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# The ejecta sheet generated by the impact of a drop

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When a drop impacts on a liquid layer it ejects a thin horizontal sheet of liquid, emanating from the neck region connecting the two liquid masses. Dual-frame imaging and pulsed lasers are used to study the origin, speed and evolution of this ejecta sheet for a range of viscosities. The initial ejecta speed can be more than 10 times the impact velocity of the drop. Visualizations using fluorescent dye show the sheet originating from the underlying liquid layer, not the drop liquid. The sheet undergoes a characteristic instability, bending out of its plane and hitting the bottom layer. For some impact conditions the sheet folds in on itself.

## 1. Introduction

Drops impacting onto liquid layers are ubiquitous in nature and technology. Various facets of this fascinating phenomenon have been studied for more than a century starting with the spark observations of Worthington (1876, 1907, 1908). The generation of secondary droplets during drop impacts is of considerable technical interest, e.g. regarding the uniformity of spray coatings, the dispersion of contaminants, the efficiency of fuel injectors, fidelity of inkjet printing etc. Recent reviews include those of Rein (1993), Prosperetti & Oguz (1993) and Frohn & Roth (2000).

Here, we report the first experimental observations of an intriguing aspect of the impact process, i.e. a thin axisymmetric ejecta sheet which arises during the earliest stages of the impact. The sheet is ejected horizontally at high speeds and can evolve into *intriguing* shapes during the first milli-second from the initial contact. Such sheets are important for the study of splashes, as they can generate fast-moving small droplets, which can travel far. Figure 1 shows a typical ejecta sheet as it emerges in the neck region between the drop and the bottom layer. Similar sheets have recently been observed in numerical work by Weiss & Yarin (1999) and Josserand & Zaleski (2000). In the inviscid and axisymmetric numerical simulations the sheet quickly intersects with the bottom layer, never reaching the later evolution observed here in the presence of viscosity.

## 2. Experimental setup

The ejecta sheets were studied using dual-cavity Nd-Yag lasers of 532 nm wavelength (NewWave) and a LaVision imaging system with a dual-frame 1280 × 1024-pixel 12-bit CCD camera. The timing is controlled by the drop blocking a laser-beam/photo-diode setup during its fall, see figure 1($a$). To minimize reflection of laser light from the liquid surfaces, the liquid was dyed using Fluorescein, at a

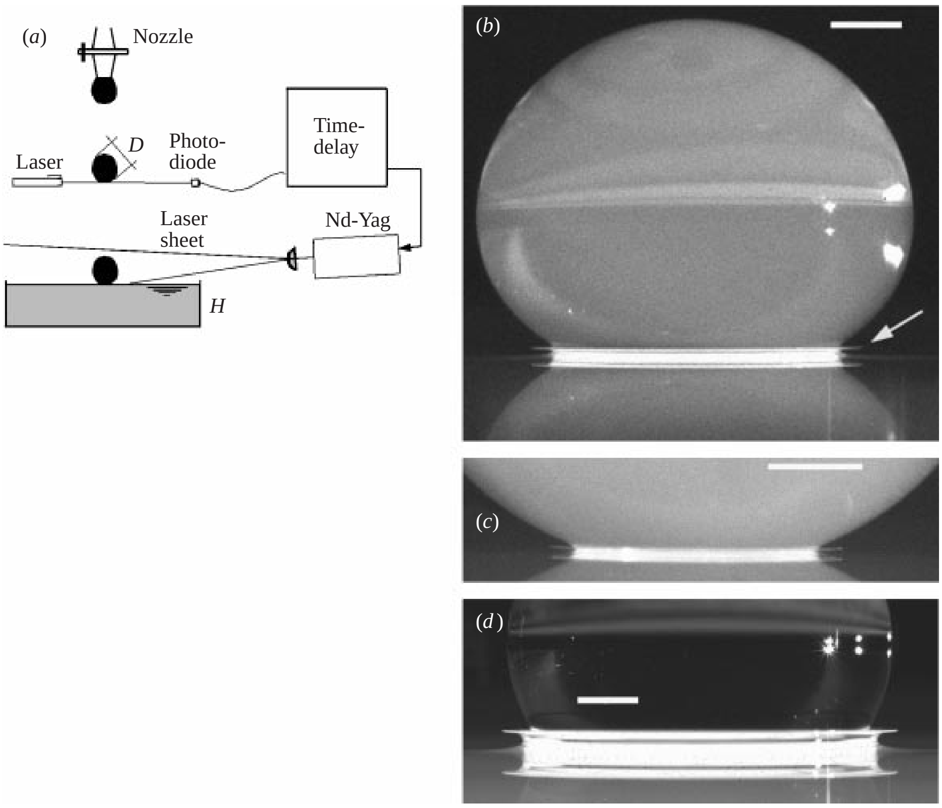


FIGURE 1. Examples of ejecta sheets. (*a*) Sketch showing the experimental setup. The ejecta sheets are shown for the following impact conditions: (*b*) $\mu = 43$ cP, $U = 6.2\,\mathrm{m\,s^{-1}}$ ($Re = 1080$, $We = 4170$), (*c*) $\mu = 7.1$ cP, $U = 4.65\,\mathrm{m\,s^{-1}}$ ($Re = 4640$, $We = 2190$), (*d*) $\mu = 73$ cP, $U = 4.65\,\mathrm{m\,s^{-1}}$ ($Re = 480$, $We = 2370$). The arrow points to the sheet. The lower images in each panel are reflections in the free surface. The scale bars are 1 mm long. The drop liquid in the bottom panel has not been dyed with Fluorescein.

concentration of $70\,\mathrm{mg\,l^{-1}}$ and a narrow-bandpass filter was used on the camera to record only the fluorescence (Thoroddsen & Sakakibara 1998). The filter was centred at 550 nm with a half-maximum transmission bandwidth of $\pm 5$ nm. The drops were generated by a gravity-driven pinch-off from a nozzle, 11 mm ID covered with a fine wire mesh to stabilize the release. The resulting drop diameters $D$ were about 6 mm.

The initial ejecta speeds were measured using the dual images from the CCD camera over a range of viscosities for a fixed impact velocity $U$. The viscosity $\mu$ was varied using different mixtures of water and glycerin (G31-4). The addition of glycerin has a minor effect on the surface tension of water ($\sigma = 73\,\mathrm{dyn\,cm^{-1}}$) reducing it by less than 10%. The impact Weber number $We = \rho D U^2/\sigma \simeq 2350$ is therefore large and kept approximately constant, while the Reynolds number $Re = \rho U D/\mu$ is varied over two orders of magnitude between 350 and 29 000. Figure 1(*b*) shows a higher Weber number case.

The initial contact between the drop and the flat surface occurs extremely fast, which may explain why this ejecta sheet has escaped previous detection. This becomes clear if one considers the geometry of a sphere intersecting a flat surface with an impact velocity $U$. The contact half-angle $\theta_c$ is reached in time $\delta t = R(1 - \cos\theta_c)/U$ from the first contact. For typical values of impact velocity and drop radius $R$, a contact

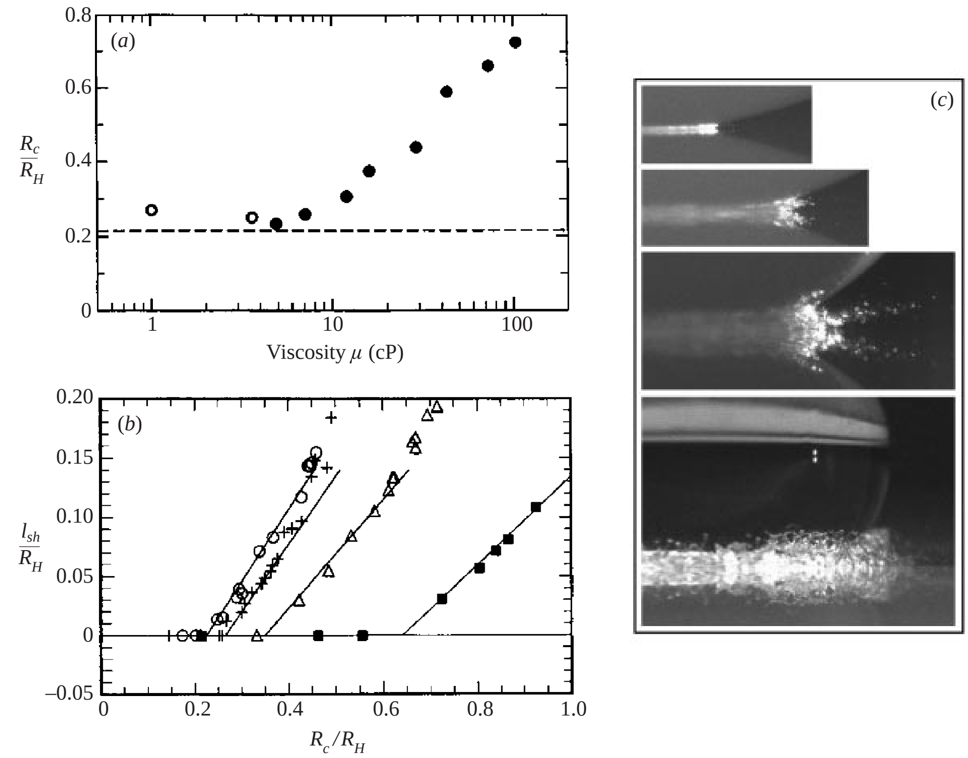


FIGURE 2. The initial emergence of the sheet. ($a$) Normalized contact radius of the drop when the sheet first emerges, plotted against the viscosity, for $U = 4.65\,\mathrm{m\,s^{-1}}$ and $D = 6.3\,\mathrm{mm}$. The broken line represents the result of inviscid numerical simulations by Weiss & Yarin (1999). The open circles indicate emergence of drops. ($b$) Sheet length vs. the radius of the contact of the drop with the underlying layer. Both axes normalized by horizontal drop radius. Results are shown for the following viscosities: 4.9 cP (○), 7.1 cP (+), 16 cP (△) and 73 cP (■). ($c$) Drops emerging from underneath the drop for pure water.

of $\theta_c = 10°$ occurs in $10\,\mu\mathrm{s}$. The triggering mechanism relies on the drop cutting a laser beam (figure 1$a$) The exact blocking of the beam is not repeatable to μs precision, making it necessary to deduce the exact timing from the images themselves. This is done by looking at the height of the top of the drop above the initial liquid level for example. The duration of the laser pulses is however only a few ns and the interval between the two images is precisely controlled by the electronics, giving a very accurate measurement of the sheet velocity. Numerous images are required to catch the sheet as it first emerges.

## 3. Results

### 3.1. *Speed of ejecta sheet*

Figure 2($a$) shows the size of the contact between the drop and the bottom layer, at the instant when the sheet emerges. This is obtained by extrapolating the data of sheet lengths $l_{sh}$ vs. radii of the drop contacts $R_c$ (figure 2$b$). These lengths are normalized by the horizontal radius of the drop at impact $R_H$. The sheet emerges earlier for lower viscosities, converging to a fixed value for the smallest viscosities. This value is in excellent agreement with that of the inviscid calculations by Weiss

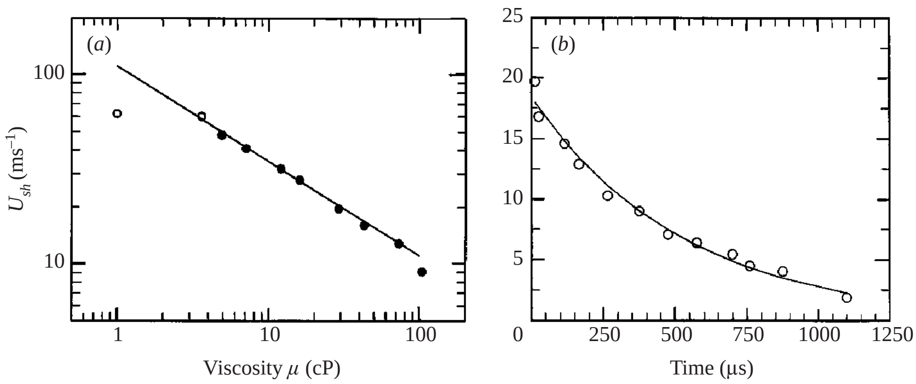


FIGURE 3. Ejecta sheet velocities. ($a$) Initial sheet velocity vs. viscosity, for $U = 4.65\,\mathrm{m\,s^{-1}}$, $D = 6.3\,\mathrm{mm}$. The open symbols represent velocity of droplets, whereas solid symbols show velocity of the tip of the sheet. The solid line has a slope of $-1/2$. ($b$) The deceleration of the radial velocity of the sheet for $\mu = 29\,\mathrm{cP}$.

& Yarin (1999), who obtain 0.215. One should keep in mind that in the numerics there is no air between the drop and the bottom layer. The presence of the air in the experiments does therefore not appear to alter the initial ejection of the sheet. This might be expected as the sheet emerges after the neck region, between drop and bottom layer, has formed.

Figure 3($a$) shows the velocity of the sheet as it emerges, for a range of viscosities. For pure water, the stabilizing effects of viscosity are minimal and no ejecta sheet was observed, only droplets, as shown in figure 2($c$). If an ejecta sheet is present it breaks up too quickly for detection in the present experimental setup.

The initial speed of these droplets is as high as $62\,\mathrm{m\,s^{-1}}$ which is 13.5 times the impact velocity of the drop. The intact sheet is observed at velocities as high as $48\,\mathrm{m\,s^{-1}}$ or 10.4 times the impact velocity. These velocities are significantly higher than have been observed in previous studies of secondary droplets (e.g. Levin & Hobbs 1971; Mundo, Sommerfeld & Tropea 1995; and Cossali, Coghe & Marengo 1997). This is also twice as high as observed in the numerical work by Weiss & Yarin (1999).

The velocity of the intact sheets is found to decrease as viscosity $\mu$ to the $-1/2$ power as shown in figure 3($a$). A simplistic explanation can be constructed. If the sheet thickness $\delta$ increases linearly with $\mu$ and if one assumes that the fraction of the drop energy carried away by the jet $0.5\rho U_j^2 L\delta$ remains constant, then $U_j \propto \mu^{-0.5}$ as observed.

Drops impacting onto smooth solid surfaces generate a thin lamellar jet travelling along the surface. The normalized speeds of these jets, under similar conditions, from experiments (e.g. Chandra & Avedisian 1991 and Thoroddsen & Sakakibara 1998) and inviscid calculations of Harlow & Shannon (1967), are much lower than the present ejecta sheets, for comparable impact conditions. One should keep in mind that at the current impact velocities compressibility plays no significant role in the process, see Lesser & Field (1983).

The ejecta sheets decelerate rapidly owing to the viscous forces induced by the strong radial and azimuthal stretching. Figure 3($b$) shows the radial velocity for one of the higher viscosity cases. Here the sheet has almost stopped expanding after 1 ms. The sheet also bends out of its plane as will be shown below.

One can obtain a rough estimate of the thickness of the ejecta sheet from the

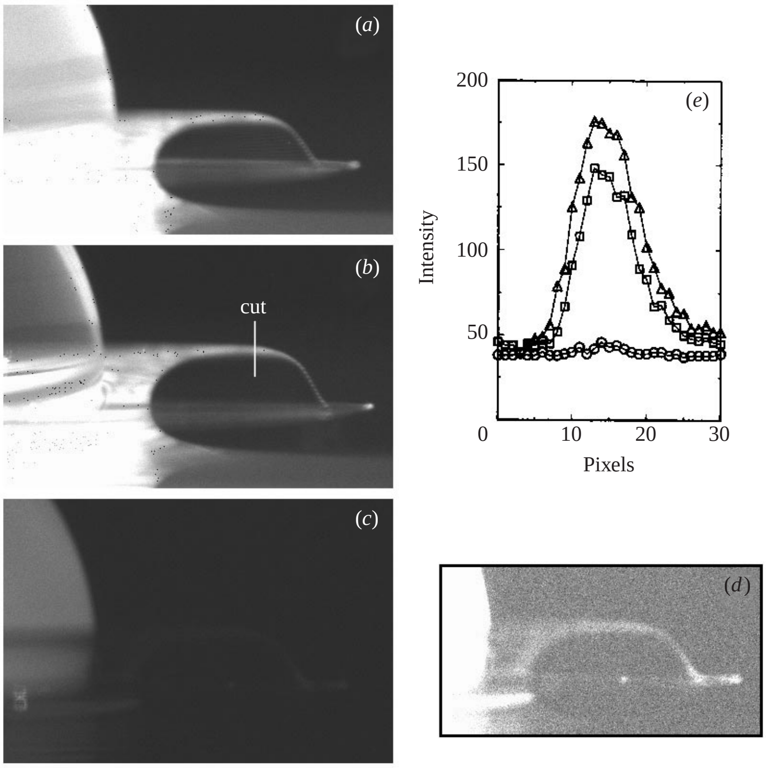


FIGURE 4. The intensity of fluorescence is used to identify the origin of sheet liquid. Impact velocity $U = 5.28\,\mathrm{m\,s^{-1}}$, $H = 6\,\mathrm{mm}$, $D = 6.3\,\mathrm{mm}$, $\mu = 43\,\mathrm{cP}$. Fluorescein in (*a*) both drop and bottom layer, (*b*) bottom layer only, (*c*) in drop liquid only. (*d*) Greatly enhanced section of the image in (*c*), to verify the presence of the sheet. (*e*) The intensities (arbitrary units) along vertical cuts (marked in *b*) through the sheets. The triangles and squares correspond to (*a*) and (*b*) respectively and the circles to (*c*).

images. The thinnest sheets arise for the lower viscosities and appear about 17 μm thick for $\mu = 4.9\,\mathrm{cP}$. This value should be considered an upper bound, due to the edge-on viewing and the thickness of the laser sheet. The inviscid simulations of Weiss & Yarin (1999) give a jet thickness of $10^{-3}D$ if surface tension is neglected ($We = \infty$). For the present drop this would give a thickness of 6 μm. For $We = 1000$ the numerical jet thickens to about 10 μm, which is remarkably close to the experimental results. In the experiments the sheet thickness increases to about 70 μm for the highest viscosity of $\mu = 105\,\mathrm{cP}$.

### 3.2. *Sheet origins*

The origin of the liquid in the sheet was investigated by mixing fluorescent dye into only the drop, only the bottom layer, or both. Figure 4(*a–c*) shows the fluorescent light intensity observed through a green band-pass filter, while using the same laser power and lens aperture. The resulting images show clearly that, without dyeing the underlying liquid layer, the sheet fluorescence all but disappears. This demonstrates that the sheet originates from the liquid in the bottom layer. This was not studied for other impact conditions, but appears to apply at least for the higher viscosities, as is clear in figure 1(*d*).

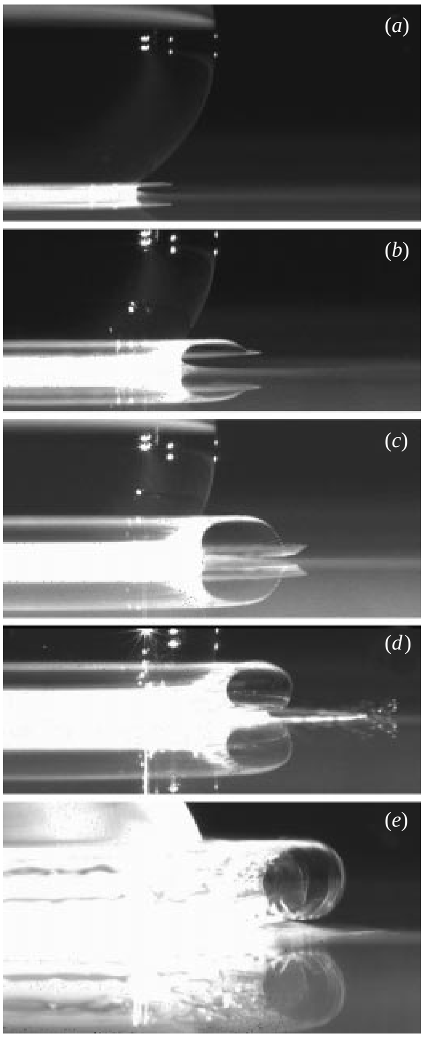


FIGURE 5. Evolution of the ejecta sheet for low viscosity, showing the typical bending of the sheet and impact with the bottom layer, sending off tiny droplets; $\mu = 16\,\mathrm{cP}$, $U = 4.65\,\mathrm{m\,s^{-1}}$ and $D = 6.5\,\mathrm{mm}$. The instants shown are (*a*) 80 μs, (*b*) 150 μs, (*c*) 190 μs, (*d*) 270 μs and (*e*) 480 μs after the initial contact.

### 3.3. *Ejecta shapes*

The ejecta sheet emanates initially very close to horizontally. However, subsequent parts of the sheet are emitted more upwards, forming the characteristic shape shown in figure 5. Conceptually this curved shape can therefore be thought of as arising from pure kinematics, similar to a streakline in unsteady flow. The subsequent dynamics stretch out the sheet and force its edge downwards to hit the free surface sending off a spray of tiny droplets, figure 5(*d*). The edge of the remaining sheet is pulled inwards by the surface tension, impacting onto itself, figure 5(*e*). What remains of the initial sheet is subsequently pulled up by the developing crown. The location where the sheet hits the underlying liquid layer moves closer to the impact axis as the viscosity decreases. The drops observed for the lowest viscosities (figure 2*c*) may therefore arise from the continuing Rayleigh breakup of the rim, or they might arise

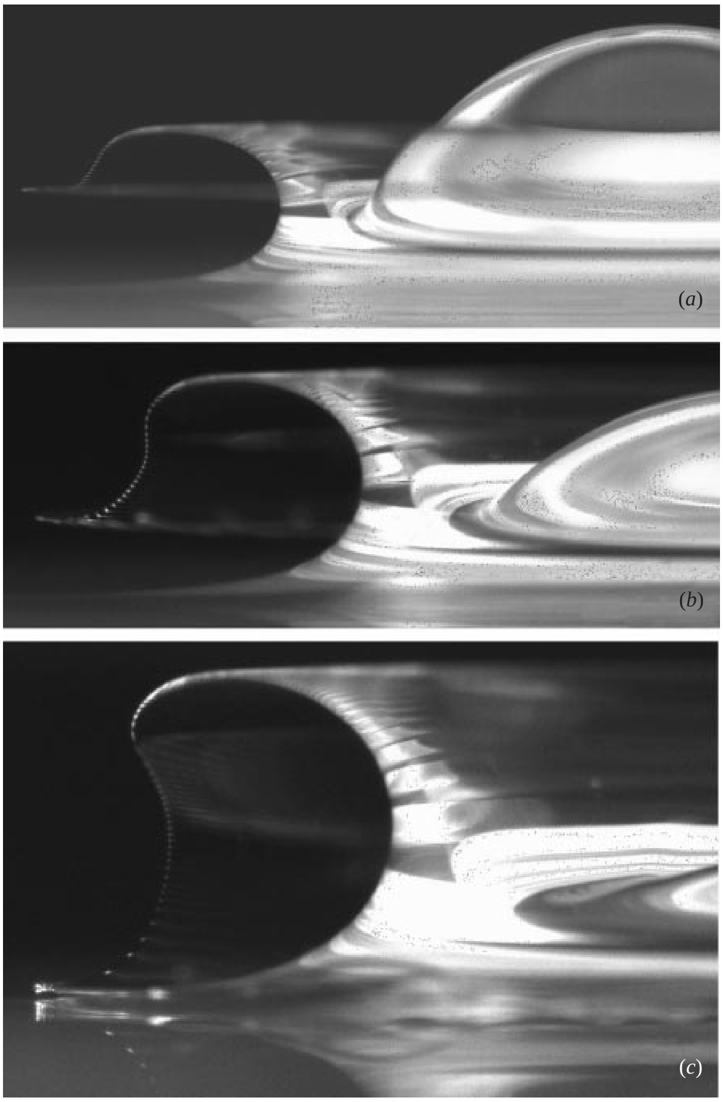


FIGURE 6. Ejecta shapes for $\mu = 43\,\mathrm{cP}$, $U = 5.28\,\mathrm{m\,s^{-1}}$, $D = 6.3\,\mathrm{mm}$, $H = 3\,\mathrm{mm}$, $We = 3340$, $Re = 770$. The three panels have been shifted horizontally w.r.t. each other. The instants shown are (*a*) 0.45 ms, (*b*) 0.65 ms and (*c*) 1.10 ms after the initial contact.

from the sheet hitting the bottom layer. The resolution of the present optical system cannot resolve the sheet initiation for these smallest viscosities, only the emerging drops. The stream of droplets observed in figure 2(*c*) appears to travel at an angle to the bottom layer, suggesting that the drops may have bounced off the two liquid surfaces after their formation. The breakup of a liquid edge subjected to viscosity as well as surface tension is not fully understood and is difficult to simulate numerically, see Yarin & Weiss (1995), Fullana & Zaleski (1999) and Scardovelli & Zaleski (1999).

For the higher viscosities the sheet is more stable and in some cases does not touch the bottom layer until long into the crown formation, figure 6. These curved shapes resemble more a Napoleonic hat than the royal crown immortalized by Edgerton's photographs, see for example Edgerton & Killian (1987).

The bottom layer depth $H$ was about 11 mm in most of the experiments (except figures 4 and 6). This is sufficiently deep ($H/D \simeq 1.7$) that it does not affect the initial dynamics of the sheet. Results for $H/D \simeq 0.5$ and 0.8 are indistinguishable. One concludes that these ejecta sheets are not driven by the presence of the solid boundary.

## 4. Discussion and conclusions

The drop impacts studied here focus on the real physical situation, but were not intended to model the idealized conditions studied in the numerical work by Yarin & Weiss (1999), where the drop is exactly spherical and the liquid is inviscid. Furthermore, there is no air outside the numerical drop. The presence of the air is bound to affect the shape of the drop at initial contact and the evolving sheets. However, the apparent agreement between these numerics and the experiments is remarkably good. This would indicate that the presence of the air is not of fundamental importance for the initial ejection of the sheet. The drop distortions are bound to have some effects on the details of the mechanism, but for these Weber numbers such distortions are unavoidable in experimental work and are certainly present in the physical situations listed in the Introduction.

However, the inviscid numerical simulations of Oguz & Prosperetti (1989) show no ejecta sheet being formed during the impact of two flat surfaces. This suggests that the sheets may be highly sensitive to the geometry outside the initial contact neck region.

In conclusion, we have studied the details of a novel ejecta sheet generated by an impacting drop. Such sheets represent a new mechanism for generating secondary droplets and suggests a repeatable way of studying the dynamics of rapidly stretching thin liquid films subjected to surface tension and viscous forces.

This work was begun while the author was at the University of Illinois. It is dedicated to the memory of Professor Charles W. Van Atta (1934–2001).

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