Schematic of the Experimental Setup

**AFTERGLOW PLASMA**

1) The evolution of a cloud of charged dust particles in the afterglow plasma is governed by a number of processes which occur on different timescales.
   (a) The timescale for plasma density decay which is determined by a combination of diffusion to the walls, and recombination on the floor of the vacuum vessel.
   (b) The timescale for the relaxation of the electron temperature, $T_e$ due to energy exchange with the neutral gas atoms. The dust cloud is directly affected by any change in $T_e$.
   (c) The timescale for the de-charging of the dust due to variations of the electric field and ion fluxes.

2) Depending on the conditions, there are two general scenarios for the evolution (expansion) of a dust cloud in the afterglow:
   (a) Coulomb Expansion—At low gas pressures the decay of the plasma density occurs on a timescale that is faster than that for the decrease in $T_e$. Under these conditions, the Debye shielding of the particles becomes increasingly less effective and dust charge remains close to its initial value. Thus, the dust cloud expands (or explodes) under the nearly unshielded Coulomb interaction between the particles themselves.
   (b) Yukawa Expansion—At higher gas pressures, the frequent electron-neutral collisions causes $T_e$ to drop rapidly while the plasma density falls less rapidly. The reduced particle charge coupled with the persistent shielding leads to a much weaker expansion.

**A. INTRODUCTION**

1. We have studied the evolution of dust suspensions in the afterglow of a DC glow discharge.
2. Small dust clouds (0.5 – 1.5 cm) were trapped using a conical mesh electrode located near a larger primary dust suspension produced in a DC glow discharge plasma in argon gas ($p = 0.1 – 0.2$ Torr) formed using a 2 cm diameter anode disk at a gas pressure of 80 cm diameter by 80 cm high grounded vacuum chamber.
3. The mesh was initially at ground potential and at $t=0$ both the mesh potential and anode potential were switched off, leaving both electrostatically floating. This extinguished the DC glow discharge which removed the confining force (ion drag) which sustained the secondary dust cloud under the mesh electrode.

4. The evolution of the dust suspension initially trapped by the mesh was studied by illuminating the cloud with a vertical sheet of 532 nm laser light and recording its dynamics using a Pho Tube Fastcom CMOS video camera at 2000 frames/second.

**EXPERIMENTAL SET-UP**

- A suspension of micron diameter silica spheres is suspended in a DC glow discharge plasma produced in argon gas using a 3.4 cm diameter stainless steel anode disk in a large (1 m long by 0.6 m diameter) stainless steel vacuum vessel.
- Discharge Parameters:
  - Gas pressure: 70-220 mTorr
  - Discharge voltage: 200 – 300 V
  - Discharge current: 2 – 20 mA
  - Magnetic field: 1 mT
  - Plasma density: $10^3 – 10^5$ m$^{-3}$
  - $T_e = 2 – 4$ eV, $T_i = 0.03$ eV
- Setup:
  - A biased stainless steel mesh draws dust from the main cloud creating a secondary cloud
  - The mesh is shaped as a cone with the dust cloud confined below the mesh (cone shape)
  - When the anode and mesh are set to float the cloud expands and falls under gravity (shuttle)

**DIAGNOSIS**

- The cloud is illuminated by a vertical sheet of 532 nm light that was expanded using a cylindrical mirror and a 4f/242 laser
- The cloud is imaged using a video camera operating at 60-2000 frames per second.
- Single frame bitmap images of the dust are stored for analysis.
- An electron probe is used to measure the plasma potential (absent dust).
- A double probe is used to measure the plasma density and electron temperature (absent dust).

**B. EXPERIMENTAL OBSERVATIONS**

1. In two instances at 200 mtorr the cloud expanded uniformly.
2. Piel and Goree provided a theoretical equation for the expansion of a cloud with Coulomb potentials and neutral drag forces.
3. The neutral drag term was calculated to be 330 s$^{-1}$ by measuring the terminal velocity of the dust after the expansion stopped and equating the drag and gravitational forces.
4. The width of the cloud is determined using a routine in Mathematica and is normalized to the initial width of the cloud before release.

**D. COMPARISON WITH THE PRESENT EXPERIMENTS**

1. The simulations of dust cloud expansions, typically assume that the initial cloud is symmetric and homogeneous.
2. In our experiments, neither the shape of the clouds nor the dust distributions within the clouds were controllable. The dust cloud expansion is a transient event which leads to the termination of the cloud, as in each experiment begins with a nearly spherical cloud. The details of the formation and trapping of these clouds is not understood in any quantitative way. Even though the plasma conditions may be identical, this does not ensure that similar clouds will be formed. We are thus forced to deal with whatever clouds form, and attempt to characterize their temporal evolution, as best possible. Since the cloud conditions are not of the ideal types assumed in the simulations, qualitative comparisons are usually possible.
3. Our experiments revealed a variety of expansion phenomena. Characteristics of both the Coulomb and Yukawa expansions were found.
   (a) One particularly striking result was the observation, in one instance, of the focusing of a dust cloud into two fragments. A larger fragment was rapidly accelerated away from a smaller fragment and expanded as it separated. The smaller fragment remained nearly stationary during the fusion process, and remained largely intact until it eventually fell under the combination of gravity and neutral drag forces. This observation was made at $p = 0.1$ Torr.
   (b) Cloud expansions observed at $p = 0.15$ and 0.2 Torr showed characteristics of Yukawa expansion at early times and Coulomb-expansion at late times, when compared to the MD simulations of Piel and Goree. This indicates the possibility of a transition from a Yukawa to Coulomb-like behavior as the plasma density decays and the screening effect becomes more effective.
   (c) Another interesting case occurred at a neutral pressure of $p = 0.2$ Torr when the expansion seemed to be uniform across the entire cloud. The expansion was observed over a long time sequence and seemed to be qualitatively in agreement with the MD calculations under the action of the unshielded Coulomb force and neutral drag.

**EXPERIMENTAL RESULTS**

- The response of the dust is recorded at 2000 fps at neutral pressures of 100, 150, and 200 mTorr.
- Above is a typical expansion at 150 mtorr (1 ms between frames).
- The point in the cloud, with respect to the density distribution, at which the separation occurs does not correlate with the background pressure or initial mesh potential.
- Above is a typical expansion at 150 mtorr (1 ms between frames).
- A portion to the bottom and sides of the dust cloud is accelerated downward and outward while another portion of the cloud remains separated. The smaller fragment remained nearly stationary while the larger fragment was rapidly accelerated away from a smaller fragment and expanded as it separated.
- In two instances at 200 mtorr the cloud expanded uniformly.
- The neutral drag term was calculated to be 330 s$^{-1}$ by measuring the terminal velocity of the dust after the expansion stopped and equating the drag and gravitational forces.
- The width of the cloud is determined using a routine in Mathematica and is normalized to the initial width of the cloud before release.

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The profile in each image is the last frame before release and the next seven after release.

In them you can find both the expansion of the separating portion and the portion that remains.

The fourth image is of the profile of the cloud that expanded uniformly at 0.2 Torr. The line for these profiles was chosen as shown in the montage below.

- Above are profile plots of the secondary cloud taken vertically across the cloud at each pressure.
- The profiles in each image are the last frame before release and the next seven after release.
- In them you can see both the expansion of the separating portion and the portion that remains.

**REFERENCES**

- COULOMB EXPANSION
  - Ivlev (PRE 87, 025102, 2013) obtained analytic solutions to the Yukawa regime was seen.
  - Piel and Goree (PRE 88, 063103, 2013) performed MD simulations of the expansion of a dust cluster in a homogeneous plasma.

- DUST EXPANSIONS
  - Yukawa expansion simulations showed that initially the outer layers do not begin expanding until after a layer of the ball is blown off at a much faster rate than the inner layers. The inner layers do not begin expanding until after a layer of the ball is blown off.
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