anode located at the end of a 3 cm diameter tube which rose vertically 50 cm from the larger tube containing the filament (cathode). By interrupting the cathode heating circuit for about a half second, the cathode temperature was momentarily lowered, decreasing the electron emission and causing the voltage across the arc to rise to a sufficient value to produce sputtering of tungsten due to ion bombardment. Langmuir noted that these minute 'globules' of tungsten, perhaps as small as 100 microns in diameter, had "a profound effect upon the arc." Under certain conditions the particles moved through the arc at velocities of 10-30 cm/s, and appeared as brilliant 'streamers," hence he referred to this as a "streamer discharge." He described this as a "phenomena of remarkable beauty which may prove to be of theoretical interest." Langmuir was right on the mark in foreseeing the great interest that would be devoted decades later to the study of dusty plasmas. He was also correct in his understanding that the particles would be negatively charged and surrounded by a positive shielding cloud. Since Langmuir's experiments preceded the invention of the laser by some 34 years, he used a concentrated beam of sunlight focused into the discharge tube to show that the globules would give rise to a 'very intense scattering' of light when they passed through the beam.

It is worth remembering that Langmuir also provided the genesis of our theory of dust charging with his "theory of collectors." He appears to be the first to point out that the potential assumed by a floating probe in a plasma is not the same as the plasma potential, but will be negative with respect to the surrounding plasma by an amount roughly four times the potential corresponding to the average energy of the electrons for a Hg plasma. He was also the first to recognize that the ion current to a probe would be limited by orbital motions. Spitzer, however first wrote down the equation ,$1-\varphi_f-(m_i/m_e)^{1/2}e^{\varphi_f}=0$, for computing the normalized floating potential, $\varphi_f = eV_f/kT$, for the case of dust grains charged by electron and ion collection [2].

Langmuir's suspicion that dusty plasmas would captivate the interest of plasma physicists is borne out by the data shown in Fig. 1 showing the exponential growth in dusty plasma journal publications from 1981 to present.

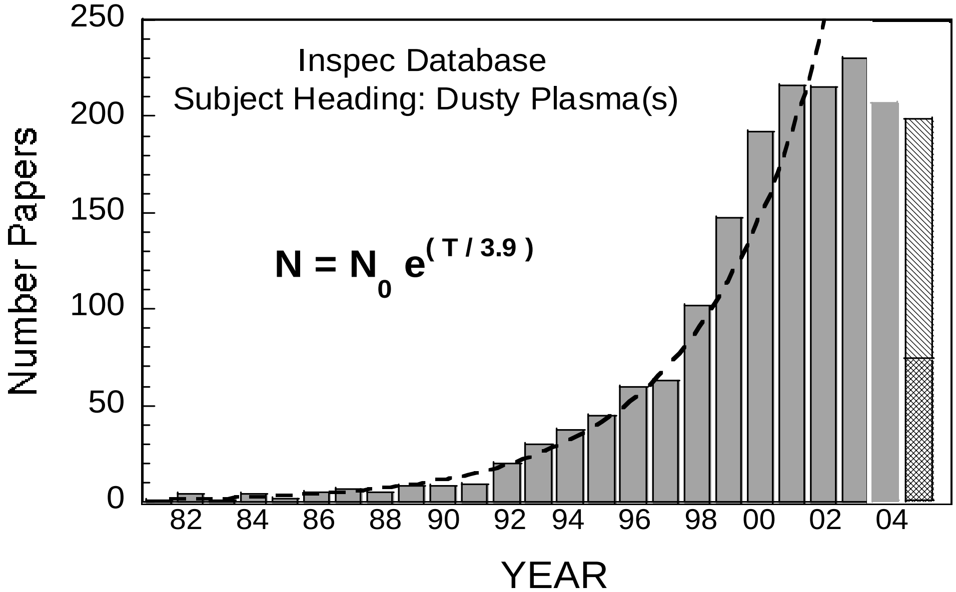

FIGURE 1. The number of journal publications per year containing the keyword 'dusty plasma' from 1981 to 2004. Data available through May 2005 is shown as the crosshatched bar. The continuing hatched bar is an extrapolation for 2005. An exponential fit to the data from 1981 to the peak publication year 2003 is shown as the dashed line. The e-folding time is 3.9 years.

The number of publications peaked in 2003 and appears to have leveled off now. The exponential growth in dusty plasma research was driven primarily by discoveries in the widely different areas of planetary science and applied plasma science: the observation of the spokes in Saturn's B ring, reported in 1982 [3], and the realization that the contamination of semiconductor material in plasma processing tools was due to particles grown in the plasma [4]. Further details and color pictures of these phenomena can be found in the Physics Today Article of July 2004 of Merlino and Goree [5]. These are considered milestone events in dusty plasma research. The Voyager discovery of the radial spokes in Saturn's B ring, and the ensuing theoretical activity attempting to provide an explanation, was the impetus for the important review article, "Dusty Plasmas in the Solar System," by Chris Goertz, published in 1989 in the Review of Geophysics [6]. This article, which has been cited 544 times, has been for many of us, our initial exposure to and source of basic knowledge of dusty plasmas. The need to understand the basic physics of the plasma processing tools also led to another significant development – the introduction, in 1988, of the GEC reference cell for generating a radio-frequency discharge at 13.56 MHz. This device, which grew out of the need to provide an experimental platform to compare measurements from separate but identical systems, proved to be an ideal device in which to carry out studies of strongly coupled dusty plasmas, and in particular plasma crystals. This cross-fertilization between the basic plasma physics community and the applied plasma physics and engineering communities has been essential to progress in dusty plasmas and is an excellent counterexample to the view held by Alfvén that "Scientists tend to resist interdisciplinary inquiries into their own territory."

In the following section, I provide a few examples of some of the early experimental work on dusty plasmas, including the methods used to create dusty plasmas. This is not meant to be an inclusive review, but rather a brief discussion of some laboratory work that is well known to this author. Before proceeding, it is perhaps fitting to quote once again from Alfvén on his view of the necessity for experiments, "We have to learn again that science without contact with experiments is an enterprise which is likely to go completely astray into imaginary conjecture."

EARLY EXPERIMENTAL WORK ON DUSTY PLASMAS

This section highlights some early experimental work on dusty plasmas. The first hurdle was to figure out how to get dust into a plasma. Although the work of the plasma processing laboratories showed how to grow dust in the plasma, it was necessary to develop methods of introducing dust of a particular size and concentration in order to perform controlled experiments.

Dust Dispersal Devices (Dusters)

This is a class of devices in which dust is dispersed (dropped) into a plasma by some mechanical means. The first such device was introduced by Sheehan, Carillo and Heidbrink [7], and utilized the Q machine at the University of California at Irvine as the plasma source. This device consisted of dust dispersing cell which was shaken at a frequency of 5 – 80 Hz by a pneumatic driver. The cell was adapted to the vacuum using a bellows. The cell consisted of three chambers each separated by a mesh of decreasing coarsness. The violent shaking and sifting action was able to break up large dust clumps into fine particles. This turns out to be a very important consideration in any dust dispersal system, since fine particles are subject to clumping action making it very difficult to ensure that any particular size dust is being introduced into the plasma. This device was used to introduce a 1 cm^2 stream of kaolin dust (hydrated aluminum silicate) perpendicularly across the center of a 5 cm diameter Barium Q Machine plasma. By collecting the dust on plates mounted below the duster, it was inferred that the dust had acquired a negative charge. Further evidence was obtained from observations of depletions in the electron density.

An interesting variation of the UC Irvine dust shaker device was developed by the Colorado group of Walch, Robertson and Horanyi [8] to drop one dust grain at a time into a chamber. The device basically consisted of a thin plate with a tiny central hole through which the grains fell when the plate was given an impulse from an electromagnet. As the grain fell, it passed through a region in which a negatively biased tungsten filament sprayed it with electrons. The electron energy determined the surface potential of the grain. After charging the grain fell into a sensitive Faraday cup, where its charge was measured. This rather simple and elegant device was used to study the basic physics of dust charging, establishing that (a) the charge was directly proportional to the grain potential, and (b) by using dust of various diameters, that the charge scaled linearly with diameter.

The device used by the Irvine group was important in showing the effects of dust on a plasma, however, it did not produce a dusty plasma of sufficient volume in which the effects of dust on plasma waves and instabilities culd be studied. A good deal of theoretical work on dusty plasmas had concentrated on wave phenomena (One should consult Shukla's and Mamun's textbook [9] for a detailed exposition of much of the work on waves in dusty plasmas.) so D'Angelo and I at the University of Iowa sought to develop a device for producing a plasma with an extended region of dispersed dust. Our dusty plasma device (DPD) also used the Q machine as the plasma source. To disperse dust particles into the plasma, the 1 m long and ~ 4 cm diameter plasma column was surrounded over a 30 cm portion of its length by a concentric cylinder which could be loaded with dust (typically kaolin in the 1 – 15 micron range) and rotated around the plasma column. As the cylinder rotated, dust was carried to the top where it then fell as a rain of solid particles through the plasma. The fallen dust would then collect at the bottom of the cylinder where it could be recycled through the plasma. The effect of the dust was observed on a Langmuir probe which showed a decrease in the electron saturation current due to the removal of electrons to the dust. This device was used initially to investigate the predicted reduction in grain charge for the case in which the dust grains are 'closely packed' so that the intergrain spacing is less than the plasma Debye length [10].

RF Parallel Plate Devices (The GEC Reference Cell)

This device produces plasma using 13.56 MHz rf power applied to a pair of 10 cm diameter parallel plate electrodes located inside an ultrahigh vacuum chamber, as shown schematically in Fig. 2.

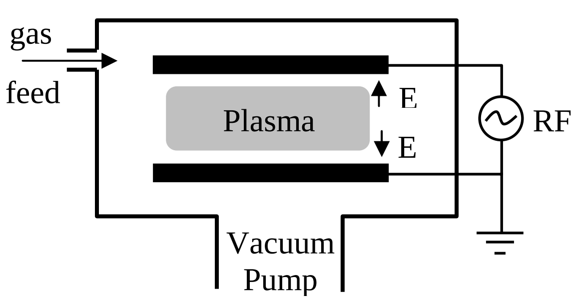

FIGURE 2. Schematic diagram of the rf driven parallel plate GEC reference cell.

The devices are typically operated in argon gas with pressures in the range of 10 – 300 mTorr. When operated with a mixture of silane, oxygen and argon ($SiH_4/O_2/Ar$) or with graphite electrodes which sputter carbon, dust particles can be grown in the plasma. For more controlled dispersal of dust, dust can be introduced from ‘droppers’ located above the lower electrode. Typically these devices are operated with microspheres of monodisperse particles (manufactured spherical dust particles with a dispersion in the dust diameter of only a fraction of the mean diameter). Although this device was developed primarily for studies related to materials processing applications, it has three characteristics that favor the formation of strongly coupled dusty plasmas (the interparticle potential energy >> mean kinetic energy). First, its relatively high electron temperature (3 – 4 eV) results in a high dust charge with $Q_d/e \sim 10^4$, for a dust grain of 1 micron radius. Second, it has strongly inhomogeneous vertical and horizontal electric fields that provide a trap for the negatively charged dust particles. Since the plasma potential is positive, there exists a downward pointing inhomogeneous electric field at the lower electrode which can levitate negative particles against gravity. Horizontal confinement is provided by the outward horizontal electric field. Third, at the relatively high operating pressures, collisions between the dust particles and neutral gas atoms are sufficiently frequent to cool the dust particles, allowing them to settle into the strongly coupled state. It is therefore not surprising that Coulomb crystals were first produced in this type of device [11].

Dust in DC Glow Discharges

Perhaps the simplest and least expensive method of producing a dusty plasma is to use a DC glow discharge. A schematic of such a device used by Fortov’s group is shown in Fig. 3 [12].

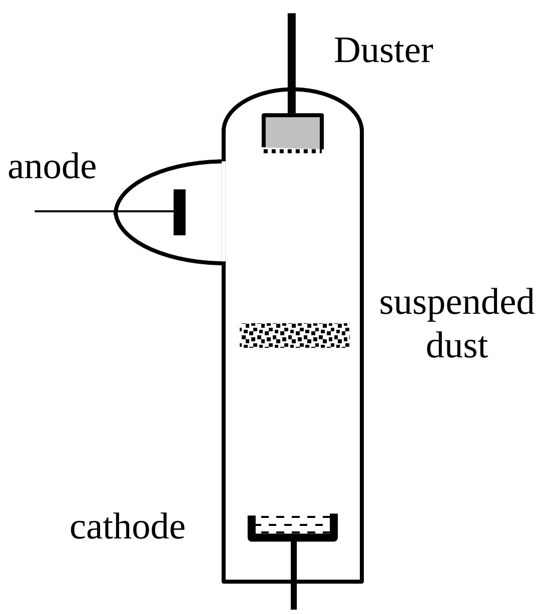

FIGURE 3. DC glow discharge device (positive column) for dusty plasma studies.

The discharge is formed between an anode and a cathode, usually in a noble gas at relatively high pressures, ~ 0.1 – 1 Torr. These discharges are usually subject to the formation of striations which are regions of elevated plasma potential. Dust grains falling from the dispenser acquire a negative charge and get trapped in the positive striations. The dust particles can then be observed with a sheet of laser light and a video camera. Variations of this basic method have been used by Pramanik *et al.*, [13] Nunomura *et al.*, [14], and Thomas *et al.* [15].

Dusty plasmas have also been formed and confined in anode double layers. Barkan and Merlino [16] used an anode double layer formed along the column of the magnetized Q machine with a rotating dust dispenser (DPD) to confine spherical dust structures that we called dust balls. An anode double layer formed in a strong magnetic field is extended along the direction of the magnetic field and contains strong radial electric fields which can be used to levitate dust particles. Thompson *et al*., [17] used a similar approach, with the exception that the plasma was formed by a discharge between a 3 cm diameter anode disk and the grounded walls of the vacuum chamber. Kaolin dust was supplied from a floating tray located just below the anode disk. When the discharge was initiated, some of the dust would be swept up into the plasma and trapped there, forming the dusty plasma. Dust acoustic waves were spontaneously excited in this dusty plasma [17].

SOME UNEXPECTED FINDINGS

The nature of experimental work is such that sometimes, unexpectedly, one finds interesting effects in an experiment that was designed to observe some totally different phenomena. This is, of course, one important reason why we do experiments. The experimental observations of dust acoustic waves and Coulomb crystals provide examples of role of serendipity in experimental physics. Establishment of a dusty plasma laboratory onboard the International Space Station afforded researchers a microgravity environment and also uncovered new phenomena.

Coulomb Crystals and Dust Acoustic Waves

In the experiment of Chu, Du and I, [18] an rf hollow post magnetron system was used to form a dusty plasma through gas phase reactions. The SiO_2 particle that were formed in the discharge were negatively charged and suspended in a region of lowest electrostatic potential energy. Associated with the formation and trapping of one micron particles were low frequency fluctuations at about 12 Hz, and wavelength 0.5 cm. When the gas pressure was increased to 300 mTorr, the fluctuations were suppressed and a solid structure (Coulomb solid) of the dust particles was observed.

In July of 1994, Adrian Barkan and I were studying the confinement of dust in an anode double layer formed at the end of the Q machine (DPD) opposite the hot plate [16]. Negatively charged dust was easily trapped inside the anode double layer which was electrically positive relative to the surrounding plasma. We were able to confine spherical collections of dust particles of about 1 cm diameter which we referred to as ‘dust balls.’ A video capture of one of these dust balls is shown in Fig. 4. The dust ball was observed by light scattered from the 2500 K hot plate plasma source. The geometry of the setup did not allow us to use a sheet of laser light to perform more detailed measurements on these dust balls. In an attempt to improve the visual access, the anode plate was moved further back away from the hot plate into a larger section of the vacuum chamber. This section was beyond the last magnetic field coil, so the magnetic field was diverging in this region and thus the plasma expanded as it flowed into this region. The net result was that the spherical dust ball was transformed into a dust cloud which did not have a definite structure but was clearly in a more fluid state.

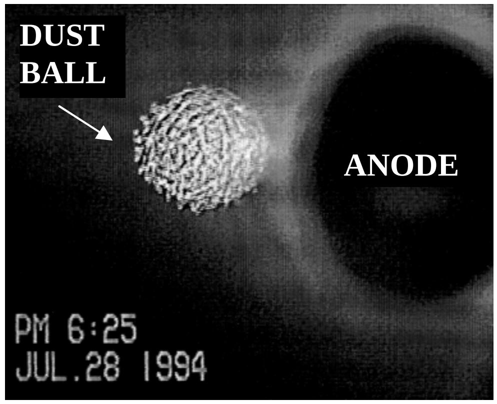

FIGURE 4. Dust ball confined in an anode double layer.

One could easily see a wave propagating through the dust cloud away from the anode disk. Analysis of the video images showed that the wave propagated at a speed of ~9 cm/s and had a wavelength $\lambda \approx 0.6$ cm, so that the frequency was 15 Hz [19]. We identified this as the dust acoustic wave (Fig. 5) that had been predicted theoretically by Rao, Shukla and Yu [20] five years earlier. D'Angelo pointed out that the fluctuations observed by Chu, Du and I [18] was also a dust acoustic wave [21]. We now realize through further study that the presence of dust acoustic instability can preclude the formation of a dust crystal, since the instability heats the dust particles increasing their average kinetic energy.

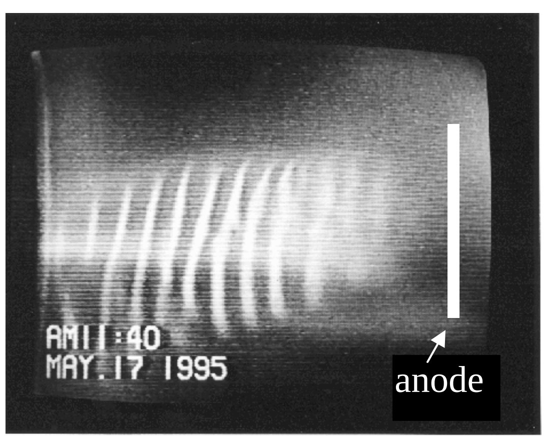

FIGURE 5. Single frame video capture of a dust acoustic wave (From [19]).

The Ion Drag Force and Formation of Voids in Dusty Plasmas Under Microgravity

The behavior of dusty plasmas in earth–based laboratories is strongly affected by gravity. As a result, strongly coupled dusty plasmas in the lab are usually only a few layers thick and are compressed vertically, usually occupying a small vertical region just above the lower electrode of the rf driven parallel plate devices. Thus on earth, dust crystals tend to be two dimensional. To circumvent the effects of gravity, experiments were designed to be operated either on parabolic orbit flights or on the MIR and International Space Station (ISS). The PKE–Nefedov device (Plasmakristall experiment) was a self contained dusty plasma experiment designed and built under a German–Russian collaboration for deployment onboard the ISS [22]. Although this experiment was successful in producing a large three–dimensional dusty plasma, elimination of the force of gravity allowed the effects of the ion drag force to be manifested. Ions created in the center of the discharge, were expelled from this positive potential region, dragging the dust particles along with them creating a void, which is a region containing plasma but no dust particles, as shown in Fig. 6.

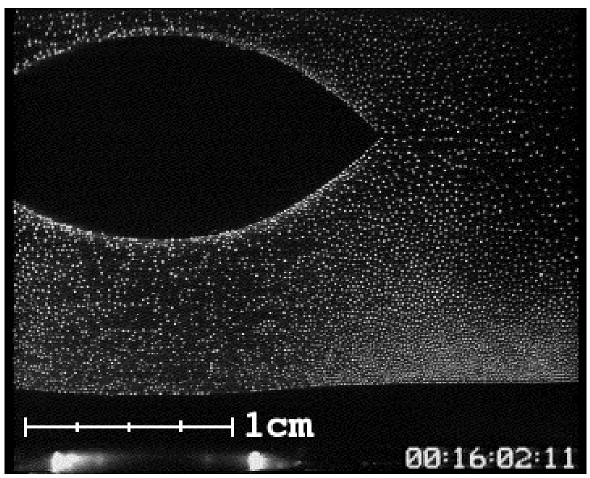

FIGURE 6. Charged micro-particles inside the discharge gather around the 'void' (particle-free zone) in the center of the plasma. Photo available at http://www.mpe.mpg.de/theory/plasma-crystal/PKE/PKE-Nefedov_e.html, used courtesy of MPE, Garching.

CONCLUDING REMARKS

It is instructive to see how the topics discussed at various dusty plasma conferences have evolved over the years. In 1990, at the 4th Workshop on Dusty Plasmas, held in Iowa City, IA, there were 23 presentations and the dominant topics were dusty plasmas in planetary rings and comets, with only one talk from the plasma processing community. Of the 23 presentations, there were only 3 dealing with preliminary laboratory experiments on dusty plasmas. There was no mention of dust crystals or strongly coupled dusty plasmas. Ten years later in 2000, the 8th Workshop was held in Sante Fe, NM with 76 presentations including 16 talks and 18 posters on laboratory experiments in dusty plasmas. The dominant topics at this Workshop were plasma crystals, waves in strongly coupled dusty plasmas and experiments performed under microgravity conditions.

At this 4th ICPDP, one again notices new topics emerging: the effects of strong magnetic fields on dusty plasmas, realization of and consideration of the effects of dust in fusion devices, dust phenomenon in the earth's atmosphere, more emphasis on nonlinear dusty plasma physics and nanoparticle growth. From the point of view of the experimentalist, I see that a positive development is underway in the field of dusty plasmas. Although experimentalists are still working to test much of the theoretical work that has been published, the field has now come full circle in the sense that, to a greater and greater extent, the laboratory results are now influencing and motivating new theoretical work.

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