Observation of Laser-Pulse-Induced Traveling Microbubbles in Dusty Plasma Liquids

Hong-Yu Chu, Yen-Kun Chiu, Chia-Ling Chan, and Lin I

Department of Physics and Center for Complex Systems, National Central University, Chungli 32054, Taiwan, Republic of China

(Received 28 June 2002; published 21 February 2003)

We report a direct experimental observation of traveling microbubbles induced by intense laser pulses in strongly coupled dusty plasma liquids. The dense plasma ablated from a suspended dust particle generates a spherical plasma bubble with a low dust density, in the quiescent regime before a transition to self-organized longitudinal dust density waves. It travels downwards at a velocity about 6 cm/sec inside the dust liquid. Dust density fluctuations trailing the bubble are also observed. The bubble generated in the high pressure dissipative regime collapses right after formation.

DOI: 10.1103/PhysRevLett.90.075004 PACS numbers: 52.27.Lw, 52.35.Sb

In a weakly ionized dusty plasma, the suspended micrometer size dust particles can be negatively charged (about 10^4 electrons per particle) [1,2]. The strong Coulomb interaction between dust particles leads to the formation of dust Coulomb crystals and liquids [3–5]. In addition, through Coulomb interaction and charging processes, the massive dust particles are strongly coupled with the background plasma, in which ionization, diffusion, and space charge induced transport further enrich the dynamical behaviors. It leads to many interesting nonlinear phenomena associated with collective dust particle motions and background plasma fluctuations [1,2]. For example, dust density (acoustic) waves or solitary waves can be excited [2]. The ionization instability further provides a positive feedback to sustain the excitation [6–11]. Self-organized longitudinal and transverse dust density waves [6,7], oscillation around sheath boundaries [8,9], filamentary modes and voids with varying shapes [10], and stationary large voids in the microgravity experiment [11] have been observed in the past few years. In this Letter, through the ablation by intense laser pulses, we demonstrate the first observation of traveling microbubbles with low dust density in strongly coupled dusty plasma liquid (DPL) and study the relation with dust density waves. In a DPL, dust particles are arranged as the molecules in a liquid, so that they strongly interact with their neighbors sliding past them.

From a more general view, the formation of bubbles, cavities, or 3D pulse-type spatial structures in extended media are interesting nonlinear phenomena [12–15]. They are formed either through self-organization or external drives. Gas bubbles in liquids, by heating or strong acoustic field, and self-organized voids in colloidal liquid suspensions are the good examples [13,14]. Recent studies also demonstrated that, using intense laser pulses, the solitonlike electromagnetic wave in underdense gaseous plasma [15] and the gas bubble with luminescence in water [16,17] could be generated. The generic dynamical behavior of plasma microbubble at about ten interparticle scale in DPL is certainly an interesting issue to be explored.

Using intense laser pulses, the ablation from the solid surface, water, or particles suspended in gas and liquid can generate a dense plasma plume which nonlinearly interacts with the background medium [16–19]. In this work, a plume is generated from the ablation of a suspended dust particle at the laser focal point in our quiescent DPL. Intuitively, we might expect that it induces a transient explosion to blow away the surrounding particles. Then, similar to the quick collapse of the laser induced bubble in water [16,17], the void collapses right away due to the strong Coulomb repulsion between dust particles. However, we find that, in the proper pressure regime before the transition to the spontaneous formation of dust density waves, the dense plume expels dust particles and forms a spherical dust-free plasma bubble with about a few mm diameter (7 to 20 interparticle distance). Unlike the rising bubble in liquids, it travels downward as a sinking sphere, and exits the sheath boundary above the bottom electrode. By reducing the collisional dissipation, we can drive the system through the various states: fast collapsing bubble, stable traveling bubble, dust density fluctuations after bubble exits DPL, and the spontaneous formation of dust density waves in DPLs without external laser drive.

The experiment is conducted in a cylindrical symmetric rf dusty plasma system described elsewhere [20]. A hollow coaxial cylindrical trap with 3-cm inner diameter and 14-mm height is put on the bottom electrode to confine the dusty plasma with polystyrene particles (5 μm diameter) (Fig. 1). The weakly ionized glow discharge ($n_e \sim 10^9$ cm^{-3}) is generated in Ar gas at about 200 mTorr using a 14 MHz rf power system at 2.2 W power. Through the dipoles induced by the downward vertical ion flow, the suspended dust particles are aligned to form vertical chains [Fig. 2(e)] [22,23]. The confined chains are separated from the trap wall and the bottom electrode by the dark space (sheath). Horizontally, the dust particles in the same chain move together. It forms a quasi-2D DPL with interchain distance a about 0.3 mm, and a few a correlation lengths for the translational and bond-orientational order in the horizontal plane [20]. The

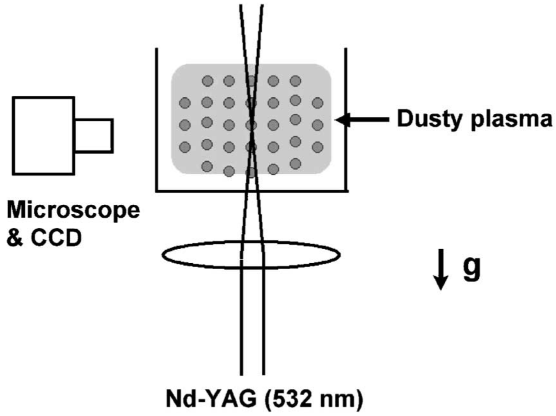

FIG. 1. The sketch of the side view of the system setup.

dust mass and the dust charge are 1.9×10^{-10} g/dust and about $5000e$/dust, respectively. The Debye length λ_D is between 100 and 200 μm. Along the center vertical axis, a Nd-YAG laser beam (532 nm wavelength, 6 nsec pulse width, and 50 mJ/pulse) is passed vertically (upward) through the bottom glass electrode coated with transparent conducting indium-tin-oxide thin film. It is focused to 0.1 mm at the center of the DPL. Dust particle motions are monitored through digital video microscopy. Because of the limit of the 60 Hz CCD frame rate, we concentrate on the slow dust dynamics instead of addressing the initial transient plume dynamics in the μs time scale after ablation. An expanded vertical Ar^+ laser sheet through the center vertical axis is used for particle illumination.

Figure 2 shows the typical sequential snapshots (15 msec exposure time) of the formation of the traveling plasma bubble associated with dust particle motion at 185 mTorr pressure. Basically, when the thermal fluctuation makes the dust particles fall at the laser focal point, the sudden laser heating causes the formation of a dense plasma plume. The dust particles are expelled by the plume. Figure 2(a) is taken 1/60 sec after the laser pulse. It corresponds to the end of the bubble expansion and the bubble is about to move downward. Unlike other spontaneously formed voids in dusty plasmas [10,11], the shape of our bubble is nearly spherical, like the gas bubble in water. It maintains its size, travels downwards at a speed at 5.8 cm/sec as a 3D inverse traveling solitonlike pulse, and disappears after hitting the bottom sheath. The DPL returns to the quiescent state with vertical chains in about 0.4 sec.

Figure 2(f) shows the sketch of the directions of the particle velocities while bubble travels. The downward advance of the bubble (the solid circle to the dotted circle) is accompanied by the depletion (repelling) of particles in the region (zone I) ahead of the bubble (solid circle) and attraction of particles into the rear end (zone II) of the

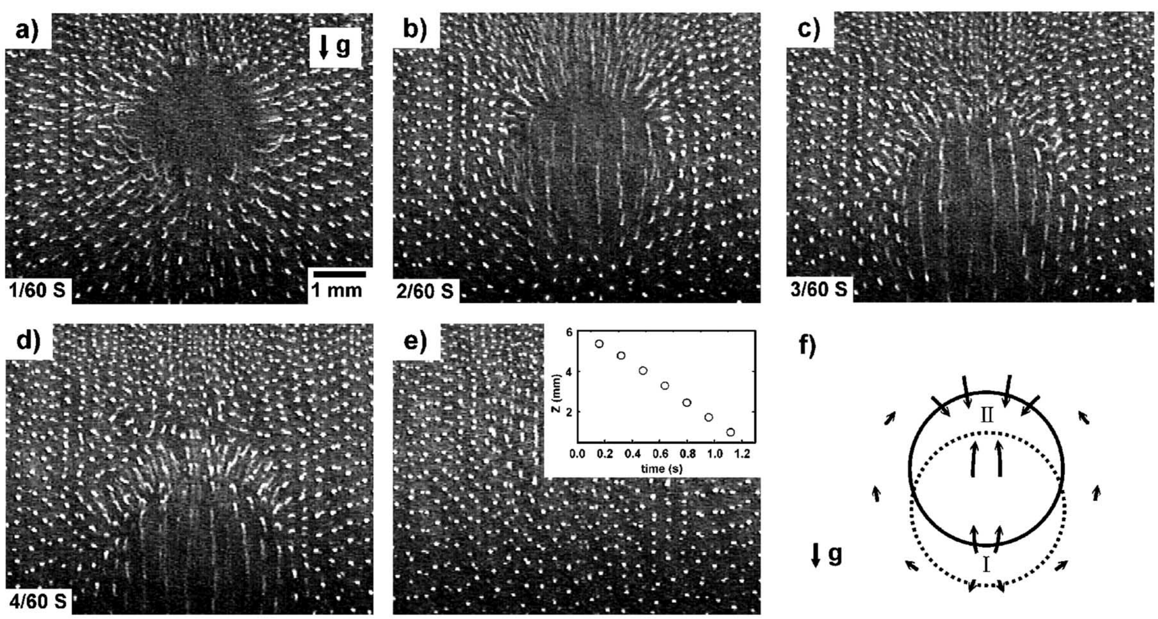

FIG. 2. (a)–(d) The sequential snapshots (15 msec exposure time) of the side view of the downward traveling bubble in DPL at 185 mTorr [21]. The number in each lower left corner indicates the picture taken time (the laser pulse is introduced at time zero). (e) The snapshot taken 1/60 sec before the laser pulse. The magnifications for (a)–(e) are the same. The inset shows the temporal evolution of the trailing edge of the bubble. (f) The sketch showing the directions of particle velocities surrounding and inside the bubble while the bubble travels downward. The bubble represented by the solid circle at t_1 advances downwards to the dotted circle at t_2 by repelling particles from zone I and attracting particles into zone II with some phase delay. The length of each arrow is proportional to its speed.

bubble, with some phase delay between them. Outside the sinking bubble, the velocity field follows a dipolelike returning flow field. Unlike a hard sphere, the bubble is permeable. Inside the bubble, a few particles can directly move upward from the repelling zone I to the attracting zone II, at a slightly larger speed than the bubble [see the low density long faint trajectories inside the bubbles of Figs. 2(b) and 2(c)].

The above traveling bubbles are formed in the quiescent DPLs free from self-organized dust density waves or voids [see Fig. 2(e) for the side view of the quiescent DPL state $1/60$ sec before the laser pulse]. The ablation of one or a few suspended dust particles in the focal zone forms a dense plume. The plasma density of a typical plume with a few mm diameter formed by fully ionizing a dust particle ($5\ \mu$m diameter) is about $10^{13}\ \mathrm{cm}^{-3}$. The plume quickly expands and pushes dust particles away. However, in our test of the laser ablation from a solid surface into Ar gas background at the same ambient pressure but without turning on the discharge, the plume lifetime is very short ($< 20\ \mu$sec) due to its high expanding speed [19]. Namely, in our quiescent DPL, the laser ablation mainly provides an initial kick over the barrier for the formation of the dust-free plasma bubble. After bubble formation, the denser plasma inside the bubble is further sustained by the rf discharge. In the model of the spontaneous formation of nontraveling voids in other dusty plasma experiments [10,11], it was proposed that the reduced electron depletion in the region with low dust density increases the ionization rate. It compensates the outward diffusion loss, and sustains the denser plasma which exerts outward ion drag on the surrounding dust particles to prevent the void from collapsing. Our bubble might partially share the similar mechanism.

The downward bubble motion indicates that more complicated dynamical processes than the stationary voids are involved. The gravitational force and the net downward ion flow to the bottom electrode from the background rf discharge both break the system symmetry. The ion flow effect is evidenced by the long vertical particle chains through the ion focusing induced dipole effect in our DPL [22,23]. However, it is not sufficient to argue that the traveling bubble is simply blown down by the background ion flow, through which the leading region suffers from a stronger net outward ion flow than the trailing region. The overshooting or space charge induced effects in the compression and rarefaction processes might also need to be taken into account to explain the phenomena such as the upward high speed motion of low density particles permeating through the bubble from zone I. A theoretical model with nonlinear dynamical equations including the effects of charging, ionization, diffusion, space charge induced transport, ion flow, dust inertia, etc., is needed.

The above nonlinear processes for the traveling bubble strongly depend on the system operating parameters which affect the state of the DPL. We observe that, in the absence of the laser drive, the system bifurcates from the quiescent liquid state [regimes I–IV in Fig. 3(a)] to the fluctuating state with self-organized longitudinal dust density waves (regime V), when the pressure is reduced below 150 mTorr. In regime V, self-organized horizontal stripes with alternating strong compression and rarefaction are easily observed [Figs. 3(f) and 3(g)]. The frequency is centered around 28 Hz and the wavelength is

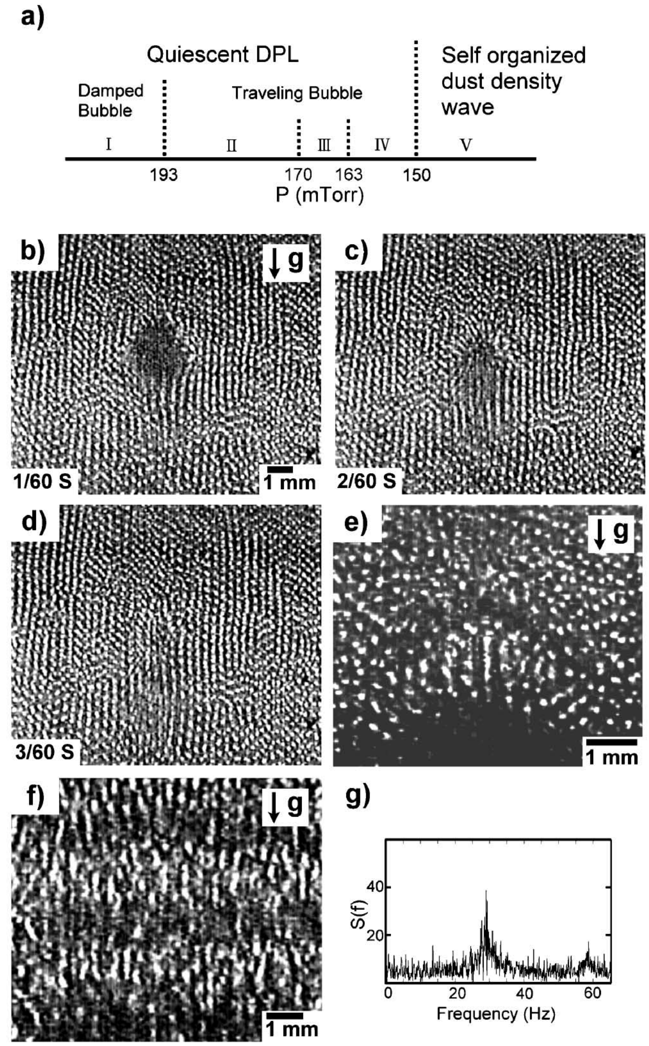

FIG. 3. (a) The regimes for the states with different responses to the laser pulses as pressure varies. Without laser perturbation, the DPL is quiescent in regimes I–IV and with self-organized dust density waves in V. (b)–(d) The sequential snapshots showing the side view of the collapsing of the bubble in the dissipative cold state at 200 mTorr (regime I). The three pictures have the magnification. (e) The snapshot showing the formation of the bow shape dust depletion zones trailing the bubble at 166 mTorr (in regime III). (f),(g) The snapshot and the power spectrum (from a point measurement of the scattered Ar^{+} laser light) showing the self-organized dust density wave at 140 mTorr (regime V) without the pulsed laser perturbation [21].

about 1.8 mm. The wave propagates downwards at a speed 5 cm/sec, similar to the speed of the traveling bubble. On the other hand, in the high pressure regime I, the DPL is cold and the dust density waves are strongly damped. Figures 3(b)–3(d) show the bubble collapses, and the straight vertical chains are fully recovered in 50 msec after the laser pulse. The state with the stable spherical traveling bubble mainly exists in a wide window (regimes II–IV) before the transition to regime V. In regime II, the bubble travels without obvious density depletion zone in the wake. In regime III, the dust density fluctuations are much less strongly damped and the liquid is more compressible. Damped solitarylike density oscillation in the bubble wake is observed. Figure 3(e) shows the bow shaped dust depletion zone in the bubble wake due to the overshooting of particles rushing into the trailing edge of the bubble at 166 mTorr. If we further reduce the pressure (regime IV), the dust density fluctuations (similar to the fluctuations in regime V) trailing the bubble still survive after the bubble leaves the bottom sheath (not shown). Namely, regime IV is the regime with bistable states: the quiescent DPL state and the state with the self-organized dust density waves. In regime V, the bubble is quickly deformed and mixed with the self-organized dust density fluctuation in the background (not shown).

The above observations suggest that the traveling bubble might share a similar origin to the self-organized dust density waves assisted by ionization instability [6]. At the high pressure end, where the collisional dissipation dominates, the DPL is cold and the dust density fluctuations are strongly damped. The bubble quickly collapses after formation. The traveling bubble forms only in the intermediate pressure regime before the spontaneous formation of dust density fluctuations, where the damping is less severe.

In conclusion, we demonstrate the experimental observation of spherical traveling plasma bubbles with low dust density inside rf DPLs through pulsed laser ablation from suspended dust particles, and investigate the relation with the self-organized dust density waves. The dense plasma plume from ablation expels dust particles and forms the bubble. The lower dust-induced electron depletion in the bubble causes a denser plasma through the higher ionization rate, which compensates the diffusion loss and exerts outward ion drags to keep the bubble from collapsing. The downward motion of the bubble is associated with the repelling and attracting of the particles in the leading and trailing zones of the bubble, respectively. Decreasing the pressure reduces the collisional dissipation and leads the system visiting the following states: the collapsing bubble, the traveling solitonlike bubble, the solitarylike traveling bubble trailed by damped density oscillation in the wake, and the self-organized longitudinal dust density waves. Before the transition to regime V, the bubble at small diameter also collapses right after formation.

This work is supported by the National Science Council of the Republic of China under Contract No. NSC-90-2112-M008-050.

[1] For example, C. K. Goertz, Rev. Geophys. **27**, 271 (1989); D. A. Mendis and M. Rosenberg, Annu. Rev. Astron. Astrophys. **32**, 419 (1994).
[2] P. K. Shukla and A. A. Mamun, *Introduction to Dusty Plasma Physics* (Institute of Physics, New York, 2001).
[3] J. H. Chu and Lin I, Phys. Rev. Lett. **72**, 4009 (1994).
[4] H. Thomas *et al.*, Phys. Rev. Lett. **73**, 652 (1994).
[5] Y. Hayshi and K. Tachibana, Jpn. J. Appl. Phys. **33**, 804 (1994).
[6] J. H. Chu, J. b. Du, and Lin I, J. Phys. D **27**, 296 (1994); J. M. Liu and Lin I, Phys. Rev. E **62**, 5571 (2000).
[7] J. Pramanik, G. Prasad, A. Sen, and P. K. Kaw, Phys. Rev. Lett. **88**, 175001 (2002).
[8] S. Nunomura *et al.*, Phys. Rev. Lett. **83**, 1970 (1999).
[9] Y. C. Wang, W. T. Juan, and Lin I, Phys. Rev. E **62**, 5667 (2000).
[10] G. Praburam and J. Goree, Phys. Plasmas **3**, 1212 (1996); D. Samsonov and J. Goree, Phys. Rev. E **59**, 1047 (1999).
[11] G. E. Morfill *et al.*, Phys. Rev. Lett. **83**, 1598 (1999); J. Goree, G. E. Morfill, V. N. Tsytovich, and S. V. Vladimirov, Phys. Rev. E **59**, 7055 (1999).
[12] See, e.g., A. V. Gaponov-Grekhov, *Nonlinearities in Action* (Springer, Berlin, 1992); M. C. Cross and P. C. Hohenberg, Rev. Mod. Phys. **65**, 851 (1993).
[13] For example, A. Walton and G. Reynolds, Adv. Phys. **33**, 595 (1984); C. E. Brennen, *Cavitation and Bubble Dynamics* (Oxford University Press, New York, 1995).
[14] K. G. Wang, Phys. Rev. E **62**, 6937 (2000).
[15] M. Borghesi *et al.*, Phys. Rev. Lett. **88**, 135002 (2002).
[16] V. Venugopalan *et al.*, Phys. Rev. Lett. **88**, 078103 (2002).
[17] For example, O. Baghdassarian, B. Tabbert, and G. A. Williams, Phys. Rev. Lett. **83**, 2437 (1999).
[18] *Laser Ablation: Mechanisms and Applications—II*, edited by J. C. Miller and D. B. Geohegan (American Institute of Physics, New York, 1994).
[19] D. B. Geohegan and A. A. Puretzky, Appl. Phys. Lett. **67**, 197 (1995).
[20] W. T. Juan, M. H. Chen, and Lin I, Phys. Rev. E **64**, 016402 (2001); Y. J. Lai and Lin I, Phys. Rev. Lett. **89**, 155002 (2002).
[21] See EPAPS Document No. E-PRLTAO-90-031307 for movies corresponding to the observations in Figs. 2 and 3. A direct link to this document may be found in the online article's HTML reference section. The document may also be reached via the EPAPS homepage (http://www.aip.org/pubservs/epaps.html) or from ftp.aip.org in the directory /epaps/. See the EPAPS homepage for more information.
[22] S. V. Vladimirov and M. Nambu, Phys. Rev. E **52**, 2172 (1995).
[23] A. Melzer, V. A. Schweigert, and A. Piel, Phys. Rev. Lett. **83**, 3194 (1999); V. Steinberg *et al.*, Phys. Rev. Lett. **86**, 4540 (2001).