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Spray and microjets produced by focusing a laser pulse into a hemispherical drop

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We use high-speed video imaging to study laser disruption of the free surface of a hemispheric drop. The drop sits on a glass surface and the Nd:YAG (yttrium aluminum garnet) laser pulse propagates through the drop and is focused near the free surface from below. We focus on the evolution of the cylindrical liquid sheet and spray which emerges out of the drop and resembles typical impact crowns. The tip of the sheet emerges at velocities over 1 km/s. The tip of the crown breaks up into fine spray some of which is sucked back into the growing cavity at about 100 m/s. We measure the size of the typical spray droplets to be about 3 μm . We also show the formation of fine microjets, which are produced when the laser is focused inside the drop and the shock front hits small bubbles sitting under the free surface. For water these microjets are 5–50 μm in diameter and exit at 100–250 m/s. For higher viscosity drops, these jets can emerge at over 500 m/s. © 2009 American Institute of Physics. [doi:10.1063/1.3253394]

I. INTRODUCTION

The laser ablation of liquid and soft-matter surfaces, such as skin and ocular material, has been the focus of recent studies, primarily motivated by biomedical applications.¹ Its use for eye surgery is well known and recent applications include catapulting of soft material through a liquid surface for selection and/or separation.² Horneffer *et al.*³ studied the role of splashing and hydrodynamic phenomena for laser-induced transport of live cells. Vogel *et al.*⁴ performed the first detailed study of jet-induced tissue damage in ophthalmic surgery. Other potential applications of laser disruption of droplets is for generation of fine spray to improve combustion efficiency, or to produce minute droplets needed in mass spectrometry for complex biomolecules in solution.

In Fig. 1 we present to the reader an overview of the rich hydrodynamics of the crown of liquid ejecta after the fluid interface has been impulsively accelerated with a focused laser pulse. The importance of hydrodynamic mechanisms to the expulsion of liquid and soft materials, has been known since the work of Frenz *et al.*⁵ The best images to date of this phenomenon are due to Aplitz and Vogel,⁶ who presented snapshots of the sheet structure during laser disruption of water as well as liver and skin surfaces. Vogel *et al.*⁷ also developed a new Schlieren technique to observe the shock structure in the surrounding air, with detailed time resolution under 100 ns. See also images by Kim *et al.*⁸ Laser ablation and cutting of solid surfaces are rich areas of relevant research for material processing and for thin film deposition.^{9,10}

Previous works on the interactions of bubbles and free surfaces have primarily focused on underwater explosions^{11,12} or laser-produced cavitation bubbles. The formation of jets from collapsing cavitation bubbles, generated

near a solid surface, has been widely studied. Work by Blake and Gibson¹³ studied cavitation bubbles near a free surface showing jetting. Robinson *et al.*¹⁴ further studied, both experimentally and numerically, the interaction of two closely spaced cavitation bubbles next to a free surface. These are transient laser-produced cavitation bubbles.

The explosive breakup of small drops was imaged by Lindinger *et al.*¹⁵ Here a submillimeter droplet is subjected to a femtosecond laser pulse, observed in submicrosecond sequence of snapshots, revealing ejected spray and complete breakup.

Jetting from cavitation bubbles within large drops was recently studied by Obreschkow *et al.*¹⁶ The cavitation in these centimeter sized drops is generated with an electric discharge and the drop is stabilized in a microgravity environment. Here, the jet is formed during the collapse of the bubble, both inside the drop through the bubble's center and from the surface of the drop very similar to flat surface—for a more detailed discussion, see Ref. 16.

Jetting can also be induced by a shock wave passing over a stable gas or expanding/collapsing cavitation bubble. Kodama and Tomita¹⁷ studied how such jets can penetrate into soft materials, used to simulate tissue. This is done by positioning a bubble next to a gelatin surface and then subjecting it to a laser-produced shock. The resulting jets had penetration velocities between 35 and 60 m/s. Limited imaging of such jets from a bubble next to a free surface was obtained with an image-converter camera by Tomita *et al.*,¹⁸ without characterization. Recently it was demonstrated that jetting of stable gas bubbles^{19,20} and transient cavitation^{21,22} bubble in an infinite liquid can be induced through shock-wave excitation. Here, the bubble jets in the direction of the wave propagation are very similar to cavitation bubbles close

FIG. 1. The formation of a laser crown for a water drop. The radius of curvature of the drop hemisphere is about 3 mm. Frames are shown at $t = 0, 1, 2, 5, 10, 18, 36$, and $60 \mu\text{s}$, with an exposure duration of 500 ns. Scale bar is 1 mm. The bright circle in this and other images is an optical artifact. See also the online video clip (enhanced online). [URL: <http://dx.doi.org/10.1063/1.3253394.1>]

to an elastic boundary.²³ Brujan *et al.*^{24,25} also gave detailed imaging of bubble collapse, near elastic boundaries, measuring jet velocities as high as 960 m/s.

Shock-wave induced jetting is conceptually similar to hydrodynamic jets,^{26–28} which occur, for example, when cavitation bubbles collapse near a wall,^{29,30} or the Worthington jet following the impact of a drop onto a deep pool of liquid, with the subsequent collapse of the crater. Similar jets also form in large-amplitude Faraday waves which are forced until they break^{31–33} and even from oscillating drops.³⁴

Herein we focus on the dynamics of the ejecta and spray droplets, generated with higher laser energy than used in the above studies. Our configuration differs from the typical ablation experiments, by the laser traveling through the liquid before being focused at the free surface. We also highlight the formation of microjets due to the presence of small bubbles, sitting inside the drop under the free surface. First we describe the experimental setup, then show the ejecta and spray formation in Sec. III, followed in Sec. IV by the microjetting.

FIG. 2. (Color online) Setup of the laser and objective.

II. EXPERIMENTAL METHODS

The experimental setup is sketched in Fig. 2. We used a pulsed Nd-YAG (yttrium aluminum garnet) laser (Ultra CFR by Big Sky Laser), with pulse duration of ~ 7 ns and a nominal maximum energy of 30 mJ/pulse along with an attenuator to vary the energy level of each pulse. Unless otherwise stated, the laser energy is 30 mJ. The hemispherical drop sits on a 1 mm thick glass microscope slide. It is confined to a 6 mm circular clear patch, which is surrounded by hydrophobic coating. Our configuration differs from the typical ablation setup, by bringing the laser light through the liquid directed toward the air. The laser beam is focused with a $20\times$ microscope objective, sitting immediately under the glass plate. The objective can be moved vertically with a micrometer to change the depth of the laser focus dz , relative to the drop surface.

A long-distance microscope is used to observe the phenomenon (Leica Z-16 APO Zoom). It has adjustable magnification, interchangeable objectives, and a mechanical aperture. With a $2\times$ planapochromatic objective we obtain a magnification of up to 18.4. The numerical aperture (NA) is as large as 0.224 NA, giving a minimum visible structural width of $0.74 \mu\text{m}$. At the largest magnification the working distance is 4.5 cm. We use a band cutoff filter on the camera lens to block the laser wavelength, but the plasma radiates at all wavelengths, as is evident in the flash in Fig. 1. The spray and liquid motions were observed with an ultrahigh-speed video camera (Shimadzu Hypervision) at frame rates up to 1×10^6 frames/s,³⁵ with diffuse backlighting from a 350 W metal halide lamp (Sumita LS-M350). With the above microscope, the maximum pixel resolution becomes $1.45 \mu\text{m}$.

The video camera has an on-chip image storage and can take a total number of 102 full frames irrespective of the frame rate used, with each frame having 260×312 pixels. The exposure duration of each frame can be adjusted and at 1 Mframe/s the exposure can be set to either 500 or 250 ns. The imaging is triggered by a TTL (transistor-transistor logic) signal identifying the laser pulse and generated by the Q-switch of the laser. However, the camera is free running and the trigger signal is not synchronized with the timing of the camera framing. The laser pulse can therefore arrive at any time during the specific triggered frame, resulting in timing jitter from one realization to the next, by as much as the interframe time. This leads to some uncertainty in imaging the initial dynamics of the plasma and the onset of the jetting.

From the plasma size in the figures, we can roughly estimate the size of the laser spot at maximum laser energy as $300 \mu\text{m}$ in diameter, which gives us an estimate of the radiant exposure of 42 J/cm^2 , which is more than an order of magnitude larger than the energy studied by Apitz and Vogel⁶ using 70 ns Er:YAG laser pulse. The typical shape of the plasma breakdown is visible in Figs. 11(b), 19, 20(c), and 20(f) below, showing an arrowlike region, very similar to the detailed time-resolved images of Vogel *et al.*^{36,37} and Ref. 38. It should be pointed out that the arrow shape is produced by interaction of the plasma and the laser beam, where the plasma region starts at the point of optical breakdown close

TABLE I. Properties of the different liquids used in the experiments.

Liquid	Density ρ (g/cm ³)	Viscosity μ (cP)	Surface tension σ (dyn/cm)	Capillary length a (mm)
Ethanol	0.789	1.19	23.2	1.7
Distill. water	0.996	1.004	72.1	2.7
Glycerin	1.26	~1200	65.0	2.3

to the focus and then propagates due to plasma shielding against the laser direction, producing a cone shaped plasma. The details of this optical breakdown region are not resolved, in particular, aberration due to optical imperfection in the focusing geometry may lead to multiple regions of optical breakdown. Thus the shock wave generated is not perfectly spherical but is a superposition of multiple shocks from different regions of optical breakdown. Our optical setup cannot visualize these details as was done, for example, by Vogel *et al.*⁷

The liquids used were de-ionized water, glycerin/water mixtures of various concentrations, and ethanol (99.5% pure). Table I lists the various liquid properties. The stationary drops are slightly deformed by gravity, as their size is larger than the capillary length

$$a = \sqrt{\sigma/(\rho g)},$$

where σ , ρ , and g are the surface tension, liquid density, and acceleration of gravity, respectively. The corresponding Bond number is defined as

$$\text{Bo} = \rho g R^2 / \sigma,$$

where R is the radius of the drop. For water $\text{Bo} \sim 1.2$ and for ethanol $\text{Bo} \sim 3.8$ suggesting a much more sessile drop.

The experiments were carried out over a wide range of liquid viscosities, generating jetting over a large range of Reynolds numbers,

$$\text{Re} = \frac{\rho D U}{\mu},$$

where D and U are the characteristic size and velocity and μ the dynamic viscosity.

III. RESULTS FOR LASER DISRUPTION

A. Ejecta motions

Figure 1 shows the evolution of the fine ejecta sheet, which emerges immediately following the laser pulse at the free surface. The sudden rise in pressure formed by the plasma generates an impulsive pressure akin to the recoil-induced pressure in surface ablation.⁶ In the incompressible limit the impact of a solid plate would generate vertical walls of liquid, see Sec. 6.10 in Batchelor,³⁹ with the highest velocity at the plate edge. Here the walls of the conical crown emerge at velocities between 1100 and 1400 m/s, as shown in Fig. 3(a). This is very similar to the velocities extracted from the single-frame sequences obtained by Vogel *et al.*^{2,6} The initial velocity is therefore close to the speed of sound in water. However, the tip of the sheet breaks up into fine spray

FIG. 3. Laser-produced sheets. (a) Tip velocity of the sheet following the laser pulse. The horizontal broken line is the speed of sound in air. (b) The ejecta cone traced by the tip of the sheet following the laser pulse. The cone angle is $2\theta = 70^\circ$.

which decelerates rapidly, below the speed of sound in the air. This occurs within the first 4 μs . The initial Mach number of the tip of the sheet, inside the air, is therefore

$$\text{Ma} = \frac{u_{\text{tip}}}{c_{\text{sound}}} \sim 4,$$

where the speed of sound in air $c_{\text{sound}} \approx 350$ m/s.

The size of the spray droplets, in the tip spray, is smaller than the spatial resolution of these overall images, but is investigated in Sec. III E.

Figure 3(b) shows the trace of the tip of the spray sheet as it emerges from the drop immediately after the laser pulse. It forms a cone with a full cone angle of about 70° . Here we follow the tip after it has broken into fine spray, but still continues along this cone, while decelerating rapidly.

Figure 4 traces out the shape of the ejecta sheet, for the condition in Fig. 1. The conical sheet contracts on the upper sections and closes up. The thicker sections of the crown continue upward due to their higher momentum, while the spray is left behind, forming a vortexlike structure. This convergence of the sheet is driven by a suction pressure inside the cylindrical cavity, which penetrates into the drop. The suction is produced when the plasma has expanded beyond equilibrium, thus producing reduced density. The radius of the cavity near to the drop surface continues growing in size due to the much larger momentum in the motions within the

FIG. 4. Shape evolution for the cylindrical sheet. Times shown are $t=0, 2, 4, 7, 10, 15$, and $29 \mu\text{s}$ after the laser pulse.

drop. This laser-produced cavity also grows downward into the drop, similar to that following the impact of a solid onto the surface due to the downward vertical momentum, imparted to the liquid. We can again think of the sudden plasma acting as an impacting plate at the free surface. This cavity can be visualized in the larger field of view shown in Fig. 5. The cavity reaches the glass plate after $350 \mu\text{s}$. This corresponds to the bottom moving downward at an average velocity of 8 m/s , which is two orders of magnitude slower than the emergence velocity of the vertical sheet. The bottom

FIG. 5. Development of the cavity inside the water drop. Frames are spaced at $0, 8, 32, 96, 240, 336, 352, 448, 568, 656$, and $768 \mu\text{s}$. The scale bar is 1 mm and $dz \approx 50 \mu\text{m}$, for laser energy of 30 mJ . The arrow points to the bottom of the air cavity (enhanced online). [URL: <http://dx.doi.org/10.1063/1.3253394.2>]

FIG. 6. The suction of the fine spray into the growing crater for a water drop. The frames are separated by $1 \mu\text{s}$, with a 250 ns exposure. Scale bar is 1 mm , laser energy is 30 mJ , and $dz \approx 50 \mu\text{m}$.

width of this air cavity is typically 0.5 mm , as it emerges in the sixth panel of Fig. 5 (see white arrow). When the air cavity reaches the bottom it expands along the wall, showing clearly that it is not purely a product of laser-induced cavitation, as occurs when the laser hits fully inside the drop. Here we propose that the suction of air down the growing cavity will produce an enclosed air bubble. This is also clear as the bubble has not collapsed at the end of this video clip which extends about $800 \mu\text{s}$ after the laser pulse. For a fully submerged cavitation bubble, the collapse takes about $200 \mu\text{s}$, as shown below in Fig. 11(a).

The spray converging along the vertical center line retains its vertical momentum and rises at velocities $\sim 100 \text{ m/s}$ (dark arrow in the third panel in Fig. 5) and contains larger droplets than the spray left behind. These droplets, in the later panels of the figure, are up to $100 \mu\text{m}$ in diameter.

The flow structure in the air around the crown is revealed by the motion of the fine spray. Some of this spray is sucked into the top of the crown as it closes. Figure 6 shows the spray inside the crown. The spray is pulled from the sides and concentrates along the axis of symmetry, thereby forming a mushroom shape, pointed out by the arrow. The bottom of this spray sheet is here pulled into the growing crater at about 110 m/s . This shows clearly that air enters the cavity before it closes up.

Even after the sheet closes, the large pressure difference manages to break up and pull air through the liquid sheet, producing more spray. The rapid compression of the cylindrical sheet helps break it up through a buckling instability. Figure 7(a) shows two images of the top section of the water sheet as it is pulled together by the internal suction pressure. Figure 7(b) shows vertical striations, which indicate onset of buckling. If we assume that only the buckling undulations on the front side of the cylinder are visible in the image, then the wavelength of these disturbances are about $50 \mu\text{m}$. The thickness of the sheet should therefore be significantly thinner than this value, as buckling of liquid sheets is characterized by length scales which are a few multiples of their thickness. Using the images in Fig. 7(a) we can estimate the contraction of the cylindrical sheet leading up to the formation of the buckling lines. The contraction rate is here $3 \times 10^4 \text{ s}^{-1}$. This buckling will lead to filamentation of the sheet followed by breakup into droplets.

When the crown closes up the suction pressure pulls in

FIG. 7. Buckling of the cylindrical sheet. (a) Two superimposed frames, taken $4 \mu\text{s}$ apart. (b) The arrow points to one of the vertical ridges. Frame exposure is 250 ns . Scale bar is $500 \mu\text{m}$.

liquid pockets and produces spray. This entrainment is obscured in the water case but can be directly imaged for higher viscosity liquid, as is shown in Fig. 8 and in the accompanying video. Figure 8(a) shows an overall view and Fig. 8(b) shows a close-up of the entrainment at the top of the closing crown. The inward velocity of the bump in the left sidewall (pointed out by the left arrow), between frames 3 and 4, is about 60 m/s before it disintegrates into fine spray, which is pulled downward as was observed for water in Fig. 6.

B. Effect of laser depth

Figure 9 shows the changes in the spray, as we increase the depth of the laser focus below the drop surface. In the top panel, the laser produces very small volume of plasma, which can freely expand into the surrounding air and thus only ejects a minute amount of liquid. When the laser is

FIG. 8. Suction of spray into the crater from the crown wall for 80% glycerin drop, with viscosity $\mu \approx 59 \text{ cP}$. (a) $t = 14, 24, 30, 34, 42, \text{ and } 65 \mu\text{s}$ after the laser pulse. (b) Close-up images of the sheet breakup, taken at $t = 4, 14, 20, 23, 25, 28, 34, 48, 74, \text{ and } 93 \mu\text{s}$. Note the direction of air marked by the arrows. Scale bars are both 1 mm , 30 mJ , at $dz \approx 50 \mu\text{m}$. See also the corresponding video clip taken at 1 Mframe/s (enhanced online). [URL: <http://dx.doi.org/10.1063/1.3253394.3>]

FIG. 9. Changes in the laser disruption dynamics for de-ionized water as a function of the depth of the laser dz . Frames are selected to show the overall shape evolution and are not evenly spaced. (a) $dz \approx 0$ at $t = 0, 1, 2, 10, 59 \mu\text{s}$. (b) $dz \approx 50 \mu\text{m}$ at $t = 2, 4, 7, 15, 40 \mu\text{s}$. (c) $dz \approx 100 \mu\text{m}$ at $t = 0, 2, 4, 12, 55 \mu\text{s}$. (d) $dz \approx 150 \mu\text{m}$ at $t = 1, 4, 8, 33, 82 \mu\text{s}$. (e) $dz \approx 250 \mu\text{m}$ at $t = 1, 3, 7, 24, 84 \mu\text{s}$. (f) $dz \approx 750 \mu\text{m}$ at $t = 28, 84, 148, 228, 556 \mu\text{s}$. Scale bars are 1 mm long and all laser pulses are 30 mJ .

above this level, neither plasma nor any motion of the liquid surface is observed. We therefore identify this height with a reference level $z=0$, keeping in mind the significant vertical extent of the laser spot, as is clear in some of the later images, e.g., Fig. 20. The visible laser spot in that figure resembles an arrow head, which is about $300 \mu\text{m}$ long. However, the plasma region grows from the top of this arrow downward,³⁸ once the critical intensity in the beam waist is surpassed. The depth of this critical spot must therefore be within the drop, for any plasma to occur. This gives a much more precise vertical location than the length of the arrow might indicate.

The spray looks very similar to that in Fig. 1, when the focus is moved 50 or $100 \mu\text{m}$ below the surface. However,

FIG. 10. The breakup of the crown wall, into a treelike shape, for a water drop at $t=48, 128, 284$, and $800 \mu\text{s}$. The last frame shows the jet-and-collar shape. Laser pulse energy is 21 mJ and laser depth $dz \approx 470 \mu\text{m}$.

at a depth of $150 \mu\text{m}$ the sheet begins to thicken, as shown in Fig. 9(d). This trend continues and the bubble, which is enclosed by the closing cylindrical sheet, becomes progressively larger. Eventually, the cavitation bubble is entirely confined inside the drop and the ejected liquid changes qualitatively, when the ejected sheet is not open to the atmospheric pressure. Figure 9(f) shows this kind of evolution, as the cavitation bubble grows and collapses without entraining outside air. This generates a growing protrusion at the top of the drop, which becomes more slender [in panel 3 of Fig. 9(f)] when the internal cavitation bubble contracts again. The pressure wave generated at the end of this internal bubble collapse produces a collar around the base of this protrusion, to form a characteristic jet-and-collar shape, as imaged by Obreschkow *et al.*¹⁶ We suggest that the collar rises out of the neck region, when the pressure wave accelerates this curved free surface at the base of the jet, just as the acceleration of a concave hemispherical free surface produces a central jet. This formation will be described in more detail in a future publication.⁴⁰ Figure 10 shows another realization of this structure, for a lower laser energy, for which it is more regular. This characteristic structure is also more regular for higher viscosity liquid, as will be shown in Fig. 12(c) below.

The qualitative change that occurs with increased laser depth is therefore from an open cavity, to a fully enclosed cavitation bubble. For a water drop in our setup, this transition occurs for a laser depth around $z_c \sim 550 \mu\text{m}$, but is rather uncertain due to randomness of the splashing. This critical depth will certainly also depend on the laser power, but this dependence has not been characterized here.

For an even deeper laser pulse ($dz \sim 800 \mu\text{m}$), the cavitation bubble does not generate a large protrusion at the top of the drop, but smaller and more numerous undulations, as shown in Fig. 11. In the second frame of Fig. 11(a) the bottom of the bubble is visible during its growth phase. In the third panel it has reached the maximum size and in the fourth panel an arrow points at the well-known jet inside the bubble, which is generated during the collapse phase and is directed toward the substrate. The surface undulations are greatly enhanced by the downward acceleration of the top of the drop, during the collapse phase, which makes the surface unstable to Rayleigh–Taylor instability. Note that the bubble has fully collapsed about $200 \mu\text{s}$ after the laser pulse. The final panel shows the irregular turbulent surface, on the top of the bubble, generated by the first rebounding and the

FIG. 11. Bubble inside the water drop and undulations on the top surface. (a) The arrows point to the original laser pulse ($dz \approx 870 \mu\text{m}$) and the jet produced by the collapse of the bubble and is directed toward the solid wall. $t=0, 20, 160, 176$, and $280 \mu\text{s}$ after the laser pulse of 28.5 mJ. See also online video [URL: <http://dx.doi.org/10.1063/1.3253394.4>]. (b) Breakup of the free surface, shown at $t=0, 120, 200, 432$, and $768 \mu\text{s}$ after the laser pulse, of 30 mJ for $dz \approx 700 \mu\text{m}$. The arrows point to the bubble surface and the capillary waves coming from the contact line. The scale bars are 1 mm long. See also online video [URL: <http://dx.doi.org/10.1063/1.3253394.5>]. (c) The height of the protrusions above the original top of the drop vs time which is normalized by the time T from the laser pulse to the first collapse of the internal bubble, where $T=196 \mu\text{s}$. ($\square$) The first protrusions on top of the drop during the expanding bubble and ($\blacktriangle$) longer jets following the first collapse of the internal bubble (enhanced online).

splashing when the jet impacts onto the surface, as demonstrated by the well-resolved images of Lindau and Lauterborn.²⁹

Figure 11(b) shows more vigorous breakup of the drop surface, from a slightly more powerful laser pulse than in Fig. 11(a). In Fig. 11(b) the bubble has reached maximum width in the second frame and has fully collapsed back in the third frame. The multiple jets, emanating from the top of the drop, are formed by interactions of the waviness of the free surface and the pressure pulse emanating from the collapse of the cavitation bubble. The concave regions in the free surface promote the formation of new jets when subjected to the subsequent pressure pulses. Figure 11(c) tracks the height of the undulations and protrusions above the top of the drop. When the internal bubble contracts the original protrusions stop growing and following the first collapse new jets emerge at larger velocity.

Note also the generation of waves on the sides of the drop, where the liquid meets the substrate, indicated by an

FIG. 12. Changes in the ablated liquid as a function of the depth of the laser dz , for 75% glycerin drop with $\mu=35$ cP. (a) Laser spot at $dz \approx 50$ μm below the drop surface. Shapes shown at times $t=1, 10, 32$, and 77 μs . (b) Laser spot at $dz \approx 250$ μm , shown at $t=16, 44, 180$, and 388 μs . (c) Laser spot at $dz \approx 550$ μm , shown at $t=40, 136, 248$, and 560 μs . Scale bars are 1 mm long and laser energy is 30 mJ.

arrow in Fig. 11(b). These waves are promoted by the volume expansion and contraction of the drop/bubble in combination with the pinning of the contact line, at the edge of the hydrophobic paint which we use on the glass slide. These waves are shown traveling up the sides of the drop in the last panel. The wavelength of this disturbance is $\lambda \sim 0.32$ mm, with a phase velocity of about 1.3 m/s. This confirms the capillary nature of these waves, for which the theoretical phase speed is⁴¹

$$c = \sqrt{\frac{2\pi\sigma}{\rho\lambda}} \approx 1.2 \text{ m/s}.$$

C. Effect of liquid viscosity

Figures 12 and 13 show ejecta shapes for larger liquid viscosities. Figure 12 shows the change in shapes as a function of the laser depth, for intermediate viscosity (75% glycerin, $\mu=35$ cP). The overall trends are similar to the water drop but the critical depth, between spray and enclosed cavitation, becomes shallower, i.e., only when the laser is right at the surface do we observe ejecta spray. We estimate the critical depth $z_c \approx 200$ μm , which is less than half of the critical depth for water. Furthermore, the breakup of the sheet is now characterized more by tendrils of liquid, which do not break as quickly by capillary instability. For the fully enclosed cavitation bubble, in Fig. 12(c), we see the jet-and-collar structure. The initial velocity of the disruption sheet [like in Fig. 12(a)] emerges at velocities around 1400 m/s, i.e., the same speed as observed for water. Only for the very highest

FIG. 13. The laser disruption for 99% glycerin drop, with viscosity $\mu \sim 1200 \pm 200$ cP. The laser focus is moved further below the surface from the top to bottom rows. (a) $t=2, 4, 9, 17$, and 39 μs , for $dz \approx 50$ μm . (b) $t=1, 3, 5, 8, 12, 15, 22, 34$, and 71 μs , for $dz \approx 90$ μm . (c) $t=16, 32, 48, 64, 96, 160, 304, 736$, and 864 μs , for $dz \approx 170$ μm . (d) $t=4, 44, 100, 180, 236$, and 668 μs , for $dz \approx 340$ μm . Scale bars are 1 mm and laser energy is 30 mJ.

viscosity have we noted any significant reduction in this initial spray velocity. Figure 13 shows results for glycerin (99% pure), which has the largest viscosity studied, i.e., $\mu \approx 1200$ cP. Figure 13(a) shows conical splash, which now emerges at 1090 m/s, which is significantly slower than the water case. Figure 13(b) shows another case, where the laser bubble sits under the surface and does not break through. Here the bubble top rises initially upward at 160 m/s and liquid is pushed along the free surface of the bubble. Then when the cavitation bubble starts collapsing the flow converges and a central jet emerges from the top at 95 m/s.

Figure 13(c) shows another characteristic feature which emerges at the highest viscosities, i.e., a viscous tail, which meanders and twists along its length due to asymmetries of the collapsing cavity walls. The typical localized winding rates are of the order of 4000 rps [arrow in Fig. 13(c)]. Figure 13(d) again shows similar jet-collar shape as in Fig. 12(c).

FIG. 14. Large plasma generated above the ethanol surface, (a) for $t = -1, 0, 1, 2, 3, 4, 5, 11$, and $21 \mu\text{s}$. (b) For $t = -1, 0, 1, 2, 3, 4, 5, 7, 15, 41$, and $72 \mu\text{s}$. The scale bars are 1 mm and laser pulse energy is 30 mJ.

D. Ethanol drop

We also performed some disruption experiments with ethanol drops. The results show significant quantitative differences from the water drops. Here the capillary length $a = 1.7 \text{ mm}$ is much smaller than the 6 mm drop base and the drop is therefore much flatter and shallower. The plasma visible above the free surface appears to be larger than in the water case, see Fig. 14, for two realizations where the laser barely touches the surface generating small disruption crowns. The larger plasma region may be due to the higher volatility of ethanol. It is unlikely that plasma luminescence will last for $3 \mu\text{s}$ and that it extends as far as the bright region on the video frames indicates. It seems more likely that the bright light arises from combustion/detonation of ethanol vapor above the droplet surface where it is mixed with the surrounding air. Therefore it can readily burn while the liquid ethanol in the drop does not. In the third panel of Fig. 14(a) the initial ejecta crown has a diameter of about $130 \mu\text{m}$. This crown breaks up by the formation of typical fingers at its edge, so familiar from drop impact studies.⁴² In Fig. 14(b) the crown closes up and is pulled into the cavity.

For the laser pulse close to the free surface, Fig. 15 shows that the overall spray sheet is very similar to those for water. The laser focus is slightly below the surface, which explains the absence of ethanol combustion. However, dur-

FIG. 15. The breakup of the crown wall for an ethanol drop, for $dz \sim 100 \mu\text{m}$ and $t = 1, 2, 3, 4, 5, 8, 15$, and $48 \mu\text{s}$. See also online video. Scale bar is 1 mm and laser pulse is 30 mJ (enhanced online). [\[URL: http://dx.doi.org/10.1063/1.3253394.6\]](http://dx.doi.org/10.1063/1.3253394.6)

FIG. 16. The holes forming in the crown wall for an ethanol drop for laser depth of $dz \approx 150 \mu\text{m}$. Four separate pocket formation sequences with the frames inside each row spaced by $1 \mu\text{s}$. Scale bars are $500 \mu\text{m}$.

ing the contraction of the cylindrical crown the sheet produces pronounced triangular fingers (arrows in Fig. 15) before the sheet closes up. These fingers can form a dense forest in some realizations, as shown in Fig. 17(a). These shapes are associated with holes which form in the crown. Figure 16 shows some specific realizations where such holes form. The unavoidable impurities or microbubbles present in the drop are swept up with the emerging crown. When they encounter the large suction pressure from the growing cavity, these bubbles are shown to expand to form pockets extending into the cavity, which subsequently break up into fine spray. The arrows pinpoint four separate hole formations but their evolution is easier to perceive in the online video with Fig. 15. It is not clear from the images but we propose that the resulting holes reduce the local pulling of the sheet toward the center line, with the upward momentum of the fluid around the holes being dragged out into the fingers. Even though the fingers are almost horizontal, their paths are essentially ballistic. Following the tip of some of these fingers, we do indeed show straight more vertical-aligned paths, as shown in Fig. 17(b).

E. The size of spray droplets

Separate sets of experiments were conducted, using larger optical magnifications, to measure the size of the typical spray droplets emerging during the initial disruption. The large initial velocity of the spray makes it impossible to

FIG. 17. (a) The breakup of the crown wall for an ethanol drop, $t=10, 30, 50$, and $70 \mu\text{s}$. Scale bar is 1 mm , laser energy is 30 mJ and $dz \sim 200 \mu\text{m}$. (b) The paths of the tips of the fingers, such as those shown in (a).

freeze the images of this spray during the early disruption stage, even with a 250 ns exposure. We therefore must observe the spray after it has decelerated to low subsonic velocities. In the recirculating region the droplets can be almost stationary and smearing by their motion becomes insignificant. Figure 18(a) shows the approximate region of the spray, used for this purpose.

Figure 18(b) shows close-up images of the water spray, at the maximum resolution of our system, i.e., $1.5 \mu\text{m}/\text{pixel}$. The sequence of frames shows numerous droplets, of fairly uniform size, which move in and out of focus, allowing for a rough estimate of their size. The typical droplet diameters are $d_s \approx 3 \mu\text{m}$.

From the volume of the close-up image compared to the overall spray volume in Fig. 18(a), this suggests that of the order of 6×10^5 droplets are contained in the spray. The droplet paths also reveal strong turbulent motions inside the spray cloud as well as random clustering. This can be expected by the large Reynolds number of these motions, i.e., $\text{Re} = DU/\nu \sim 10^5$, where ν is now the kinematic viscosity of the gas and we estimate D by the diameter of the crown $D \sim 1 \text{ mm}$ and U by its typical emergence velocity of 1 km/s .

Similar imaging was also performed for the ethanol and glycerin sprays. The droplet sizes are rather insensitive to the large change in viscosity. However, images for the glycerin drop show much fewer droplets in the spray [see Fig. 13(a)]. These droplets are only slightly larger than for water, with $d_s \sim 4.5 \mu\text{m}$.

On the other hand for ethanol we have observed a very dense spray in Fig. 15. The droplets appear to be slightly smaller than for water, i.e., $d_s \sim 2.5 \mu\text{m}$. Table II collects these rough estimates of the droplet sizes.

FIG. 18. Close-up imaging of the water spray. (a) The region in the close-up view is from a different video clip, taken at 15 times larger magnification. Scale bar is 1 mm . (b) Sequence of frames with $dt=8 \mu\text{s}$. Scale bar is $50 \mu\text{m}$.

IV. MICROJETTING FROM SUBMERGED BUBBLES

A. Water drops

Figure 19 shows an example of an intriguing fine jet, which frequently emerges from the top of the drops when the laser pulse is located inside the drop. This jet is driven by a fundamentally different jetting mechanism than the jet produced by focusing the laser pulse at or slightly below the droplet surface.

Figure 20 shows close-up imaging of numerous other examples of this jetting from a water drop. We believe these jets are formed when the shock wave from the onset of the laser-produced cavitation hits small bubbles sitting right under the free surface. This conclusion is supported by a number of observations. First, the fine jets occur most frequently from the apex of the drop, where small bubbles are eventually driven by buoyancy. Often, more than one of these jets are produced close to each other [Fig. 20(d)], which rules out focusing of acoustic waves by the shape of the drop. Furthermore, they also emerge within $2 \mu\text{s}$ after the laser pulse, not giving enough time for acoustic reflections from the solid

TABLE II. Estimates of the spray droplet size for the different liquids.

Liquid	Ethanol	Water	Glycerin
Droplet size (μm)	2.5	3	4.5

FIG. 19. Example of a fine jet emerging from the top of a water drop. Panels shown for $t=0, 8, 28 \mu\text{s}$. This jet is about $20 \mu\text{m}$ in diameter and emerges at 90 m/s . The scale bar is 1 mm and laser energy is 30 mJ at $dz \approx 850 \mu\text{m}$.

glass substrate. The presence of these bubbles was indeed verified visually in some cases, by direct observation of the drop, in top view. These bubbles are produced by earlier laser pulses and do not fully dissolve into the liquid. Furthermore the microjets disappear when these bubbles are removed with a small syringe.

These jets are always accompanied by an outer crown [arrow in Fig. 20(e)]. The varying width of this crown and

the thickness of the jets indicate the size of the original bubble, as shown below for a more viscous drop. The microjets in Fig. 20 are all for de-ionized water drops, showing a range of jet widths between about 5 and $50 \mu\text{m}$, emerging at velocities between 250 and 160 m/s , respectively. In other words the thinner the jets, the faster they emerge out of the drop surface. The jets are slightly tapered with the listed thicknesses estimated away from the very tip. Figure 20(e) shows the thickest jet, which is around $50 \mu\text{m}$ and emerges at 160 m/s . The surrounding crown rises up at 35 m/s . Its diameter grows initially, reaching about $200 \mu\text{m}$ when the jet emerges. We suggest that the width of this crown should give an estimate of the underlying bubble. In Sec. IV B we show that the crown is about 72% of the bubble size. Therefore, the bubble is about five times wider than the microjet that emerges. The crown emerges here just before the jet tip, see panel 2 in Fig. 20(e). This suggests that the internal pressure inside the bubble breaks the top surface of the bubble before the jet arrives from the hydrodynamic focusing, which occurs at the bottom of the bubble crater.²⁶ Note that the edge of the crown sheds some microdrops similar to the typical impact crown. This shedding of droplets is not observed for the smaller crowns in the other panels. The finest jet, see

FIG. 20. Laser-produced microjets from small bubbles sitting under the free surface, at the top of the hemispheric de-ionized water drop. The frames are spaced by $1 \mu\text{s}$, unless otherwise stated and the scale bars are all $200 \mu\text{m}$ long. The laser depth $dz \sim 400 \mu\text{m}$ and laser power of 30 mJ . (a) Fine jet, $D_j \approx 14 \mu\text{m}$, which emerges at 170 m/s . The white arrow points to the faintly visible plasma showing the relative timing of the laser pulse and the start of the jet. (b) The emergence of a finer $7 \mu\text{m}$ jet at 218 m/s . The first frames are spaced by $1 \mu\text{s}$ and the last two frames are at 17 and $24 \mu\text{s}$ after the first frame, showing the breakup of the jet into droplets. (c) The emergence of one very fine jet and another thicker one. The fine jet marked by the arrow (less than one pixel, i.e., $D_j \leq 5 \mu\text{m}$) emerges at 250 m/s . The thicker jet ($D_j = 34 \mu\text{m}$) emerges at 120 m/s . (d) The emergence of two closely spaced jets. The last frame shows the breakup of the jets into drops and is taken $27 \mu\text{s}$ after the plasma flash which is indicated by the arrow in the first frame. (e) Thicker jet, which is around $50 \mu\text{m}$ (the thickness of a human hair) and emerges at 160 m/s . (f) Two fine jets, emerge at 240 m/s and $D_j \leq 6 \mu\text{m}$ (enhanced online). [URL: <http://dx.doi.org/10.1063/1.3253394.7>]

FIG. 21. Forest of fine microjets, for drops of 60% glycerin/water mixture, with $\mu \approx 10$ cP. (a) For laser depth of $dz \approx 300$ μm , at $t = 0, 8$, and 20 μs . (b) For laser depth of $dz \approx 150$ μm , at $t = 0, 4$, and 8 μs . Both scale bars are 1 mm long.

arrow in Fig. 20(c), is around 5 μm in diameter and emerges at the highest observed velocity for water of 250 m/s.

Even though the microjets are very narrow, their velocities are so large that viscosity plays only a secondary role, as is shown by their Reynolds number,

$$\text{Re}_j = \frac{U_j D_j}{\nu}.$$

For the microjets in water Re_j is always over 1000, e.g., $\text{Re}_j = 1800$ in Fig. 19. In Fig. 20, those values are $\text{Re}_j = 2400$ (a), 1500 (b), 1250 and 4100 (c), 8000 (e), and 1500 (f).

B. Higher viscosity microjets

These jets are more common for drops of higher viscosity liquids, where bubbles rise more slowly and reside longer before coalescing or breaking at the free surface. Figure 21 shows *forests* of jets produced from a 60% glycerin drop, with viscosity $\mu = 10$ cP. In Fig. 21(b) we count 28 fine jets, which are subpixel in size, i.e., $D_j \leq 17$ μm . These jets emerge at widely different velocities ranging from 100 to 500 m/s depending on the depth of the laser pulse below the free surface and location of the jet along the drop surface. The fastest jets are close to the tip of the drop, with slower jets along the sides, where they are further away from the laser pulse. We have no control over the number, sizes, or location of the progenitor bubbles from which the jets arise and can therefore only give qualitative observations. However, the fastest jets for each realization show clear increase in velocity as the focus point of the laser is moved closer to the surface, as is shown in Fig. 22. Here we interpret the laser being at the surface, when the typical splashing crowns (as in Fig. 1) are formed and measure the depth of the laser

FIG. 22. Jet velocity of the fastest fine jets observed for a given depth of the laser pulse below the surface. For a drop of 60% glycerin solution, with dynamic viscosity $\mu \approx 10$ cP. The laser energy is 30 mJ.

focus from there. The focus position is adjusted with a micrometer, which moves the microscope objective up- or downward relative to the drop surface. The size and shape of the laser-produced plasma cannot be adequately characterized in our present setup and these jets clearly deserve more careful study.

Figure 23 shows that similar microjetting persists for even higher viscosity. Here the drop is 80% glycerin ($\mu = 59$ cP) and the fastest jet emerges at 580 m/s. The corresponding $\text{Re}_j \approx 180$.

Only for the very highest viscosities do the microjets slow down. The arrow in Fig. 13(d) points out one example of a bubble-initiated microjet, for 99% glycerin. This 20 μm jet emerges at a much lower 45 m/s, which corresponds to $\text{Re}_j \sim 1$, indicating large deceleration by viscous shear stresses.

FIG. 23. Jet formation for 80% glycerin drop, with viscosity $\mu \approx 59$ cP. Times shown are $t = 0, 1, 2, 3, 4, 6, 8, 16, 19, 31, 43$, and 66 μs after the laser pulse of 30 mJ, at $dz \approx 150$ μm . Scale bar is 1 mm (enhanced online). [URL: <http://dx.doi.org/10.1063/1.3253394.8>]

FIG. 24. Jet formation for 99% glycerin drop ($\mu \approx 1000$ cP, for $T = 22^\circ\text{C}$). (a) Times shown are 8, 16, 32, 56, 88, 232, and $664\ \mu\text{s}$ after the first image. (b) $t = -16, 0, 16, 64, 96, 144, 304$, and $1328\ \mu\text{s}$. The scale bars are 1 mm long, $dz \sim 1$ mm and laser energy is 30 mJ.

However, for larger submerged bubbles in glycerin, the jets are wider and can attain higher Re_j and larger velocity. Figure 24 shows two realizations where the jet diameters are about $\sim 150\ \mu\text{m}$ wide and emerge at ~ 110 m/s. These are most likely generated from a large bubble at the top, with diameters about $800\ \mu\text{m}$. The irregular side threads are remnants of the sidewall of the bubble crowns. The laser spot is here focused inside the drop and the outline of the top of the new cavitation bubble is visible in the last frames. Despite the very high viscosity, $Re_j \approx 20$ and the jets cannot be overpowered by viscous forces, such as the thinner glycerin jet in Fig. 13(d). The larger viscosity delays the capillary breakup of these jets. For the 80% glycerin jets in Fig. 23 they are mostly intact at the end of the video clip, after $80\ \mu\text{s}$. The pure glycerin jets in Fig. 24 are greatly stretched after remaining intact after 1.2 ms when they have stretched by a factor of 25, from an initial diameter of 150 down to $30\ \mu\text{m}$.

Figure 25 shows a more controlled experiment to investigate the relationship between the submerged bubble and the jet. Here the bubble was imaged just before the laser pulse, using a digital still camera. Figure 25(a) shows a typical image. The bubble is produced by a lower-energy laser pulse and is then allowed to rise to the top of the drop. Figure 25(b) shows a close-up of the breakup of the liquid layer at the top of the bubble, the formation of the surrounding crown, and the subsequent emergence of the jet. Here the laser is at lower energy and the jet emerges at only 55 m/s. Comparison was then made between the bubble sizes and the crown width, determined, for example, by frame 10 in Fig. 25(b). The width of the crown W is observed to be smaller than the bubble diameter D_b , i.e., $W = (0.72 \pm 0.06) \times D_b$.

FIG. 25. Bubble-produced jet for 99% glycerin drop, with $\mu = 550$ cP (29°C). (a) Typical image used to measure the size of the bubble inside the drop (arrow). The microscope objective is clearly visible under the glass slide. (b) Images are shown at 0, 1, 2, 3, 4, 5, 7, 9, 11, 14, 20, and 26 frames after the laser pulse, taken from a video sequence of 460 kframes/s, thus having $dt \approx 2.2\ \mu\text{s}$. The laser pulse is here about 15 mJ and its depth $\approx 850\ \mu\text{m}$. The scale bar is $500\ \mu\text{m}$ long.

C. Ethanol drops

Regular microjets are absent for the ethanol drops, only some irregular slow jets appear, as shown in Fig. 26. This is perhaps because of the high volatility and low surface tension of ethanol, which makes residual time of small bubbles at the free surface much shorter than for the other liquids. The observed irregular jetting may therefore originate from

FIG. 26. Irregular jet formation for an ethanol drop. (a) Times shown are 1, 4, 9, and $15\ \mu\text{s}$ after a laser pulse of 15 mJ. (b) $t = 3, 5, 8$, and $15\ \mu\text{s}$ after a laser pulse of 30 mJ. The scale bars are 1 mm long.

bubbles further below the surface, making them less coherent and slower [~ 80 m/s in Fig. 26(a)]. The opposite possibility also exists, i.e., that cavitation bubble collapse in the low surface tension ethanol produces a large number of even smaller microbubbles than for the other liquids. These bubbles might therefore form more than one layer of bubbles at the free surface, thereby shielding the surface bubbles from the shock, or the jets from lower levels interfering with the upper bubbles. Resolving these speculations will require more detailed study.

V. DISCUSSION AND CONCLUSIONS

This study has focused on two separate phenomena, i.e., the laser disruption of a hemispheric drop and the formation of microjets from microbubbles sitting under the free surface.

A. Laser disruption

We have measured the initial speed and shape of the conical disruption sheet which in water emerges at close to the speed of sound in the liquid. We have also measured the typical size of spray droplets breaking from the tip of this sheet. We interpret the typical droplet size d_s of $3\ \mu\text{m}$, as the characteristic thickness δ of the initial part of the crown wall. These measurements give us some insight into the partition of energy resulting from the laser pulse. Having also measured the initial velocity of this sheet we can roughly estimate the combined kinetic energy of the initial spray. If we arbitrarily assume that the initial 2 mm length of the sheet is on average two times thicker than the droplets, i.e., $\delta = 2d_s$, then its mass $M \sim \rho 2\delta H \pi D \sim 1.2 \times 10^{-8}$ kg, where H is the height and D is its diameter. The corresponding kinetic energy, assuming an average emergence velocity of 1000 m/s, is $0.5MU^2 = 6$ mJ, which is 20% of the 30 mJ laser energy. This simple estimate shows that a significant fraction of the laser energy goes into driving the liquid sheet. It also sets an upper bound for the thickness of the sheet to $\delta \sim 10d_s$. However, keep in mind that Vogel *et al.*⁴³ showed that more than half of the energy of the laser pulse goes into the shock waves and it is not clear how large a fraction of this shock-wave energy is extracted by accelerating the cylindrical jet.

The free surface energy (σA) generated by the breakup of the sheet into the multitude of droplets is on the other hand quite negligible. Here A is the total surface area of the 6×10^5 droplets, as estimated in Sec. III E. The surface energy is only 10^{-3} mJ, which is minuscule in comparison with the kinetic energy above.

We point out that during the early stages of the spray formation, as the liquid sheet breaks up, coalescence as well as rapid vaporization may be of importance, as this is where the sheet is moving at extreme velocities. Imaging this is however far beyond our current experimental capabilities.

We have shown how increasing the depth of the laser pulse changes the disruption qualitatively from an open cylindrical sheet to an enclosed cavitation bubble. For water this transition takes place for laser depth of about $550\ \mu\text{m}$ but reduces with liquid viscosity and will undoubtedly vary with the laser power. We also observe how the suction pres-

sure inside the growing cavity controls the shape evolution of the conical sheet closing it on top and entraining spray droplets. The large pressure difference even breaks up the liquid wall, especially where microbubbles are present inside the thin sheet. The depth of the laser focus greatly affects how much of the free surface is pulled up along the crown. For the laser close to or at the free surface, the crown produces new surface, therefore not pulling up as many bubbles. This is clear by comparing Figs. 9(b) and 9(d). The breakup of the crown wall is particularly prevalent for laser disruption of the ethanol drop. This gives new insight into the breakup of rapidly moving thin liquid sheets, such as those produced by a solid sphere impacting onto a pool,⁴⁴ where fingerlike pockets are also observed (see Fig. 6 in Ref. 44).

Perhaps surprisingly, neither the ethanol spray nor the ethanol drops combusted. However, we believe that Fig. 14 shows combustion of the ethanol vapor, above the drop.

When the cavitation bubble is entirely inside the drop, the surface breaks up through surface corrugations where shock waves from the collapsing bubble produce multitude of jets, as shown in Fig. 11. This is of similar form as the breakup induced by an oscillating base, using piezoelectric elements by James *et al.*,⁴⁵ which is of relevance to the breakup of drops in microgravity. This represents an alternative method to accomplish such breakup or atomization.

The fine spray may find other uses in applications but this may require eliminating the larger jet, which reaches much larger height. This might be done by blockage or judicious selection of the laser shape. The liquid geometry could also be adjusted to enhance the spray or one could use a much smaller liquid volume, where the larger jet does not form.

B. Microjets

For very small bubbles sitting under the surface, the shock emerging from the laser pulse is essentially a planar wave, hitting the curved bubble surface. The formation of jets in this configuration is well known, even for weak pressure pulses as, for example, in the work of Antkowiak *et al.*,²⁶ where a test tube with a curved meniscus is allowed to free fall onto a hard solid surface. Our jet diameter appears to be around 1/5 of the bubble diameter, which we estimate by the surrounding crown, see Figs. 20(e) and 25(b). This is quantitatively similar to the width of the fastest moving surface in Ref. 26 (their Fig. 7).

Our results show that only for the very largest viscosity can viscous forces slow down the microjetting. In fact the fastest jet observed (Fig. 23) with $U_j \approx 580$ m/s occurred for 80% glycerin drop, where $\mu \approx 59$ cP. Keep in mind that this speed is critically dependent on the size of the bubble under the surface, the relative location of the laser spot, and its intensity.

Numerous authors showed that the strength of the jet, generated from the collapse of a cavitation bubble, fully submerged in a liquid, depends on the distance of the bubble center from the solid surface, normalized by its maximum radius. Our setup differs significantly for the stable bubbles, as they can be assumed to sit directly next to the surface,

with only a thin film of liquid above them. Therefore, dynamically the geometry is as an open hemisphere, essentially the same as that studied by Antkowiak *et al.*²⁶

One should highlight that the microjetting phenomenon shown herein is dependent on the presence of minute gas bubbles inside the drop. This jetting would therefore not show up in experiments when a fresh drop is used in every realization. Smaller bubbles appear to produce thinner and faster microjets and smaller bubbles are more prevalent for higher viscosity. The microbubbles are primarily left over from the previous laser pulses, which might be either created through chemical reaction in glycerin and/or by rectified diffusion⁴⁶ of dissolved gas into the bubble which is likely more important for cavitation in pure water. The shocks reflected from the free surface generate expansion waves, which can also produce minute bubbles under the surface. The time between realizations was of the order of 1 min, thus allowing small bubbles to reach the drop surface in all but the most viscous liquids. The quantitative difference in the jetting is therefore highly dependent on the interaction of the bubbles with the specific liquid, i.e., how quickly do they rise under buoyancy to the free surface, moving against viscous forces. Furthermore, how long the bubbles sit under the free surface before *popping*, or merging with other bubbles, is also dependent on liquid properties, such as the viscosity and the surface tension. Although the content of the bubble may be affected by the type of the liquid, it is more important that the liquids select and distribute the air bubbles in different ways due to the difference in their physical properties, thus arranging for different initial conditions for the next laser pulse. More systematic studies with well-controlled and measured bubble sizes are needed. However, our results give both qualitative and quantitative indications of what to expect.

On the other hand, removing all microbubbles or impurities from a liquid is in many cases quite impractical, as is well known for cavitation problems which occur under many practical conditions. The production of microjets can therefore be unavoidable, during repeated laser pulses.

The beauty of these microjets is their perfect smoothness and regularity. Jets forced through a hole in a solid plate will always have an irregular tip, but the water jet in Fig. 20(a) shows no irregularity.

The breakup of the microjets is driven by Rayleigh instability but the very rapid velocity of the jets allows them to stay regular and intact during their early evolution. Figure 20(b) shows that the typical 7 μm microjet remains intact for the first 20 μs . For comparison, the characteristic instability time scale for capillary breakup, from linear stability theory, has the form⁴⁷

$$\tau \approx 2.91 \sqrt{\frac{\rho R^3}{\sigma}} = 2.2 \mu\text{s}.$$

This smaller value suggests that stretching has some stabilizing effect⁴⁸ and/or that only very small initial disturbance amplitudes are present.

In summary, we have used ultrahigh-speed video imaging to gain new insights into the dynamics of the laser dis-

ruption of liquid drops and characterized intriguing microjets which may find applications in areas of microfluidics. These bubble-induced jets could, for example, be utilized to drive jets from liquids, which are too viscous for use in conventional ink-jet printers.

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