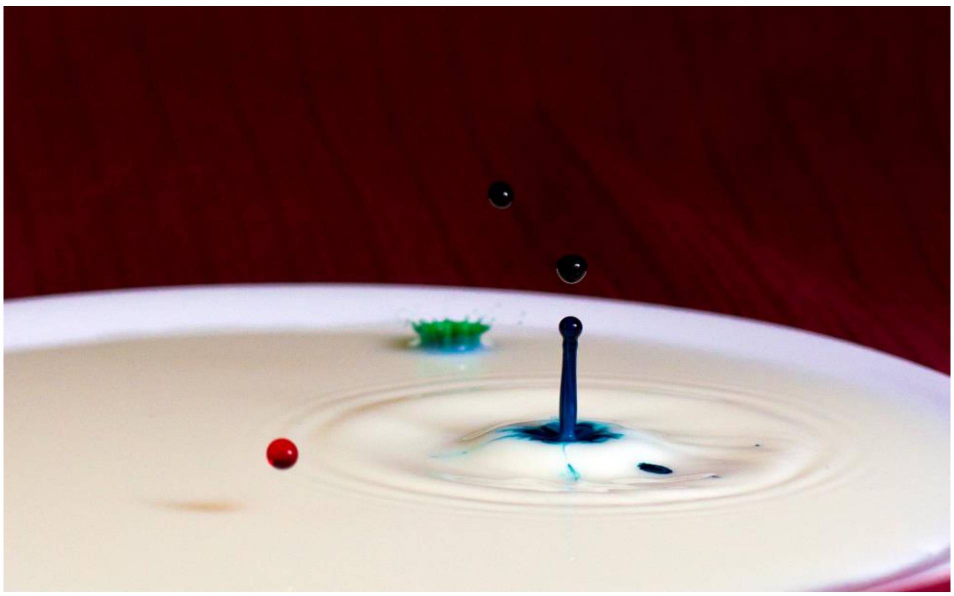
Milk Drops: A Study of Splash Dynamics and Progression



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Context and Purpose

I took this image while working on a series of photographs that explore the dynamics of water drops impacting a shallow milk surface. I wanted to capture as many stages of drop formation as I could in one photograph, and I used the Red, Green, Blue Color Model to further highlight the progression. While the image was taken during a purely experimental session, I wanted the image to have an artistic side as well. Before I took the image, I decided to focus on the elegant simplicity of drop formations, so I tried to use as simple of a background as possible.

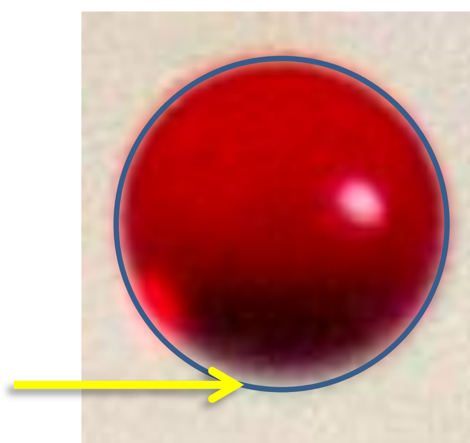
Approach and Flow Explanation

This image features three essential parts in the life cycle of a drop impacting a shallow dish of fluid:

1. Suspension above fluid directly before impact
2. Crown splash directly after drop impact
3. Worthington jet formed upon collapse of impact hemisphere

Drop Suspension and Shape

First, the shape of a drop falling at moderate speed is shown by the red drop. The drop was dropped from a height of 1m, and had an approximate width of 5mm. According to Gunn, Ross, and Kinzer,[1] this drop had a mass of .07 grams, a drag coefficient of .66, and a Reynolds number of 3033 while dropping through stagnant air at terminal velocity.[1] While it appears that the drop is nearly spherical, it has been discovered that water droplets deform slightly as they fall through air. Below, a perfect sphere is overlaid over the cropped and enlarged red drop in Figure 1. The slight deformation is shown with the yellow arrow.



(Figure 1)

Since the drop is not at terminal velocity (.91 m/s for this size droplet),[1] the deformation is very slight, but it is still visible. Dropped from a height 1 meter, the drop is travelling at a speed of approximately 4m/s. The drag force on an undeformed sphere is given by:

$$F = \frac{1}{2}\rho V^2 Sc$$

$$F = \frac{1}{2}\left(1200\frac{\text{kg}}{\text{m}^3}\right)(4^2)(.00007854m^{2)}$$

$$F = 70mN$$

Therefore, the drag force on this droplet is approximately 70 mN, resulting in a small deformation at the bottom of the falling droplet. If the drop was allowed to fall further and gain more speed, the deformation would become much more apparent.[2]

To calculate the distance that the drop covered in the image, a simple calculation can be done:

$$D = Vt$$

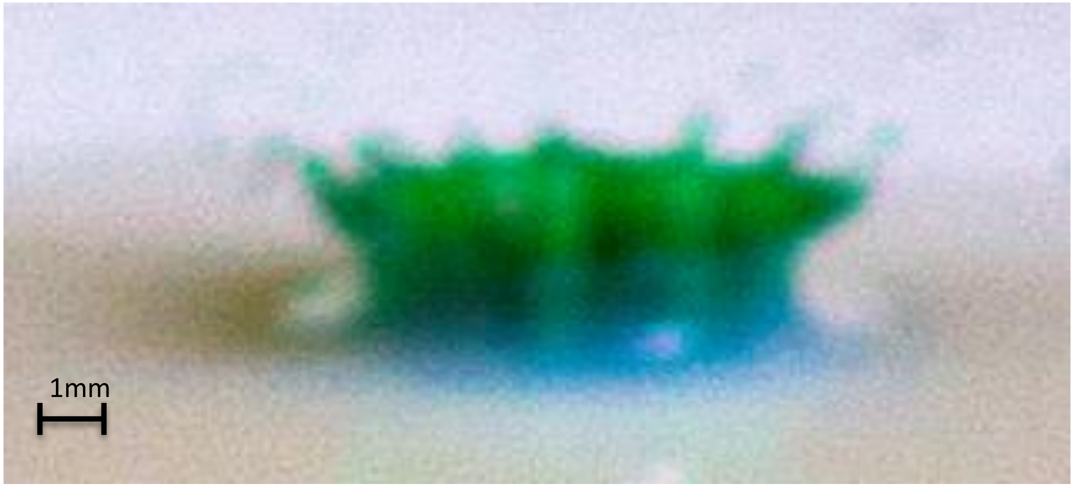
$$D = (4\frac{m}{s})(\frac{1}{10{,}000}s)$$

$$D = .4\ mm$$

Since the flash fires so quickly, this motion is essentially frozen.

Crown Splash Directly After Impact

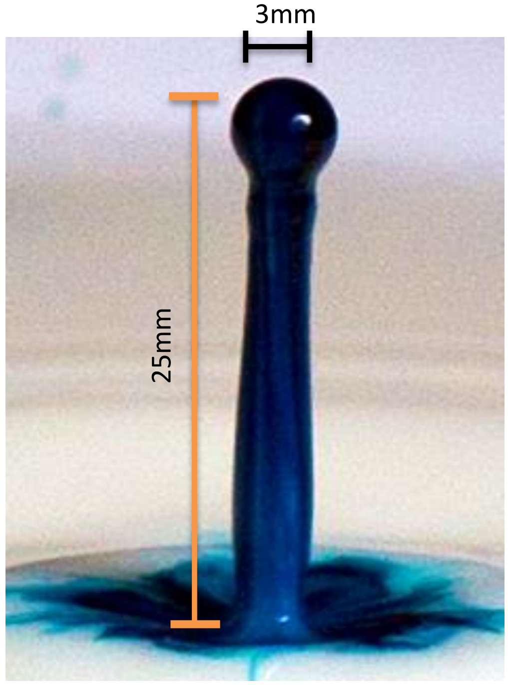
In the center of the image, a crown splash is observed in the background. These thin-walled splashes with corrugated tops take shape about 100μs after initial impact of the drop.[4] As described by Zhang Et al, a uniform thin-walled cylinder rises around the initial impact zone, and then drops begin to separate from the top of the cylinder due to Rayleigh-plateau instability, giving the splash its iconic "crown" shape. The splash observed in this photograph has a corrugation wavelength of ~1mm as seen in Figure 2.



(Figure 2)

Worthington Jet

As summarized by Ogawa et al,[3] a Worthington jet is formed as the hemispherical impact crater of a drop collapses, and fluid is ejected up and away from the surface of the fluid. The gravitational potential energy of this jet can be used to estimate the initial energy that the droplet had before it impacted the water. The size and height of the jet is estimated in Figure 3.



(Figure 3)

The gravitational potential energy of a Worthington jet is given by:[3]

$$Peh = \frac{1}{8}(\pi)(\rho)(g)(D^2)(h^2)$$

It appears that the Worthington jet is comprised mostly of the dyed water, so I will use the density of water in my calculations.

$$Peh = \frac{1}{8}(\pi)(1200\ \mathrm{kg/m^3})(9.8\ m/s^2)((.003m)^2)((.025m)^2)$$

$$Peh = .026\ mJ$$

To calculate the initial kinetic energy of the drop:

$$KE = \frac{1}{2}(\rho)(\mathrm{V})v^2$$

$$KE = \frac{1}{2}(1200\frac{kg}{m^3})(\frac{4}{3}\pi(.0025m^3))4m/s^{\ 2}$$

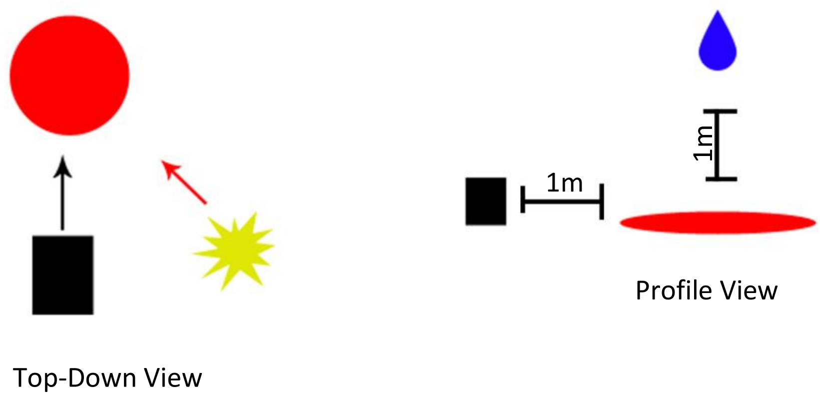
$$KE = \frac{1}{2}(\rho)(\mathrm{V})v^2$$

$$KE = .63\ mJ$$

This large discrepancy between the initial kinetic energy of the droplet and the gravitational potential energy of the Worthington Jet displays just how much energy (~96%) is lost to interactions such as initial splash motion, fluid friction, and surface tension.

Visualization Technique

To obtain this image, water, 2% milk, and food dye was used. The food dye was diluted into the water at a concentration of 15 drops per cup. Milk was poured into the splash plate to a depth of 2cm, and then bubbles in the milk surface were removed with a fork for a smooth surface. The camera was positioned 1 meter away. A single flash diffused with a shoot-through flash umbrella was positioned 45 degrees off axis horizontally from the splash plate – camera axis at 1 meter from the splash plate. The experiment was set up in a dark room so that the image would only be exposed by the flash. A low power setting was used on the flash for a short flash duration, and the flash was remotely triggered from the camera. Philip Latiff held the droppers at a height of 1 meter above the splash plate, and released one drop from each dropper at approximately the same time. Since the formation of splash structures is very fast, it took many images (over 50) to get the three desired splash phenomena in one image. See Figure 4 for a visual representation of the experiment set-up.



(Figure 4)

Photographic Technique

To take this photo, I used an 18 MP Canon T2i DSLR. The lens I used was a 50mm 1.8. To get the drops in focus, I had Philip Latiff hold a fork at the approximate impact distance, and then I used manual focus to get the correct distance in focus. Since I was using such a low power on the flash for a short exposure time, I was required to set my aperture to 4.0. This narrowed my depth of field, which regrettably put the crown splash out of focus. To minimize noise, I set the ISO to 200. The shutter speed I used was the minimum sync speed of my wireless flash controller (1/125s). The original image was 3456 x 5184 px, and was cropped down to 2216 x 1369 px to frame the flow visualization better. I kept post-processing to a minimum. Mainly, contrast was increased to make the splash formations stand out from the milk, and the image was color-corrected to make image as close to real-life as possible. The raw unedited image is shown as image 1 in the appendix.

Conclusion

Overall, I like this final image. Getting all three stages of splash formation took a lot of patience, and I am pleased with the result. The physics I was attempting to portray are very apparent in their simplicity and contrast. If I were to take the image again, I would not use a red backdrop, and I would increase the aperture so that the splashes further back in the splash plate were in sharper focus. Also, I would like to construct a laser trigger system and an automated drop system to dial in the time at which the picture is taken.

Works Cited

1 Gunn, Ross, and Gilbert D. Kinzer. "The terminal velocity of fall for water droplets in stagnant air." *Journal of Meteorology* 6.4 (1949): 243-248.

2 Magono, Chiji. "On the shape of water drops falling in stagnant air." *Journal of Meteorology* 11.1 (1954): 77-79.

3 Ogawa, Akira, et al. "Morphological study of cavity and Worthington jet formations for newtonian and non-newtonian liquids." *Particulate science and technology* 24.2 (2006): 181-225.

4 Zhang, Li V., et al. "Wavelength selection in the crown splash." *Physics of Fluids (1994-present)* 22.12 (2010): 122105.

Appendix

(Image 1)