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# Lateral jetting during off-center drop collisions on substrates

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ABSTRACT

In this work, we experimentally study the behavior of a sessile water drop impacted by another drop of water using a bottom-up viewing configuration and optically clear substrates. By varying the Weber number and the center-line impact offset distance, a variety of regimes based on the post-impact geometry are observed. A pair of side lobes/jets extending more than twice the maximum spread of the impacting drop are found to form at low to moderate Weber number at an offset distance close to three-quarter the combined radii of the two initial drops. The onset of these jets is probed further with a high-speed imaging study showing slender jets issue from the impacting drops ~0.25 ms after impact at a velocity an order of magnitude greater than the impact velocity.



## 1. Introduction

The behavior of liquid drops has been studied extensively due to their relevance in biological, heat transfer, manufacturing, microfluidics, and other systems. More specifically, studies of drop impacts have provided fundamental understanding important in applications such as inkjet printing [1], disease transmission among animals [2] or plants [3], fire propagation and control [4], internal combustion [5], and rain driven erosion of soils [6]. Drop impact studies can be partially characterized based on the target media, its geometry, and its interaction with the falling fluid. The target can be a rigid or compliant solid substrate, a liquid film, a deep liquid pool, or a geometry that seeks to tune a specific response. Almost every drop impact configuration is observed to move from a regime described by coalescence, spreading, or bouncing to more nonlinear and chaotic behaviors such as rim destabilization, splashing, or fragmentation into smaller droplets [7].

Due to the plethora of applications involving drop impact, along with their importance to the field of fluid dynamics, a multitude of experimental, numerical, and theoretical drop impact studies have been performed beginning with the photographic studies undertaken by Worthington on flat plates (1876) and deep liquid pools (1882) [8,9]. These studies have evolved with advances in cameras, surface coatings, and other technologies as evidenced by reviews written over the past few decades; Rein in 1993 [10], Yarin in 2006 [7], and Josserand and Thoroddsen most recently in 2016 [11]. The literature has focused on studies utilizing water or water-based solutions because of the large capillary length scale compared to many other fluids the myriad of coatings ranging in wettability from super-hydrophilic to super hydrophobic [12]. Fluids varying from hydrocarbon fuels [13] to liquid metals [14] have also been studied, in addition to detailed studies determining the influence of wettability, surface roughness, impact velocity, and fluid properties on impact behavior [7,11,15].

A limited number of studies have examined the concentric impact of a falling drop with a liquid volume on a substrate. For example, Fujimoto et al. [16] and Nikolopoulos et al. [17] investigated the concentric impact of drops with low-contact angle sessile drops, exhibiting similar physics to drop impacts with thin liquid films. Similarly, few studies have observed the interactions between off-center impacting falling and sessile drops. Gilet and Bourouiba investigated the behavior of offset impacting drops (terminal velocity) on plant leaves and analogous surfaces. Distinct sessile drops are commonly observed on plant foliage, rather than fluid films, and a crescent-moon splash is observed when a falling drop impacts near the sessile drop. The crescent-moon splash is characterized by the lamella of the impacting drop pushing beneath the sessile drop and ejecting some or all of the sessile drop fluid away from the substrate with significant horizontal velocity. The crescent-moon splash phenomenon is hypothesized to play a role in pathogen dispersal [18].

Collisions of droplets in mid-air, both concentric and eccentric, have been studied for a variety of fluids with experimental and numerical techniques. The review of Orme [19], summarizes the experimental work on interaction of two parcels of liquid in a variety of applications focused on combustion technology. The binary collisions of unconstrained droplets are sorted into characteristic

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regimes: coalescence, bouncing, reflexive separation, and stretching separation based on *We* and offset distance well summarized by Brenn [20]. The introduction of a solid surface to the eccentric droplet impact problem alters the system response significantly.

In this study, we focus on the interaction of a falling drop with another equal volume sessile drop on a substrate at offset distances ranging from zero (concentric impact) to a distance where the contact line of the sessile drop remains outside the maximum spreading diameter of the impacting drop. We look to characterize the multiple post-impact interactions of falling and sessile drops, where the drops are of equal volume and the interactions take place on polymethyl methacrylate/acrylic (hydrophilic) and coated glass (hydrophobic) substrates. Experiments are carried out to investigate the influence of impact offset distance for the two drops and impact velocity (Weber number). Our optical setup uses a clear substrate with a bottom-up view of the drop impact for quantification of the formation of side lobes that are not well resolved in side-view studies. The present study also quantifies the movement of the contact line of the sessile drop in the direction opposite the impact. In order to probe the onset of these events, we begin in a low-inertia range defined by coalescence and increase the velocity of the falling drop until these behaviors are readily observed. To our knowledge, a study mapping these regimes of this drop-drop collision configuration has not been previously reported.

In the present study of impacting liquid drops, the Weber number ($We = \rho U^2 D/\sigma$) is introduced to relate the inertia of the falling drop to its surface tension force; where $\rho$ is the density, U the velocity of the drop, D the diameter of the drop, and $\sigma$ is the surface tension of the gas/liquid interface. The water drops studied here ($\rho$ = 1000 kg/m$^3$) and $\sigma$ = 72 mN/m) are of the same constant volume from trial to trial, so *We* parameterizes the square root of the impact velocity. Additionally, the Reynolds number ($Re = \rho UD/\mu$) is used as a relative measure of the inertial and viscous forces, where $\mu$ is the dynamic viscosity of water ($\mu$ = 0.95 mPas). The Ohnesorge number ($Oh = \mu/(\sigma\rho D)^{1/2}$ or $We^{1/2}/Re$) describes the ratio of viscosity and surface tension forces, and is very small and constant throughout the present study ($Oh$ = 0.0021), indicating that capillary effects dominate over viscous effects and that jetting is a possibility. Typically, *We* and *Re* are used in concert to describe the spectrum of responses observed in drop impact studies. Increases in these parameters will generally lead to an increase in and progression to subsequent, more nonlinear responses including: spreading, rim destabilization, crown formation, and splashing [7,11]. In the present study, *We* is limited to a range where spreading is observed but splashing and fracturing are not. The volumes of the falling and sessile drop (equal) are sufficiently small such that the drop shapes are close to spherical or a spherical section, respectively, and the Bond number ($Bo = \Delta\rho g D^2/\sigma$), where g is gravitational acceleration) is close to unity.

## 2. Experimental method

A schematic of the present drop-drop impact experiment is shown in Fig. 1. A syringe pump (New Era NE-300) holding a syringe with removable blunt stainless steel needle (Hamilton Gastight Model 1001, 1 mL; point style 3, 22 gauge) was used to generate drops of a consistent size. The syringe pump was fastened to a breadboard on an adjustable post system. In order to observe the drop impacts from beneath the substrate, an optically transparent substrate (glass or acrylic) was clamped to an adjustable lab jack, with two mirrors to direct light from a halogen light source through the substrate and into the camera. The high-speed camera (MotionPro X3) and lens (AF-S Micro Nikkor 40 mm) typically captured the back-lit events at 1000 frames per second, at 1280 × 1024 resolution, and an exposure time of 2.6 μs. A series of images (Fig. 8) presented are acquired at 10,000 frames per second with a significantly cropped window (1280 × 104). A function generator (Agilent 33220A) was used to trigger the camera. The experiments were performed on a substantial optical table isolated from mechanical vibration, during periods of minimal lab activity, and away from air currents that could contribute to additional experimental uncertainty. The typical lab temperature was 23 °C ± 1.5 °C with a low relative humidity (<20%) and controlled using building HVAC. The syringes, lab glassware, and substrates were washed and sonicated in detergent solution, thoroughly rinsed with water, and finally triple-rinsed with each of the following: acetone (Fisher, ACS grade), isopropyl alcohol (Fisher, ACS grade), methanol (Sigma-Aldrich, CHROMASOLV® for HPLC grade), and deionized water (Evoqua deionizer). The substrates were either clean acrylic or glass microscope slides coated in commercially available water-repellant Rain-X® which leads to an optically transparent substrate with a contact angle with water in air ($\gamma \sim 98°$) reasonably similar to Teflon™, a well-studied material in the drop impact and fluids literature. Due to chemical compatibility concerns, acrylic surfaces were never rinsed with acetone. The acrylic and coated-glass substrates will be referred to as hydrophilic ($\gamma \sim 72°$) and hydrophobic ($\gamma \sim 98°$), respectively, throughout.

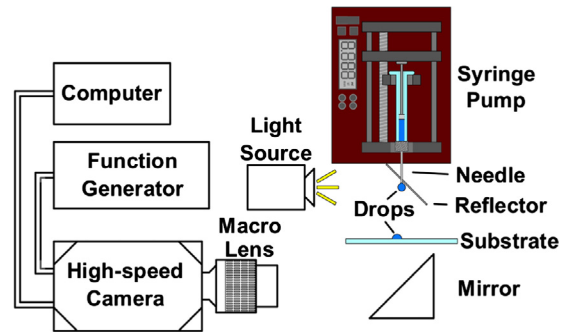


**Fig. 1.** Schematic of backlit bottom-up viewing configuration for drop impact study.

Deionized water (same used for cleaning) was used to create the sessile and falling drops. Sessile drops were placed with the needle very close to the substrate to minimize any inertia dependent hysteresis in the sessile drop shape. Once the sessile drop was placed, the substrate could carefully be moved using a linear stage to provide a horizontal offset distance for the collision between the falling drop and substrate and/or sessile drop. This distance was measured post-experiment by comparing the drop center points in the camera images at the moment of impact. Drops were generated at a flow rate of 0.2 mL/min on the tip of the needle at a prescribed height above the substrate until gravitational forces caused them to detach and fall towards the substrate. The average drop diameter generated was 2.92 ± 0.02 mm. Fig. 2 shows a photograph and schematic slightly before an impacting drop contacts the substrate. The center-line path of the drop falling at velocity, V, (measured with the same high-speed camera in a side-view configuration, without the reflector/mirror) is separated from the center of the sessile drop by an offset distance, L. The density is represented with $\rho$, surface tension, $\sigma$, and static contact angle, $\gamma$, for the liquid on each of the substrates. The diameter, $D_{i,init}$ (measured at the widest portion, not necessarily the contact patch for hydrophobic substrates), with the falling and sessile drops designated by I = 1 or I = 2, respectively. A measurement representing the time-evolving impact length scale, $D_2$, is the lamella spread diameter of the same water drop impacting a clean, dry substrate. This arrangement allows $D_2$ to remain manageable and constant across both large offset distances and those approaching zero