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Coulomb fission of a dusty plasma

R. L. Merlino,[1,a)] J. K. Meyer,[1,b)] K. Avinash,[2] and A. Sen[3]
[1]*Department of Physics and Astronomy, The University of Iowa, Iowa City, Iowa 52242, USA*
[2]*Department of Physics and Astrophysics, University of Delhi, Delhi, India*
[3]*Institute for Plasma Research, Gandhinagar, India*

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Experimental observations are presented of the splitting (fission) of a suspension of charged microparticles (dusty plasma) into two fragments when the plasma was suddenly turned off. The triggering mechanism for fissioning of the dust cloud is discussed in terms of a pinching instability driven by the ion drag force. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4954906]

One of the interesting aspects of a typical laboratory dusty plasma is that if the plasma source is suddenly turned off, the plasma may decay on a timescale faster than the time required for the dust charge to change appreciably, so that the particles retain a substantial residual charge. Under the (partially unshielded) Coulomb interaction, the cloud of negatively charged particles may *explode*, in a manner similar to the Coulomb explosion of superheated atomic clusters ionized by high-intensity, ultra-short laser pulses.[1] The Coulomb *explosion* of a cluster of negatively charged, micron-sized dust particles initially confined in an anode double layer was observed when the anode voltage was suddenly turned off.[2] The observed acceleration of the dust grains was in agreement with the results of molecular dynamics simulations.[3] The Coulomb explosion of a dense cloud of microparticles trapped deep in the sheath of a novel RF discharge device that contained an additional RF powered electrode in the center of the lower grounded electrode has also been observed.[4] A number of studies have focused on the *de-charging* of dust in a plasma afterglow.[5–8] Analytic calculations[9] and molecular dynamics simulations[10] have also been performed to study the expansion of clouds of charged microparticles under the Coulomb or Yukawa interaction.

Recently, we studied the evolution of dust clouds in afterglow plasmas at various neutral pressures in a DC glow discharge plasma.[11] At the lowest neutral pressure (0.1 Torr), the dust cloud did not explode but was observed to split into two fragments when the plasma was suddenly turned off. This brief communication provides a more detailed look at this *Coulomb fission* process and offers a possible explanation for the fission triggering mechanism in terms of a pinching instability driven by the ion drag force.

The experiments were conducted in a DC anode glow discharge device described in detail in Ref. 11. Fig. 1 is a photograph (in the vertical plane) of the setup showing the anode and a conical mesh electrode that was used to trap and suspend a small, vertically elongated (roughly 0.5 cm wide by 2 cm high) dust cloud of 1 μm diameter, negatively charged silica microspheres. The plasma and dust parameters are summarized in Table I.

The mesh electrode is initially grounded to form a trap for the dust particles, which are confined and suspended by a combination of electric, gravitational, and ion drag forces. The evolution of the cloud was studied after the anode and mesh bias voltages were simultaneously switched to the electrically floating state. A 1–2 mm thick sheet of 532 nm laser light illuminated the region containing the dust cloud, and images of the cloud were acquired at 2000 frames/s using a fast video camera. The single frame bitmap images were analyzed using ImageJ software. The gray scale image intensities were proportional to the dust density.

An estimate of the characteristic timescale for the plasma decay due to ambipolar diffusion to the device walls and plasma absorption on the dust particles using the results of Ivlev *et al.*[5] indicate that the plasma decay occurs on a timescale of a few ms. The time scale for the electron temperature relaxation which controls the de-charging of the dust is on the order of 100 μs indicating that the dust charge decays much faster than the plasma. As a result, in the afterglow phase, the dust charge is reduced (from its value in the main discharge) and is shielded by the residual plasma.

A montage of single frame images of the dust cloud before (t = 0) and at 1 ms intervals after the mesh and anode potentials were switched off is shown in Fig. 2(a). The laser sheet was positioned to pass through the approximate center of the cloud, so that vertical profiles of the cloud density could be obtained. The fission process starts with the pinching of the cloud at a vertical position just above the center of the cloud. Complete fissioning of the cloud occurs by roughly t = 3 ms. The lower fragment, which is roughly twice as large

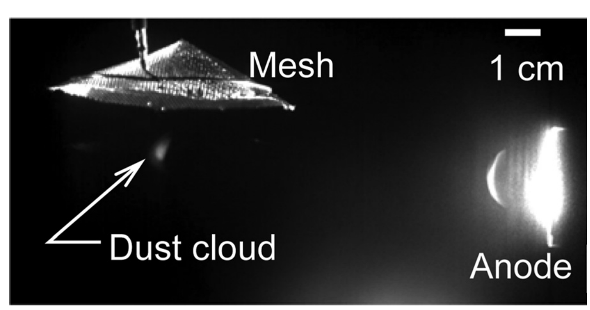

FIG. 1. Photograph of the experimental setup showing the anode and the conical mesh electrode used to trap and suspend the dust cloud. Further details are provided in Ref. 11.

a)Electronic mail: robert-merlino@uiowa.edu
b)Present address: Forschungsgruppe Komplexe Plasmen, Deutsches Zentrum fur Luft- und Raumfahrt, D-82234 Wessling, Germany.

TABLE I. Plasma and dust parameters.

Plasma	
Ion species	Ar^+
Neutral pressure	0.1 Torr (13 Pa)
Discharge current	5 mA
Magnetic field	3 mT
Density	10^{14}–$10^{15}\,m^{-3}$
Electron temperature	2–3 eV
Ion temperature	0.03 eV
Dust	
Composition	Silica microspheres
Radius	$0.5 \pm 0.05\,\mu m$
Mass	1×10^{-15} kg
Charge[a]	(200–2000)e
Density	10^{10}–$10^{11}\,m^{-3}$

[a]Estimated from OML theory.

as the upper fragment, separates, moves downward, and expands slightly. There is initially (t = 1 ms) a slight upward movement of the upper fragment, but this fragment then remains nearly stationary on this time scale but eventually falls under the influence of gravity. Fig. 2(b) shows intensity profiles (∼dust density) of the fissioning cloud taken along a vertical line from top to bottom. As the lower fragment separates, it expands, so that some particle remnants remain in the region between the upper and lower fragments. The area under the intensity profiles decreases by about 10% as the fissioning occurs, indicating that a few particles may be moving out of the image plane during the fission process.

Fig. 3 is a plot of the vertical position of the maximum dust density [obtained from Fig. 2(b)] in the lower cloud fragment vs. time. From t = 0 to t = 2 ms, the acceleration of the lower cloud fragment was $\sim 10^3\,m/s^2$. The rate of separation of the lower cloud begins to decrease by about 3 ms, after which it falls at a lower speed under gravity and neutral drag. The reduction in the speed of the lower fragment for t > 4 ms is possibly due to a reduction in the dust charge in the afterglow.

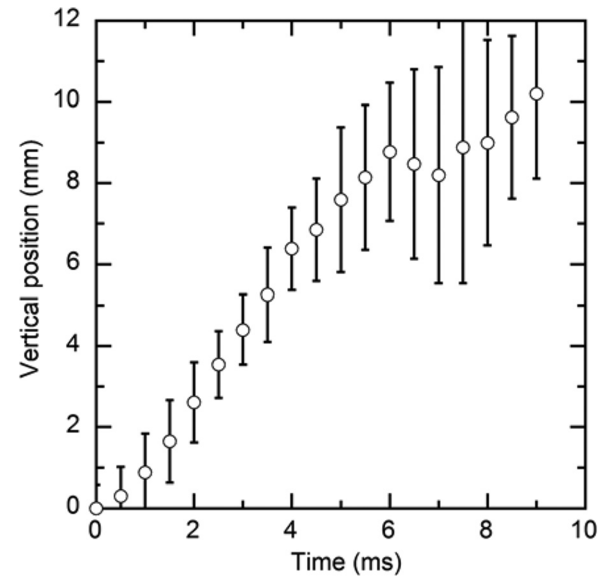

FIG. 3. Plot of the vertical position of the maximum density in the separating dust cloud vs. time, obtained from data of the type shown in Fig. 2(b).

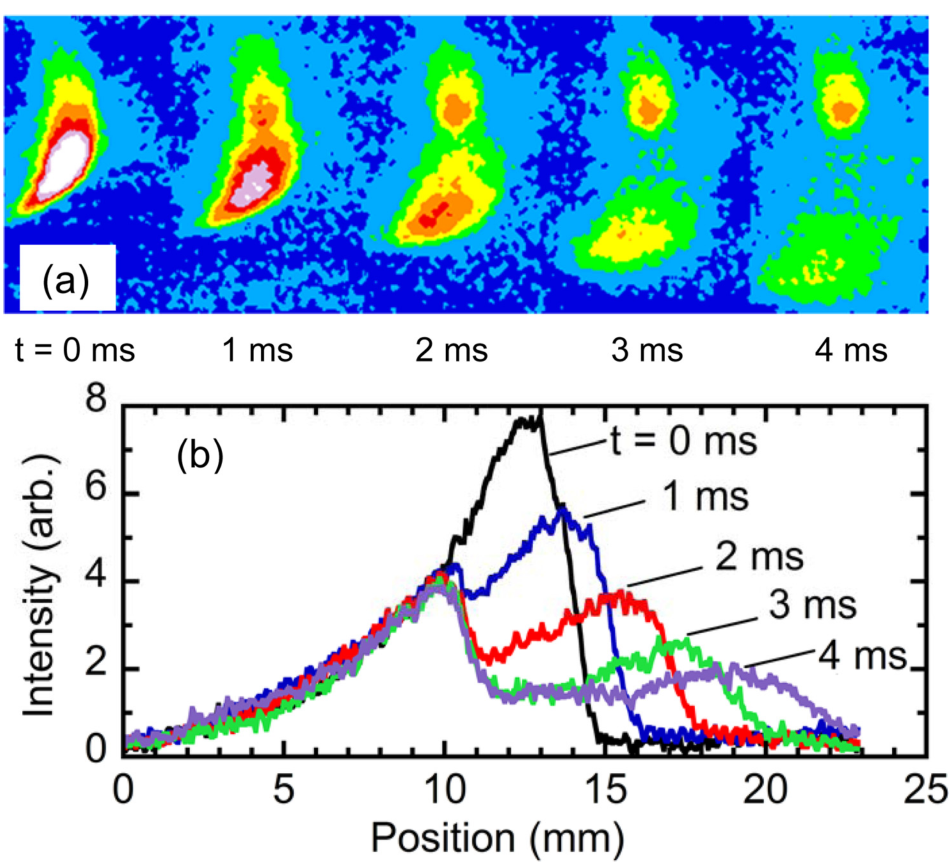

FIG. 2. (a) A montage of single-frame images at 1 ms intervals of the dust cluster after the anode and mesh were switched to the floating condition. The initially stable dust cluster at t = 0 begins undergoing a fission process and separates from the upper fragment. The lower fragment expands as it separates from the upper cloud. (b) Profiles of the gray scale intensity (proportional to the dust density) of the images in (a) taken along a line from top (0 cm) to bottom. Separation of the lower cloud is evident at t = 0, with the separation point at 10 cm.

A simple estimate shows that the acceleration of the lower cloud is consistent with Coulomb repulsion due to the upper cloud fragment. The dynamics of a dust particle in the repulsive Coulomb field of a spherical volume of charge was analyzed in Ref. 10. The acceleration is given by $a = \omega_0^2 r_0/3$, where r_0 is the cloud radius and the characteristic timescale by $\omega_0^{-1} = (n_{d0}e^2Z_d^2/\varepsilon_o m_d)^{-1/2}$, where n_{d0} is the dust density, eZ_d is the dust charge, and m_d is the dust mass. With $r_0 \approx 5\,\mathrm{mm}$, and parameter values as listed in Table I, we find that $a \sim (500\text{–}2000)\,\mathrm{m/s^2}$ and $\omega_0^{-1} \approx 1\text{–}10\,\mathrm{ms}$, both compatible with the observations. Note that on the timescale of the initial dust dynamics, dust neutral collisions can be ignored.

Next, we discuss a possible triggering mechanism for the cloud fission. Initially, before the plasma is turned off, the dust cloud is in equilibrium under the external electric field of the mesh, ion drag force, and gravity. When the plasma and mesh are switched off, the self-electric field of the charged dust particles acts to disrupt the cloud; however, this field will also accelerate ions toward the cloud, and the resulting ion drag force on the dust can provide a temporary equilibrium in the radial direction. However, a simple calculation will show that this equilibrium is unstable to a radial pinching instability, as illustrated schematically in Fig. 4. Imagine a radially inward perturbation (localized pinching) on the cloud caused by the ion drag force. A perturbation of this type causes a local compression of the cloud, which increases the dust density, further increasing the electric field.[12] If the resulting increase in the ion drag force is greater than the outward electric force, the cloud will continue to pinch off and split into two fragments. Once fragmented, the segments continue to separate due to the electrostatic repulsion between the two segments. The stability of this configuration can be addressed using a simple fluid model for the dust, assuming electrons in Boltzmann equilibrium, and assuming the ions are mobility limited with constant density. The linearized forms of the dust continuity and momentum equation (for perturbations in the radial direction), assuming cold dust, are

$$\frac{\partial n_{d1}}{\partial t} + n_{d0}\frac{\partial v_{d1}}{\partial x} = 0, \qquad (1)$$

$$m_d n_{d0}\frac{\partial v_{d1}}{\partial t} = eZ_d n_{d0}\frac{\partial \varphi_1}{\partial x} + m_d n_{d0}\alpha_{id} v_{i1}, \qquad (2)$$

where n_{d1}, v_{d1}, v_{i1}, and φ_1 are the first order dust density, dust velocity, ion velocity, and electric potential, respectively. The last term in Eq. (2) accounts for the ion drag force on the dust, where the coefficient, $\alpha_{id} = \alpha_{id}^C + \alpha_{id}^O$, includes both collection (C) and orbit (O) effects as taken from the work of Barnes *et al.*[13] Dust-neutral collisions have been ignored in Eq. (2) since the mean collision time is much longer than the timescale for fissioning. The ion velocity is expressed in terms of the ion mobility μ_i and perturbed electric field E_1 as

$$v_{i1} = \mu_i E_1 = \mu_i(-\partial\varphi_1/\partial x). \qquad (3)$$

Equations (1)–(3) are combined with the electron Boltzmann relation, $e\varphi_1/kT_e = n_{e1}/n_{e0}$, and the quasineutrality condition (with $n_{i1} = 0$), $n_{e1} = -Z_d n_{d1}$, and assuming perturbations of the form $\sim \exp[i(Kx - \omega t)]$, with wavenumber K and frequency ω, to obtain the dispersion relation

$$\omega^2 = \left(1 - \alpha_{id}/\alpha_{id}^{crit}\right)K^2 C_{DA}^2, \qquad (4)$$

where $\alpha_{id}^{crit} = eZ_d/m_d\mu_i$, and $C_{DA} = (kT_e Z_d^2 n_{d0}/m_d n_{e0})^{1/2}$ is the dust acoustic speed. Eq. (4) shows that when the ion drag coefficient exceeds a critical value, $\alpha_{id} > \alpha_{id}^{crit}$, a zero frequency, growing instability is excited which leads to the fissioning of the dust cloud, with the growth rate

$$\gamma = KC_{DA}(\alpha_{id}/\alpha_{id}^{crit} - 1)^{1/2}. \qquad (5)$$

Is this pinching model consistent with observations? First, we consider whether the instability criterion $\alpha_{id} > \alpha_{id}^{crit}$, is satisfied. The ion mobility is $\mu_i = e/m_i\nu_{in}$, where $\nu_{in} = N\sigma_{in}v_{Ti}$, is the ion-neutral collision frequency (N is the neutral gas density, σ_{in} is the ion-neutral collision cross section, and v_{Ti} is the ion thermal speed). Values for α_{id} and α_{id}^{crit} were obtained using the parameters listed in Table I and $\sigma_{in} \sim 10^{-19}\,\mathrm{m^2}$. Since the dust charge is decreasing, a conservative value of $Z_d = 200$ was used. We find that $\alpha_{id}^{crit} \approx 1 \times 10^{-3}\ s^{-1}$ and $\alpha_{id} \approx 3 \times 10^{-2}\ \mathrm{s^{-1}}$, so that the instability criterion is satisfied. Note also that this criterion is more easily satisfied at lower pressure, which is also consistent with the experimental observations. Also, since $\alpha_{id}^{crit} \propto Z_d$, it follows from the threshold condition that a higher dust charge should stabilize the pinching instability. Using a typical length scale for the dust cloud $\sim$0.5 cm ($K = 1260\,\mathrm{m^{-1}}$), the instability growth time γ^{-1} is on the order of 1 ms, which is also consistent with the observed timescale for the fissioning of the dust cloud.

In summary, observations of the fissioning of a dust cloud in an afterglow plasma have been presented. After fissioning,

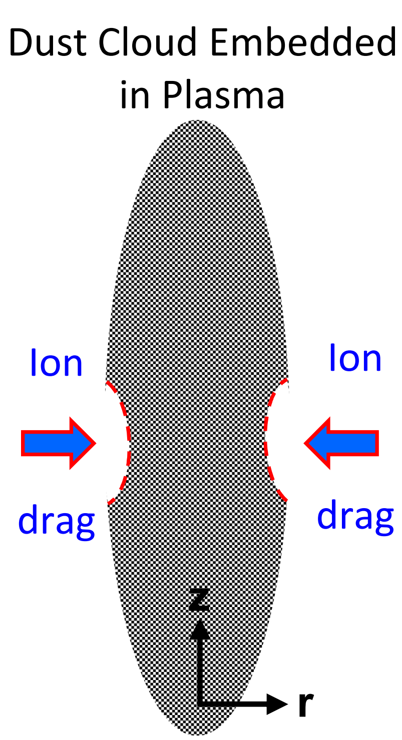

FIG. 4. Schematic of a vertically elongated dust cloud with radial compression induced by the ion drag force due to ions accelerated inward in the self-electric field of the dust.

the two cloud fragments separate under the action of their mutual Coulomb repulsion. A pinching instability due to the ion drag force was proposed as a possible triggering mechanism for the fissioning. A simple model shows that an equilibrium based on ion drag and electrostatic repulsion is unstable to a perturbation tending to locally compress the dust cloud. Estimates of the conditions for instability and the growth rate indicate that this is a plausible mechanism for the fissioning of a localized dust cloud in an afterglow plasma. Having considered the feasibility of the pinching mechanism in the admittedly oversimplified model presented here, we now plan to carry our numerical simulations of this problem, and the results will be reported in a future publication.

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