# THE ROLE OF AIR IN THE DYNAMICS OF DROPLET IMPACT

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*Summary* We use novel imaging techniques to show that when a drop of liquid impacts a surface a very thin film of air, only a few tens of nanometers thick, remains trapped between the falling drop and the surface as the fluid spreads. The thin film of air serves to lubricate the drop enabling the fluid to skate laterally outward at strikingly high velocities. The ultimate wetting of the surface occurs through the breakup of the thin film of air at multiple, discrete locations and drives an anomalously rapid spreading of the wetting front.

The initiation of contact between an impacting drop of wetting fluid and a surface is traditionally considered to be quite simple and well understood: For a drop that is brought into contact at a slow, quasi-static rate, contact initiates at a point cantered on the impact axis, and the liquid then spreads laterally to coat the surface uniformly. The rate at which the contact line spreads is initially determined by the balance between the inertia of the liquid and the surface tension of the interface[1-3]. Since the dynamics of this approach are governed by inertia, one might naively sustain this picture when the approach velocity is increased; however, this picture does not take into account the role that the surrounding air plays in the impact dynamics. Before a liquid drop can make contact with the surface, it must first drain the interstitial air. Indeed, experiments have shown that the air may have a dominant role in the dynamics of droplet impact, acting as a buffer layer to the drop as at early times the liquid spreads above the solid surface[4]. Other experiments have shown that at the more advanced stages, as a sheet is ejected from the spreading lamella to form a splash, air bubbles are trapped when the advancing contact line coalesces with wetted patches formed underneath the sheet[5, 6]. In addition, recent experimental studies showed that reducing the ambient pressure suppresses splashing altogether, underscoring the importance of the air[7, 8]. Theoretical calculations suggest that, even at moderate impact velocities, the air fails to drain and is instead compressed, deforming and flattening the bottom of the drop while serving as a thin cushion, only a few tens of nanometers thick, to lubricate the spread of the drop[9, 10], and leading to the eventual formation of a trapped bubble of air within the drop[4]. However, the initial stages of impact occur over diminutive length scales and fleeting time scales, and the very existence of this thin film of air remains controversial[11]; indeed, until recently[12] this film had never been directly observed. Moreover, the mechanisms leading to the breakup of this film and the ultimate wetting of the surface have never even been considered.

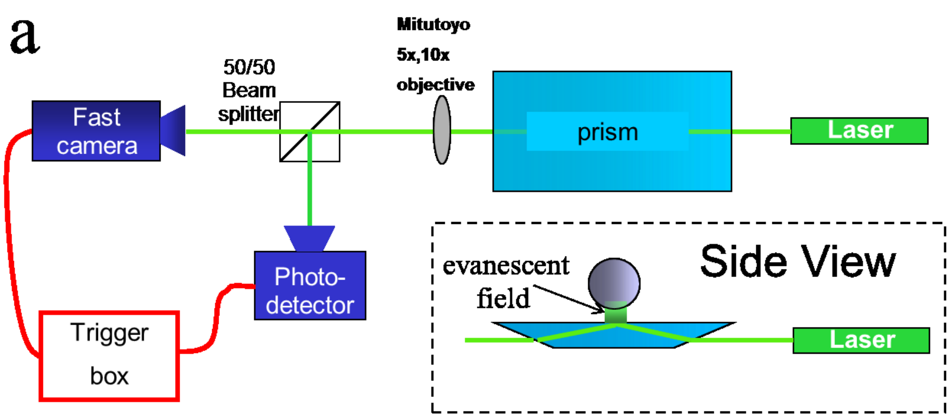


**Figure 1:Schematic of the reflectance-mode Total Internal Reflection (TIR) microscopy setup. Light from a mono-chromatic source enters the prism, totally reflecting off of the interior upper surface. Upon exiting the prism, the light passes through an objective, and**

In order to directly observe the interface between the liquid and the solid, we use a high speed camera together with Total Internal Reflection (TIR) Microscopy to image the dynamics of the impact event as they unfold. Our experimental setup is schematically illustrated in figure 1. To observe the thin film of air, we illuminate the top surface of a dove prism with a collimated laser light source at an angle of incidence greater than the angle for total internal reflection (TIR) of the glass-air interface and lesser than the angle of total internal reflection of the glass-liquid (IPA) interface; thus, an evanescent field forms above the reflecting surface. The evanescent field decays exponentially with a

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characteristic decay length of ~100 nm. As the droplet enters the evanescent field, less light is reflected. The reflected light is recorded on the camera's imaging sensor after it reflects off of the top surface of the prism, resulting in a point-wise intensity measurement, *I(x; y; t)*. Therefore a liquid drop at immediate proximity to the surface appears as a grey scale on the camera's imaging sensor (see bottom left panel of figure 2). This technic directly probes the thin layer of air.

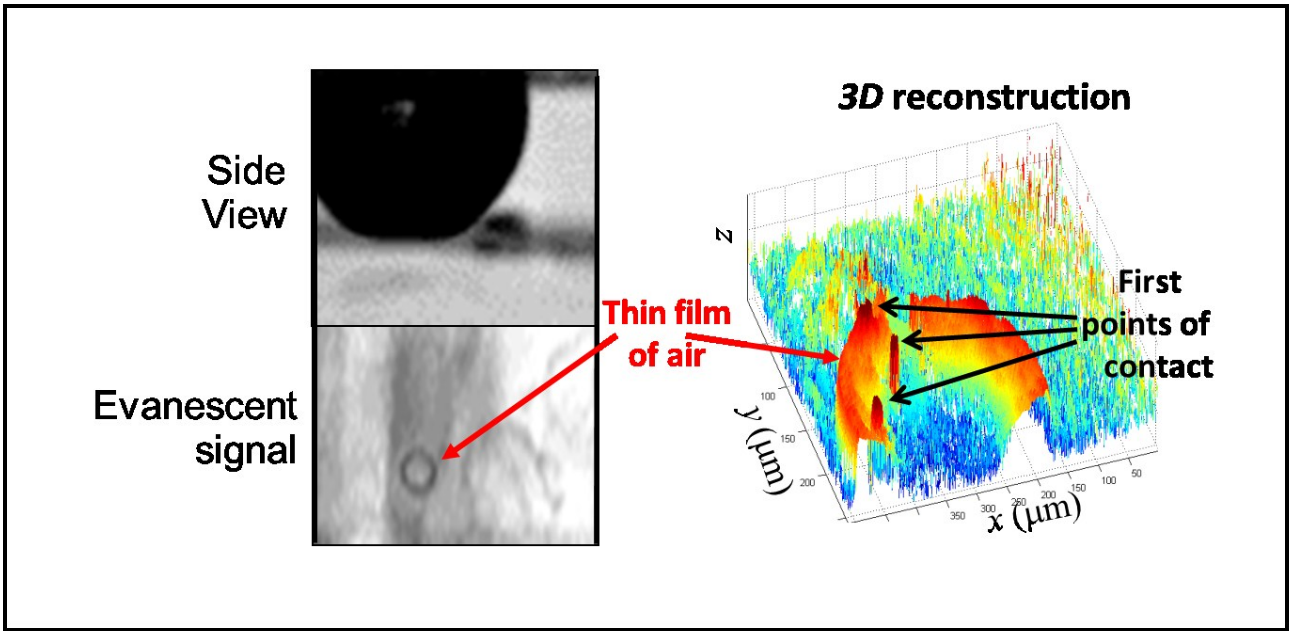


**Figure 2: Rapid Total Internal Reflection (TIR) Microscopy is used to study the impact of a liquid drop on a flat, dry surface. The bottom of the drop is deformed by the compressed air underneath it to form a ring of liquid above a thin film of air. The falling drop and formation of the ring are shown on the top left and bottom left respectfully. For contact to finally occur the liquid must first break through the thin film of air; this occurs as the surface of this ring rapidly becomes unstable and forms fingers that contact the surface at discreet location. A snapshot from this proses is seen in the 3D reconstruction of the TIR single on the left.**

Using TIR we show that the impact of a drop on a surface is a much richer, more complex phenomenon than our simple experience suggests: To completely wet the surface the drop must first expel all the air beneath it; however, this does not happened instantaneously. Instead, a very thin film of air, only a few tens of nanometers thick, remains trapped between the falling drop and the surface as the fluid spreads. The thin film of air serves to lubricate the drop enabling the fluid to skate laterally outward at strikingly high velocities that may be as high as 100m/sec[12]. Simultaneously, the wetting fluid spreads inward at a much slower,~1 m/sec, velocity, trapping a bubble of air within the drop. Our measurements also reveal that the ultimate wetting of the surface occurs through a completely new mechanism, the breakup of the thin film of air at discrete locations, as shown on the right panel of figure 2. The formation of multiple contact points which than rapidly spread and coalesce, drives an anomalously rapid spreading of an extended wetting front. These results are in accord with recent theoretical predictions[9, 10] and challenge the prevailing paradigm in which contact between the liquid and solid occurs immediately, and spreading is dominated by the dynamics of a single contact line.

## References


**[1] J. C. Bird, S. Mandre, and H. A. Stone, Physical review letters 100 (2008) 234501.**

**[2] L. Courbin, J. C. Bird, M. Reyssat, and H. A. Stone, Journal of Physics: Condensed Matter 21 (2009) 464127**

**[3] P. G. Degennes, Reviews of Modern Physics 57 (1985) 827.**

**[4] S. Thoroddsen, T. Etoh, K. Takehara, N. Ootsuka, and Y. Hatsuki, Journal of Fluid Mechanics 545 (2005) 203.**

**[5] S. T. Thoroddsen, K. Takehara, and T. G. Etoh, Physics of Fluids 22 (2010)**

**[6] M. M. Driscoll, C. S. Stevens, and S. R. Nagel, Physical Review E 82 (2010) 036302.**

**[7] L. Xu, L. Barcos, and S. R. Nagel, Physical Review E 76 (2007) 066311.**

**[8] L. Xu, W. W. Zhang, and S. R. Nagel, Physical review letters 94 (2005) 184505.**

**[9] S. Mandre, M. Mani, and M. P. Brenner, Physical review letters 102 (2009) 134502.**

**[10] M. Mani, S. Mandre, and M. P. Brenner, J. Fluid Mech 647 (2010) 163.**

**[11] M. M. Driscoll and S. R. Nagel, Physical review letters 107 (2011) 154502.**

**[12] J. M. Kolinski, S. M. Rubinstein, S. Mandre, M. P. Brenner, D. A. Weitz, and L. Mahadevan, Arxiv preprint arXiv:1110.3351 (2011)**