Coulomb explosion and fission of charged dust clusters

Conference Paper *in* AIP Conference Proceedings · January 2018

DOI: 10.1063/1.5020409

John Kenneth Meyer
LusoSpace

Abhijit Sen
Institute for Plasma Research

Coulomb explosion and fission of charged dust clusters

R. L. Merlino, J. K. Meyer, A. Barkan, K. Avinash, and A. Sen

Citation: AIP Conference Proceedings **1925**, 020021 (2018); doi: 10.1063/1.5020409
View online: https://doi.org/10.1063/1.5020409
View Table of Contents: http://aip.scitation.org/toc/apc/1925/1
Published by the American Institute of Physics

Coulomb Explosion and Fission of Charged Dust Clusters

R. L. Merlino[1, a)], J. K. Meyer[2], A. Barkan[3], K. Avinash[4] and A. Sen[5]

[1]*Department of Physics and Astronomy, University of Iowa, Iowa City, IA, 52242 USA*
[2]*Institut für Materialphysik im Weltraum, Deutsches Zentrum für Luft- und Raumfahrt (DLR) Münchener Strasse 20, 82234 Wessling, Germany*
[3]*Department of Physics, University of Illinois at Chicago, Chicago, IL 60607 USA*
[4]*Department of Physics and Astrophysics, University of Delhi, Delhi, India*
[5]*Institute for Plasma Research, Gandhinagar, India*

[a)]Corresponding author: robert-merlino@uiowa.edu

Abstract. Experimental observations of the fragmentation of small charged dust clusters suspended in a dc discharge plasma in an afterglow plasma are presented. Two examples are given: (1) Coulomb explosion, and (2) Coulomb fission.

INTRODUCTION

Insight into the structure and dynamics of small systems of interacting particles can be gained by observing the evolution of the system under highly non-equilibrium conditions. This methodology has been used by the atomic and chemical physics communities to explore the structure, energetics, function and dynamics of atomic and molecular clusters [1]. Small clusters of atoms are illuminated with ultra-intense laser fields, leading to extreme multielectron ionization, resulting in the formation of multiply charged ion clusters which then undergo Coulomb explosion or fission [2]. This research has focused on two fundamental questions: How does a finite system respond to a large excess charge, and what are the fragmentation channels and under what conditions do they occur?

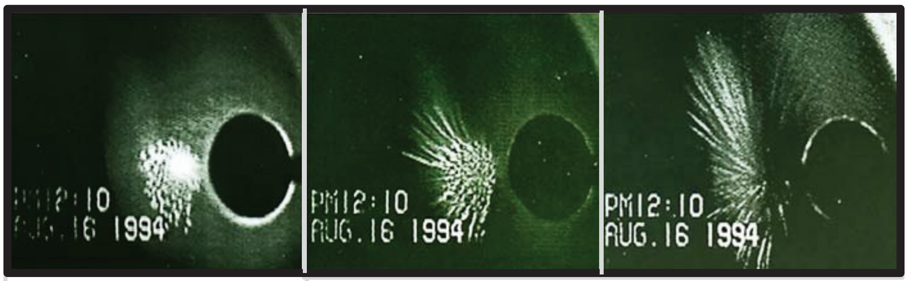
We have performed experiments in dusty plasmas (highly charged micron-sized particle suspensions in a plasma) which investigated the evolution of small (~ cm) clusters of negatively charged particles ($\approx 10^2 - 10^3$ microparticles) when the plasma and the confining potential structure was suddenly turned off. An interesting property of a dusty plasma is that the particles can retain a substantial fraction of their initial charge when the surrounding plasma is extinguished [3, 4]. The decay of the dust charge depends on the discharge conditions, in particular, the neutral pressure [3, 4, 5]. The dust charge is approximately proportional to the electron temperature, which decreases in the afterglow due to electron-neutral collisions. The neutral pressure also affects the timescale for plasma decay, and two regimes of dust cluster explosion have been identified in molecular dynamics simulations [5]. At low pressures (< 300 Pa) the timescale for plasma loss is faster than the timescale for charge relaxation, so the plasma shielding is weakened and the dust cluster explodes under the nearly unshielded Coulomb interaction. On the other hand, at high neutral pressures, the dust charge decays more rapidly than the plasma, so the particle-particle interactions are more Yukawa-like. Collisional and collisionless expansion of "Yukawa balls" have also been studied in analytically and in molecular dynamics simulations [6]. This paper describes observations of two charged dust clusters that dynamically responded in afterglow plasmas in very different manners: Coulomb explosion and Coulomb fission.

COULOMB EXPLOSION

The explosion of a small cluster of negatively charged dust particles was observed in a dusty plasma that was confined in an anode glow discharge formed in a single-ended Q-machine with a potassium plasma source [7]. A 16 mm diameter disk electrode was located at the end of the device which was filled with nitrogen gas at a neutral pressure

Diverse World of Dusty Plasmas
AIP Conf. Proc. 1925, 020021-1–020021-4; https://doi.org/10.1063/1.5020409
Published by AIP Publishing. 978-0-7354-1617-8/$30.00

of ≈ 1 Pa. When a positive potential was applied to the disk, an anode glow discharge ("firerod") was formed within the potassium plasma ($K^+ - e^-$). Dust particles dispersed into the plasma from a rotating dust dispenser were trapped within the potential structure of the firerod. The dust was kaolin powder with sizes in the range of 1−10 μm, with an average size ≈ 5 μm, mass ~ 10^{-12} kg, and charge, estimated form OML theory, ≈ -10^5 e. The dust suspension was illuminated by the light emitted by the incandescent hot plate, and was imaged using a CCD video camera at 30 fps. Fig. 1(a) shows a single-frame image of the suspended dust cluster just in front of the anode disk before the explosion (t = 0). This "dust ball" was stable and remained suspended for as long as the plasma was on. From the single frame image, we estimated the interparticle spacing to be ≈ 0.4 – 0.8 mm (≈ a few Debye lengths), and using $n_d = 3/4\pi d^3$, the average dust density n_d was in the range of 500 – 4000 cm^{-3}.



(a) (b) (c)

FIGURE 1. Single frame video images before (a), and during, (b) and (c), the Coulomb explosion of a charged dust ball. (a) t = 0, before the explosion; (b) t = 1/ 30 s; (c) t = 2/30 s. The anode disk to the right of the dust ball is 16 mm in diameter.

Figures 1(b) and 1(c) show two consecutive single-frame video images of the explosion of the dust cluster when the firerod was turned off. A nearly isotropic radial explosion of the charged dust particles occurred. The particles moved out of the field of view by t = 3/30 s. The presence of particle tracks in the video images indicates that individual particle motion during the explosion was not resolved at 30 frames per second. From the track lengths and camera exposure time, a lower limit on the particle speeds of ≈ 30 cm/s and an acceleration ≈ 30 – 40 m/s^2 was estimated. The kinetic energy of the particles acquired in the Coulomb interaction with the dust ball charge was ≈ 0.3 MeV.

A theoretical estimate for the acceleration of the particles can be obtained using a simple model of the Coulomb explosion. We assume that the plasma decays on a timescale faster than that for dust charge decay, so that the particles interact via the unshielded Coulomb force. The acceleration of a particle of charge q_d and mass m_d at the surface of a dust ball of radius r_0 is: $a = (q_d/m_d)E(r_0)$, where $E(r_0)$ is the electric field at the surface. For a dust ball of radius r_0 containing particles of charge q_d and density n_d, $E(r_0) = n_d q_d r_0/3\varepsilon_0$, giving an acceleration $a = n_d q_d^2 r_0/3\varepsilon_0 m_d$. With $q_d \approx 1\times10^5$ e, $n_d \approx 10^9$ m^{-3}, $m_d \sim 10^{-12}$ kg, and $r_0 \sim 5$ mm, we obtain $a \sim 50$ m/s^2, in reasonable agreement with the measured value, and with molecular dynamics simulations [5].

COULOMB FISSION

Fig. 2 shows an image of the setup in which the Coulomb fission of a dust cluster was observed. Details of the device are presented elsewhere [8, 9]. The plasma was produced by a dc glow discharge in argon gas at 13 Pa neutral pressure (ten times higher than in the case of the Coulomb explosion). The discharge was formed by applying +(200−300) V (relative to the grounded chamber walls) to a 4 cm diameter anode disk. The dust used in the present setup was silica microspheres of radius, $R_d = 0.5$ μm and mass, $m_d = 1 \times 10^{-15}$ kg. The dust was initially loaded on a tray below the anode, and was automatically incorporated into the discharge when the anode voltage was applied. A conical mesh electrode was also present in the device, and was used to trap a secondary dust cluster. The dust charge and number density within the secondary cloud were in the range, $q_d \approx -2000$ e, and $n_d \approx 10^{11} - 10^{13}$ m^{-3}.

The crescent-shaped dust cluster was suspended in equilibrium under the conical electrode by a combination of gravity, electric, and ion drag forces. The fragmentation of the cluster occurred when the anode voltage and the mesh voltage were simultaneously turned off. The cloud was illuminated with a 1 mm thick 532 nm vertical laser sheet, and images were obtained at 2000 fps using a 1 megapixel Photron fast video camera. A sequence of single frame images just before, t = 0, and at 1 ms time intervals after the onset of fission is shown in Fig. 3(a).

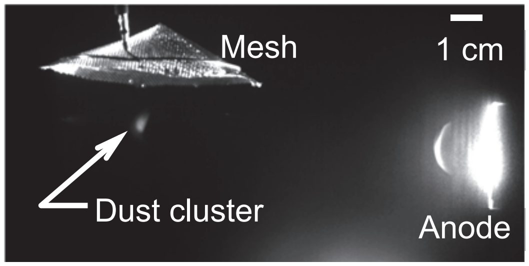
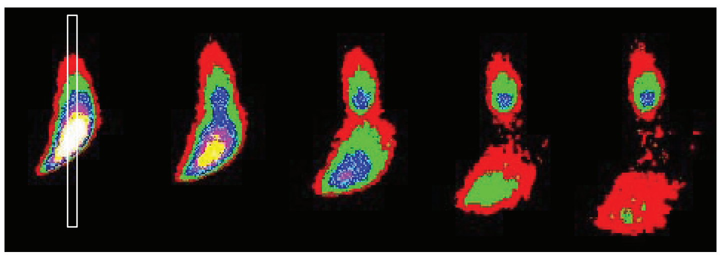


FIGURE 2. Photograph of the experimental setup used in the observation of Coulomb fission of a dust cluster. The plasma was formed by a dc glow discharge in argon at a neutral pressure of 13 Pa. A conical mesh electrode was used to trap a secondary dust cluster. Fission of the cloud was observed when the anode and mesh potentials were turned off.

(a)



(b)

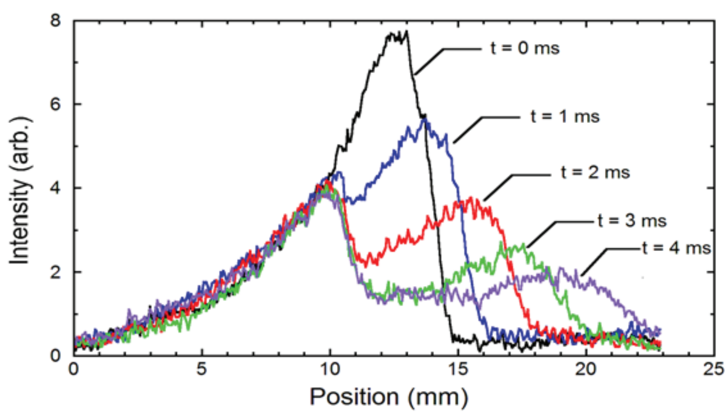


FIGURE 3. (a) Single frame video images of the dust cluster at 1 ms intervals after the plasma and mesh were turned off. (b) Intensity profiles (proportional to the dust density) along a vertical FOV [the rectangle in (a)] through the cluster.

The fission process began with the pinching of the cluster at a vertical position just above the middle of the cluster, as seen in the image in Fig. 3(a) at 1 ms. Complete fission of the cloud occurred at approximately 3 ms. The lower, larger fragment separated and expanded as it moved downward. Note that on the timescale of the fission process neither gravity nor neutral drag forces played a role. Fig. 3(b) shows vertical profiles of the light intensity (proportional to the dust density) in the dust cluster within the rectangular area (FOV) indicated. The average velocity of the lower fragment during fission was ≈ 1.5 m/s, which is well above the terminal speed of a dust particle (≈ 0.1 m/s) due to gravity and neutral drag. The rate of separation of the lower fragment began to decrease after roughly 5 ms, probably due to the decay of the dust charge. The initial acceleration of the lower fragment was ≈ 10^3 m/s^2. This acceleration is in line with a simple model in which the upper and lower fragments are treated as uniform spherical charge distributions undergoing Coulomb repulsion.

An important question is what are the possible mechanisms responsible for triggering the Coulomb fission of the dust cluster? When the plasma and confining potential is turned off, the self-electric field of the charged dust particles acts to disrupt the cluster. However, this field also accelerates ions toward the cluster, providing a temporary radial equilibrium under the combined effects of the electric force and the ion drag force on the dust particles due to the accelerated ions. A simple linear fluid analysis [8] shows that this equilibrium is unstable, since the ion drag force on the cluster would produce a local inward perturbation, increasing the local density and the electric field. The calculations show that if the ion drag force exceeds a critical value, the cluster can be "pinched-off" locally, causing it to fragment into two pieces. A discussion of the quantitative aspects of this model as compared with the experimental observations is presented in Ref. [8].

CONCLUSION

The results of investigations of the evolution of highly-charged dust clusters after the surrounding plasma was turned off have been presented. Two experiments performed under very different plasma and dust conditions were described: Coulomb explosion and Coulomb fission. Other types of dust cluster evolutions in afterglow plasmas, however, have also been reported [9].

Observation of the behavior of a dusty plasma under extreme non-equilibrium conditions is a potentially fruitful area of dusty (complex) plasma physics research. Since the dynamics of dust particles can be followed at the fully kinetic level using imaging techniques, one may be able to learn a great deal about the structure, interactions, and collective behavior of the charged particle system from the type of experiments described in this article.

ACKNOWLEDGMENTS

This work was supported by NSF and DOE.

REFERENCES

1. T. Ditmire, J. W. G. Tisch, E. Springate, M. B. Mason, N. Hay, R. A. Smith, J. Marangos, and M. H. R. Hutchinson, Nature, **386**, 54-56 (1997); I. Last, Y. Levy, and J. Jortner, PNAS **99**, 9107-9112 (2002).
2. Y. Levy, I. Last, and J. Jortner, Mol. Phys. **104**, 1227-1237 (2006).
3. A. V. Ivlev, M. Krethschmer, M. Zuzic, G. E. Morfill, H. Rothermel, H. M. Thomas, V. E. Fortov, V. I. Molotkov, A. P. Nefedov, A. M. Lipaev, O. F. Petrov, Yu. M. Baturin, A. I. Ivanov, and J. Goree, Phys. Rev. Lett, **90**, 055003 (2003).
4. L. Couedel, M. Mikikian, L. Boufendi, and A. A. Samarian, Phys. Rev. E **74**, 026403 (2006).
5. V. Saxena, K. Avinash, and A. Sen, Phys. Plasmas **19**, 093706 (2012).
6. A. Piel and J. A. Goree, Phys. Rev. E **88**, 063103 (2013).
7. A. Barkan and R. L. Merlino, Phys. Plasmas **2**, 3261-3265 (1995).
8. R. L. Merlino, J. K. Meyer, K. Avinash, and A. Sen, Phys. Plasmas **23**, 064506 (2016).
9. J. K. Meyer and R. L. Merlino, IEEE Trans. Plasma Sci. **44**, 473-478 (2016).