Dust jets produced by a dust-discharge instability

J. R. Heinrich, S.-H. Kim, and R. L. Merlino
Department of Physics and Astronomy, The University of Iowa, Iowa City, Iowa 52242, USA

(Received 16 March 2010; accepted 6 July 2010; published online 19 August 2010)

We report observations of an instability that occurs in a dc glow discharge (anodic plasma) dusty plasma when a floating plate with a 5 mm aperture is placed in front of the anode. The instability is characterized by periodic quenching and reignition of the discharge. When the discharge is quenched, the dust is ejected from the aperture at speeds on the order of the dust-acoustic speed. The ejected dust remains partially charged and retracts back to the aperture when the discharge spontaneously redevelops. © *2010 American Institute of Physics*. [doi:10.1063/1.3470093]

I. INTRODUCTION

A dc glow discharge (anodic plasma) is the simplest plasma source in which a dusty plasma can be formed. Devices utilizing anodic plasmas have been used by a number of groups to produce dusty plasmas and study their behavior.[1–6] In this article, we report observations of an unstable anodic glow dusty plasma and associated dust jets. The effect occurred when a floating plate with a small ($\sim$5 mm) aperture was placed in front of the anode. The phenomenon involves the spontaneous quenching of the discharge in which the dust is suspended, followed by the rapid ejection of the dust in a collimated jet.

Dust jets have been observed in digitally processed plates from the 1910 appearance of Comet Halley[7] and from images taken by the Giotto[8] and Vega[9] spacecrafts during their 1986 encounters. Gigantic ($\sim$9 pc) bipolar dust jets have also been detected around planetary nebulae.[10] Recently, instruments onboard the Cassini spacecraft detected highly collimated jets of charged dust in Enceladus' plume.[11]

Devices for the injection of dust jets into a plasma are being developed for technological applications as well as for fundamental studies of dust-plasma interactions.[12,13] Experiments simulating the formation of gas-dust jets from comets have been performed,[14] and the feasibility of microparticle acceleration for micrometeoroid simulation[15] and space propulsion have also been studied.[16,17]

II. EXPERIMENTAL SETUP AND RESULTS

A typical glow discharge dusty plasma was modified by placing a floating plate with a circular aperture in front of the anode, as shown in Fig. 1(a). The anode was a disk of 2 cm radius located on the axis of a large (60 cm diameter by 1 m length) grounded vacuum chamber filled with argon gas at a pressure of $\sim$100 mtorr (13 Pa). A plasma was formed by applying $\sim$300 V dc to the anode with the chamber as the cathode. The back side of the anode disk was insulated. There was an axial magnetic field of 10 mT, which was sufficient to magnetize the electrons so that an axially elongated anodic glow plasma was formed. Typical values of the electron and ion temperatures and ion density were $T_e \sim 2$–3 eV, $T_i \sim 0.03$ eV and $n_i \sim 10^{14}$–10^{15} m^{-3}, respectively.[18,19] A floating tray with kaolin powder located below the anode (not shown) was the dust source. The average size of the dust particles that were suspended in the anodic plasma was $\sim$1 μm. An aluminum plate (coated with an insulating paint) with a 4.7 mm diameter hole was placed approximately 6 mm in front of the anode and centered on its axis. A pear-shaped suspension of dust particles in a volume of approximately 60 mm^3 was formed, which protruded from the aperture.

The dust cloud was imaged using a thin, vertical sheet of 532 nm light from a Nd:YAG (Neodymium-doped yttrium aluminum garnet) laser and cylindrical lens. Light scattered from the particles was imaged and recorded using a digital CCD (charged-coupled device) video camera operating at 30 frames/s. A single frame image of the dust cloud is shown in Fig. 1(b). The aperture diameter can be discerned by the laser light illuminating the center of the anode, as indicated by the horizontal dashed lines. The diameter of the dust cloud in the aperture was about half of the actual aperture diameter because it was limited by the radial electric force on the negative particles due to the aperture plate that was at a negative floating potential.

The anodic dusty plasma was subjected to a discharge-dust instability in which the discharge was suddenly extinguished (as indicated by a drop-out of the discharge current), followed by a rapid expulsion (jetting) of the dust cloud from the aperture. A typical cycle of the instability and jet formation is shown as a series of single frame video images in Fig. 2. Figure 2(a) represents the equilibrium phase after which the extinction of the discharge current occurred, followed by the expansion of the dust cloud shown in Fig. 2(b). In Fig. 2(c) the cloud began to jet forward with the leading part forming a crescent-shaped structure that continued to jet forward in Fig. 2(d). The loss of plasma resulted in the disappearance of the confining electrostatic potential, and the dust began falling under the influence of gravity as it is accelerated away from the aperture (presumably by the electric field of the floating aperture plate), as evident in Figs. 2(c) and 2(d). As discussed later, collisions between the dust and the background gas caused the dust to drift downward rather than free fall. In the time interval between Figs. 2(d) and 2(e) the discharge was spontaneously reignited and the dust particles began to be pulled back toward the aperture, as shown in Fig. 2(f). Dust particles continued to return to the suspen-

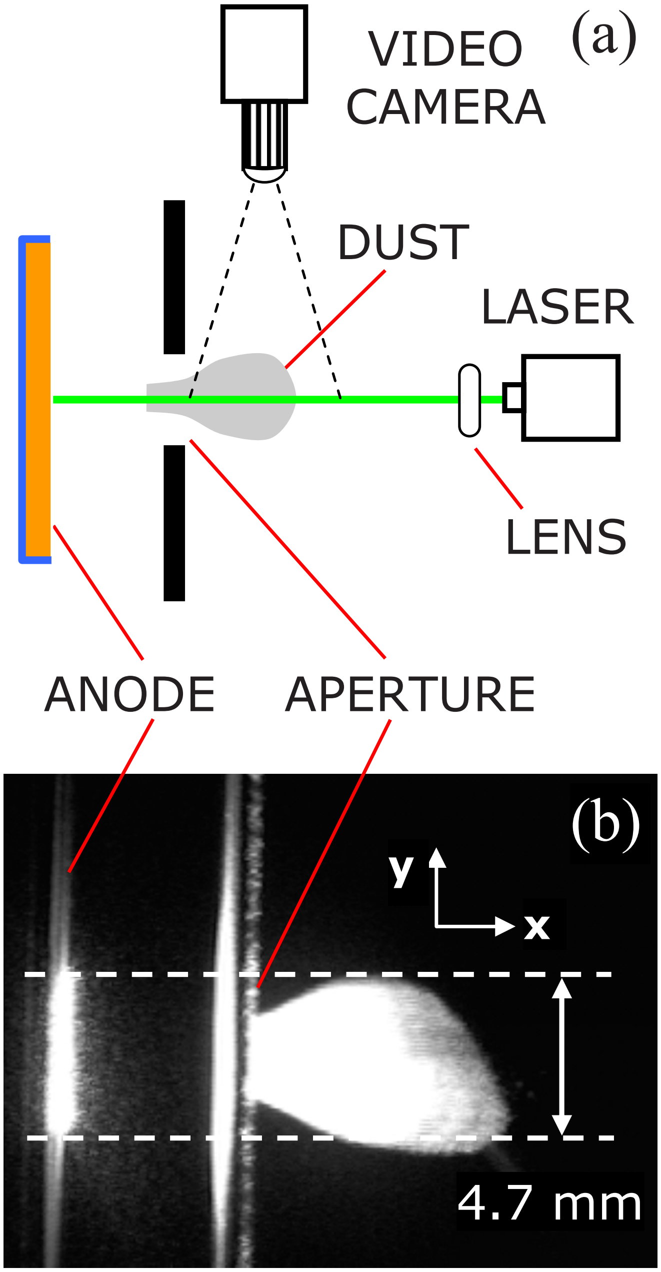

FIG. 1. (Color online) (a) Schematic diagram of the experimental setup (top view). (b) Single frame video image (side view) of the dust suspension protruding from the aperture.

sion for several frames following that shown in Fig. 2(f) until the next episode of instability and jet formation occurred. The extinction of the discharge was clearly related to the presence of a sufficient quantity of dust because the discharge was stable during the initial phase of the experiment, while the dust cloud was building up.

The observed phenomena can be characterized by two time scales: ΔT, the time for expansion, jet formation, and retraction of the suspension; and T, the time between successive occurrences of the effect. T and ΔT were determined by examining a long video record of a large number of occurrences of the instability (over 1200 video frames). The distribution of ΔT values was very narrow, with an average of $\Delta T = 0.20 \pm 0.03$ s, this uncertainty was equivalent to one

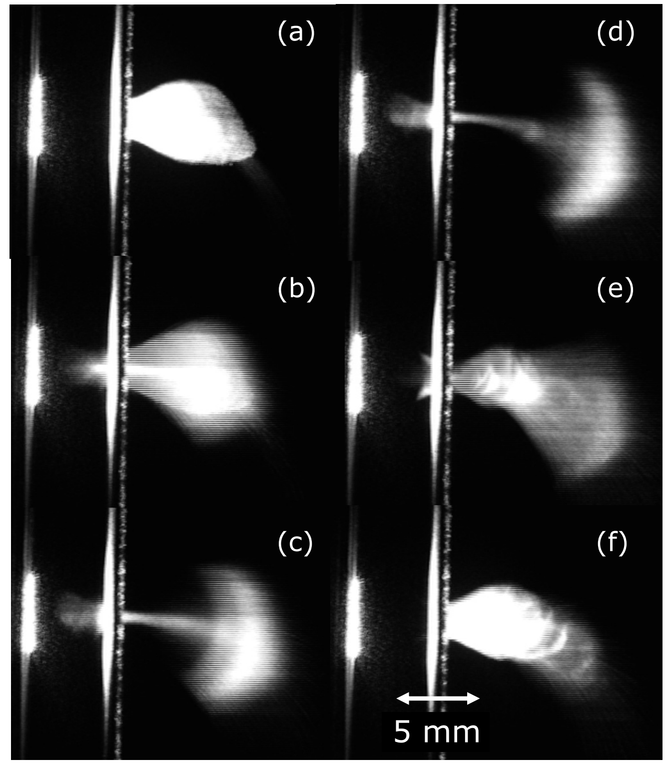

FIG. 2. [(a)–(f)] A sequence of single frame video images, acquired at 30 frames/s, showing the development of the dust-discharge instability and jet formation. In (b)–(d), the jet is moving outward from the aperture, while in (e) and (f) the dust cloud is retracting back to its original position near the aperture (enhanced online). [URL: http://dx.doi.org/10.1063/1.3470093.1]

video frame. The distribution of the T values is shown in Fig. 3. The distribution was relatively broad with an average of $T = 0.34 \pm 0.2$ s (periods of $2-6$ Hz). The tail on the high end of the T distribution was due to episodes where the dust cloud appeared to be on the brink of instability but stabilized before the jetting occurred.

The position and velocity of the expanding jet and retracting dust cloud in Fig. 2 are shown in Fig. 4, where $t=0$ corresponds to the initial equilibrium state in Fig. 2(a). The maximum jet speed, $v_{\rm jet} = 85$ mm/s, occurs at $t \approx 66$ ms, although the jet continues moving outward over the next video frame before retracting back to the initial position. Further evidence of fast particles can be seen by the streaks in the single frame images, indicating particles moving at least several millimeters over 1/30 s. The speed of the retracting cloud was typically 50% higher than the jet speed. There was some scatter in the measured jet speeds, with values ranging from 70 to 120 mm/s, with an average value of 84 mm/s. The dust-acoustic speed is given by[20,21]

$$C_{\rm DA} = \left(\frac{kT_d}{m_d} + \frac{Z_d k T_i P}{m_d[1+\tau(1-P)]} \right)^{1/2}, \quad (1)$$

where m_d, Z_d, and T_d are the dust mass, charge number, and temperature, respectively, $\tau = T_i/T_e$, where $T_{e(i)}$ is the electron (ion) temperature, k is Boltzmann's constant, and $P \equiv (n_o Z_d / n_i)$ is the Havnes' parameter,[22] where $n_{d(i)}$ is the dust (ion) density. With $T_e \sim 2.5$ eV, $T_i \sim 0.03$ eV, ρ_d (dust mass density) $= 1500$ kg/m^3, $Z_d \sim 2000$, $P \sim 0.2$,

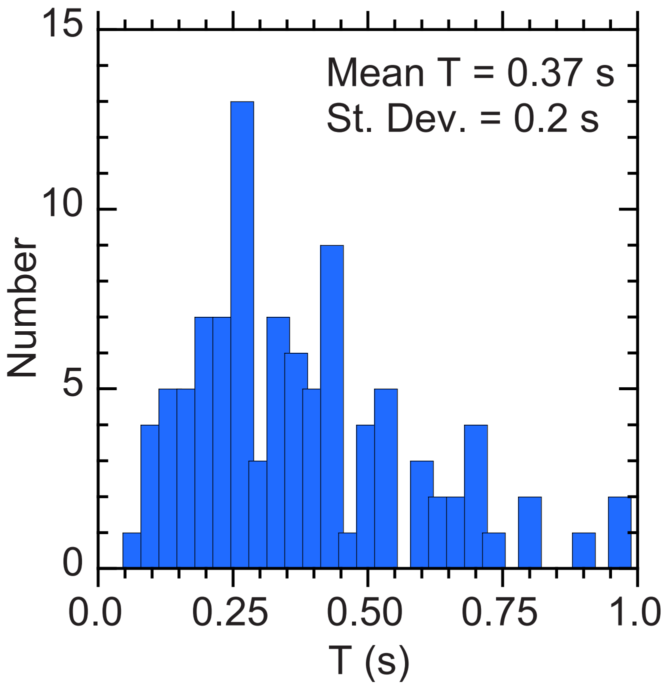

FIG. 3. (Color online) Distribution of dust-discharge instability periods.

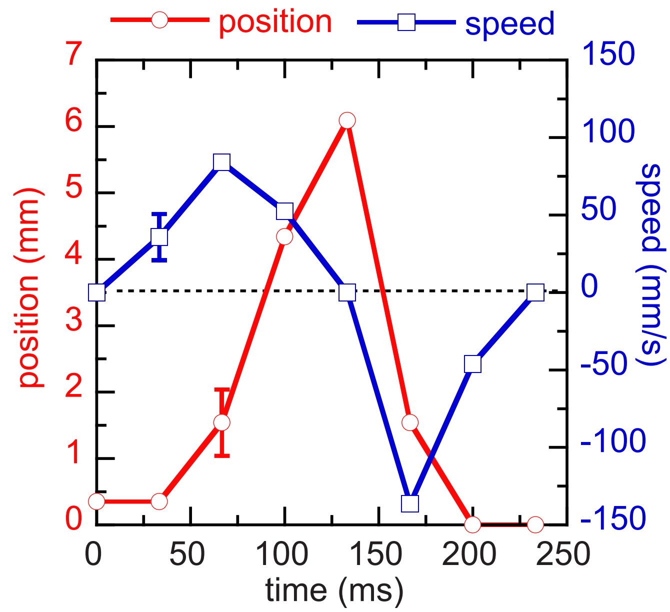

FIG. 4. (Color online) Position (circles) and velocity (squares) of dust jet (from Fig. 2) vs time.

we find that for T_d ranging from 0 to 25 eV, $C_{\mathrm{DA}} \sim 45-90$ mm/s. Thus, the Mach number of the dust jet is $M_{\mathrm{jet}} = v_{\mathrm{jet}}/C_{\mathrm{DA}} \gtrsim 1$.

III. DISCUSSION

A full explanation for the observations that have been presented will probably require numerical simulations; however, we will try to provide a reasonable picture for the instability and the resulting jet formation. The behavior of the dust suspension after the discharge is extinguished depends on the amount of residual charge that remains on the dust particles. This, in turn, depends on the time scales for plasma loss, electron temperature relaxation, and dust charge fluctuation. A model for the decharging of the dust in a plasma afterglow has been proposed by Ivlev *et al.*[23] to explain the measurements of the residual charge in a microgravity experiment after the discharge was switched off. This model was also compared to measurements of the residual charge in a ground-based experiment by Couëdel *et al.*[24] The conservation of the particle charge after switch off of the plasma was also discussed in connection with a possible microparticle thruster.[17] When the discharge current is suddenly turned off, the plasma decays by ambipolar diffusion and absorption on the dust particles, and it occurs on a time scale approximately tens to hundreds of microseconds. In the present experiment, the diffusion process is affected by the fact that the electrons are weakly magnetized, while the ions are not. If the plasma remains quasineutral during the decay, the charge on the dust can only decrease if the electron temperature decreases. The relaxation of the electron temperature occurs via collisions with the neutral gas atoms and the rate at which this occurs depends on the neutral gas pressure. According to the model of Ivlev *et al.*,[23] the rate of the decrease of the normalized electron temperature, $\tilde{T}_e = T_e/T_i$, is given by $d\tilde{T}_e/dt = -(\tilde{T}_e - 1)/\tau_T$, where τ_T is the temperature relaxation time scale given by $\tau_T = [2\sqrt{m_e/m_i}(v_{T_i}/\ell_{en})\sqrt{\tilde{T}_e}]^{-1}$, where v_{T_i} is the ion thermal speed and $\ell_{en} = (N\sigma_{en})^{-1}$ is the mean free path for collisions between the electrons and the neutral atoms with σ_{en} as the cross section for momentum transfer and N as the neutral atom density. Due to the large mass difference between the electrons and neutral gas atoms, the electron temperature relaxation process requires many collisions before equilibration is reached. As T_e decreases, τ_T increases, in our case, τ_T varies from approximately a few milliseconds to tens of milliseconds. Since the electron temperature decays on a much longer time scale than the plasma decay, we expect that the dust should remain, at least partially charged during the jetting event. The neutral pressure in our experiment is about four times less than that reported in Ref. 22 and 2–15 times less than the pressures used in Ref. 23. The fact that the dust is pushed primarily away from the aperture seems to indicate that it probably retains some, if not a good portion, of its charge during the process. During the retraction phase, it is possible, however, that the dust may be recharged, when the discharge is reignited.

The dust dynamics occurs on a time scale much longer than the plasma extinction time scale, so it is reasonable to consider the instability and jet formation processes separately. The extinction of the discharge is clearly related to the presence of the dust, and we conjecture that the discharge is quenched when the dust density builds up to the point that the ion current to the dust is comparable to the ion current in the discharge. The ion current to a dust grain from OML (orbit limited motion) theory is $I_{i,\mathrm{dust}} \approx 10^{-10}$ A. The total ion current to all grains contained within the volume of the cloud is $I_{i,\mathrm{dust\text{-}tot}} = I_{i,\mathrm{dust}} \cdot (n_d V_{\mathrm{cloud}}) \approx 10^{-10}\ \mathrm{A} \cdot [(5-10) \times 10^{10}\ \mathrm{m}^{-3} \cdot 2 \times 10^{-7}\ \mathrm{m}^3] \approx 1-2\ \mu\mathrm{A}$. The ion discharge current can be estimated as $I_{i,\mathrm{dis}} = e n_i v_i$ A, where n_i is the ion

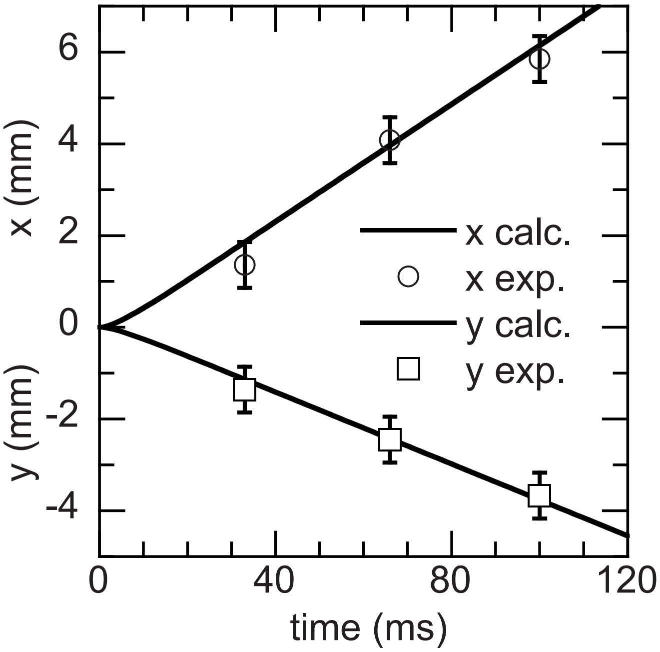

FIG. 5. Horizontal (open circles) and vertical (open squares) positions of the dust jet at various times obtained from video images, compared with calculated values (solid lines) using a neutral drag frequency $\nu_{dn}=250\ \mathrm{s}^{-1}$, $Z_d \approx 1000$, $m_d \approx 10^{-15}$ kg, and $E_x \approx -100$ V/m.

density and v_i is the ion drift speed in the plasma. The drift speed is obtained from $v_i = \mu_i E$, where μ_i is the ion mobility and E is the electric field of the discharge.[25] Assuming $E \sim (100-300)$ V/m, the ion drift speed is ~ 400 m/s, so that $I_{i,\mathrm{dis}}$ is approximately microamperes. The novel feature of the experimental arrangement is that ions which are formed by ionization between the anode and aperture must pass through the aperture. This places a severe constraint on the absorption of ions by the dust in order for the discharge to be maintained. The path of the ions through the aperture must remain open, otherwise the circuit between the anode and the grounded walls of the device which serve as the cathode for the discharge is interrupted.

If the plasma is starved by absorption on the dust, the discharge will disappear on a time scale of less than 1 ms. Consider now what would occur if the plasma suddenly disappeared. Since the dust cloud is confined by a potential structure in the plasma, the loss of plasma leaves the charged dust without electrostatic confinement, and at the same time, the charged dust particles are no longer shielded by the plasma. The cloud may then "explode" under the action of its unshielded charge or "electrostatic pressure"[26] and be pushed outward by the electric field due to the negatively charged aperture plate. Essentially, as the plasma decays, the Debye length increases and the aperture effectively becomes smaller, expelling the dust outward. From the shape of the dust cloud near the aperture, it seems clear that the electrostatic potential contours associated with the aperture have the structure of a nozzle. When the plasma disappears, the nozzle collapses radially, accelerating the dust outward. When the dust is expelled from the aperture, the ions can again flow through it and the discharge can then be reignited, which reestablished the dust confining potential so that the expelled dust will be pulled back to its original position adjacent to the aperture.

We can compare the horizontal (x) and vertical (y) positions of the dust jet obtained from the video images to calculations based on a simple dynamical model of the motion of the dust under the combined influence of gravity, electric force, and neutral drag force. If we assume that the electric field of the aperture plate is approximately perpendicular to the plate so that the downward motion of the jet is due only to the forces of gravity and neutral drag, the equation of motion is then $\ddot{y}(t) = g - \nu_{dn}\dot{y}(t)$, where $g=-9.8\ \mathrm{m/s^2}$ and ν_{dn} is the dust-neutral collision frequency, given by $\nu_{dn} = \delta(8\sqrt{2\pi}/3)(m_n/m_d)a^2 N v_{Tn}$, where m_n, N, and v_{Tn} are the neutral mass, density, and thermal speed, a is the dust radius, m_d is the dust mass, and δ is a factor of $\sim 1-1.5$.[27] For a neutral pressure $p=100$ mtorr, and $a=0.5\ \mu$m, $\nu_{dn} \sim 200-300\ \mathrm{s}^{-1}$. The solution $y(t)$ for $\nu_{dn}=250\ \mathrm{s}^{-1}$ is shown in Fig. 5 (lower plot) and compared with the experimental values. The good agreement indicates that, at least for the vertical motion, the effects of gravity and neutral drag seem to be dominant. The horizontal (x) motion is determined from $\ddot{x} = e(Z_d/m_d)E_x - \nu_{dn}\dot{x}$, where E_x is the horizontal electric field due to the negatively charged aperture plate. Using $\nu_{dn}=250\ \mathrm{s}^{-1}$, which gave the best fit to the vertical motion, $E_x \approx -100$ V/m, $m_d \approx 10^{-15}$ kg, and $Z_d \approx 1000$, we obtained the solution $x(t)$, as shown in the upper plot of Fig. 5 along with the experimental points. The values of E_x and Z_d used to obtain $x(t)$ were chosen with the following considerations. Before the discharge was terminated, $Z_d \approx 2000$, and we assumed that in the afterglow the charge decreased by a factor of 2. If we model the plate as a circular charged disk of radius R, the electric field on the axis at $x/R \ll 1$ is approximately given by $E_x \approx (V_f/R)(1-z/R)$, where V_f is the floating potential of the disk. If we treat the plate as a planar probe, we find that $V_f \approx -5kT_e/e$. With $R=3.5$ cm and at $x=5$ mm from the plate, $E_x \approx -(150-250)$ V/m, which is reasonably close to the value of -100 V/m used to obtain the calculated values of $x(t)$ in Fig. 5. We point out, of course, that the plate is large and coated with a dielectric, so there is likely to be more than one value for V_f.

In conclusion, experimental observations of the formation of a supersonic dust jet resulting from a dust-discharge instability have been presented. A simple model was proposed to account for the gross features of the observations. The formation of dust jets may be of some interest for technological applications, for example, fast dust jets have been proposed as a means of terminating unstable tokamak discharges. This would require the ability to trigger the jet on demand, as opposed to spontaneous jet formation as reported here. This might be accomplished, for example, by controlling the discharge using discharge voltage source in the form of a square wave.

ACKNOWLEDGMENTS

This work was supported by the DOE under Grant No. DE-FG01-04ER54795.

[1]A. Barkan and R. L. Merlino, Phys. Plasmas **2**, 3261 (1995).
[2]V. E. Fortov, A. P. Nefedov, V. M. Torchinskii, V. I. Molotkov, A. G. Khrapak, O. F. Petrov, and K. F. Volykhin, JETP Lett. **64**, 92 (1996).
[3]C. Thompson, A. Barkan, N. D'Angelo, and R. L. Merlino, Phys. Plasmas **4**, 2331 (1997).
[4]E. Thomas, Jr. and M. Watson, Phys. Plasmas **6**, 4111 (1999).
[5]T. Trottenberg, D. Block, and A. Piel, Phys. Plasmas **13**, 042105 (2006).
[6]I. Pilch, A. Piel, and T. Trottenberg, Phys. Plasmas **14**, 123704 (2007).
[7]Z. Sekanina and S. M. Larson, Astrophys. J. **92**, 462 (1986).
[8]Z. Sekanina and S. M. Larson, Nature (London) **321**, 357 (1986).
[9]R. Z. Sagdeev, J. Blamont, A. A. Galeev, V. I. Moroz, V. D. Shapiro, V. I. Shenchenko, and K. Szego, Nature (London) **321**, 259 (1986).
[10]R. Weinberger and B. Armsdorfer, Astron. Astrophys. **416**, L27 (2004).
[11]G. H. Jones, C. S. Arridge, A. J. Coates, G. R. Lewis, S. Kanani, A. Wellbrock, D. T. Young, F. J. Crary, R. L. Tokar, R. J. Wilson, T. W. Hill, R. E. Johnson, D. G. Mitchell, J. Schmidt, S. Kempf, U, Beckmann, C. T. Russell, Y. D. Jia, M. K. Dougherty, J. H. Waite, Jr., and B. A. Magee, Geophys. Res. Lett. **36**, L16204, doi:10.1029/2009GL038284 (2009).
[12]D. Vyalykh, A. E. Dubinov, I. L. L'vov, S. A. Sadovoi, and V. D. Selemir, Tech. Phys. **49**, 1521 (2004).
[13]S. V. Bulychev, D. V. Vyalykh, A. E. Dubinov, I. L. L'vov, S. A. Sadovoi, and V. D. Selemir, Instrum. Exp. Tech. **49**, 568 (2006).
[14]Kh. Ibadinov and A. A. Ramonov, Adv. Space Res. **29**, 705 (2002).
[15]J. F. Vedder, Rev. Sci. Instrum. **34**, 1175 (1963).
[16]K. Avinash and G. P. Zank, Phys. Plasmas **14**, 053507 (2007).
[17]Th. Trottenberg, H. Kersten, and H. Neumann, New J. Phys. **10**, 063012 (2008).
[18]S.-H. Kim, J. R. Heinrich, and R. L. Merlino, Phys. Plasmas **15**, 090701 (2008).
[19]J. Heinrich, S.-H. Kim, and R. L. Merlino, Phys. Rev. Lett. **103**, 115002 (2009).
[20]N. D'Angelo, J. Phys. D: Appl. Phys. **28**, 1009 (1995).
[21]P. K. Shukla and A. A. Mamun, *Introduction to Dusty Plasma Physics* (IOP, Bristol, 2002), p. 96.
[22]S. A. Khrapak and A. V. Ivlev, in *Complex and Dusty Plasmas From Laboratory to Space*, edited by V. E. Fortov and G. E. Morfill (CRC, Boca Raton, FL, 2010), p. 110.
[23]A. V. Ivlev, M. Kretschmer, 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).
[24]L. Couëdel, M. Mikikian, L. Boufendi, and A. A. Samarian, Phys. Rev. E **74**, 026403 (2006).
[25]S. Robertson and Z. Sternovsky, Phys. Rev. E **67**, 046405 (2003).
[26]K. Avinash, Phys. Plasmas **13**, 012109 (2006).
[27]S. A. Khrapak and A. V. Ivlev, *Complex and Dusty Plasmas From Laboratory to Space* (Ref. 22), p. 151.