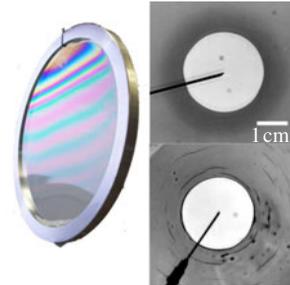


Cracks in bursting soap films

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The rupture of soap films is traditionally described by a law accounting for a balance between momentum and surface tension forces, derived independently by Taylor and Culick in the 1960s. This law is highly relevant to the dynamics of thin liquid films of jets when viscous effects are negligible. However, the minute amounts of surfactant molecules present in soap films play a major role in interfacial rheology, and may result in complex behaviour. Petit *et al.* (*J. Fluid Mech.*, vol. 774, 2015, R3) challenge standard thin film dynamics via intriguing experiments conducted with highly elastic surfactants. Unexpected structures reminiscent of faults are observed.

Key words: breakup/coalescence, foams, thin films

1. Introduction: all is but soap bubbles

As an elegant conclusion to his Nobel Lecture on soft matter, de Gennes (1997) quoted the text from an engraving of a lady blowing soap bubbles, after a painting by François Boucher. The engraving illustrates the fragility of worldly ambition, but the properties of ephemeral soap bubbles have fascinated scientists for centuries. Standard expressions such as ‘Newton black films’ or ‘Plateau borders’ reference classical works on optical interferences or on the intersection of soap films, respectively. Soap bubbles are also a great subject for popular science, as beautifully illustrated by Boys (1958). The rupture of soap films intrigued Marangoni, Stefanelli & Liceo (1872), who pioneered quantitative experiments despite a lack of sophisticated imaging technology. Indeed, the first recording of the rupture of a soap bubble was later achieved by Jules-Étienne Marey and Lucien Bull, who ingeniously converted a machine gun into a fast camera. The seminal work by Mysels (1959) later provided the basis for modern studies of soap films. Broad scientific activity in the field was then motivated by numerous applications involving foams (Cantat *et al.* 2013), the production of spray over the oceans (Bird *et al.* 2010; Lhuissier & Villermaux 2012), beautiful convective plumes (Couder, Chomaz & Rabaud 1989), two-dimensional water tunnels (Zhang *et al.* 2000), and even laboratory models of hurricanes (Meuel *et al.* 2013).

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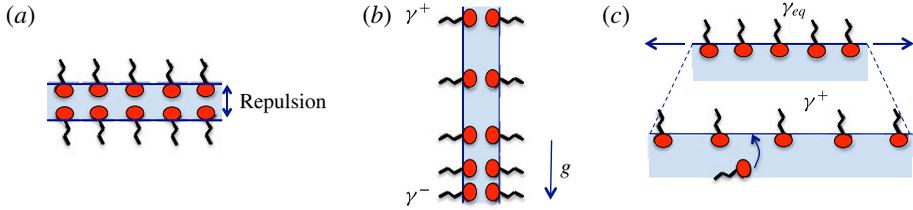


FIGURE 1. As well as decreasing the surface tension of water by an amount related to their surface concentration, surfactant molecules induce other important effects. (a) The repulsion between facing hydrophilic heads (e.g. due to electrostatic effects) tends to limit the thinning of the film. (b) Gradients in surface concentration result in gradients in surface tension that can compensate for the weight of the film of liquid. (c) A sudden increase in the interfacial area reduces the surface concentration, which results in an increase in surface tension referred to as surface elasticity. In the common case of soluble surfactants, molecules diffuse from the bulk to the interface and eventually compensate for the initial depletion. Surface viscosity can be inferred from the corresponding time scale.

2. Overview: bursting dynamics

Children discover with frustration how soap bubbles tend to disintegrate when touched. Surprisingly, projectiles may nevertheless pass through soap films, or even bounce back without much damage (Le Goff *et al.* 2008; Gilet & Bush 2009). However, once a hole of the scale of the thickness of the film is nucleated, the film is doomed. As a first approximation, a soap film may be described as a thin liquid sheet of constant surface tension. Within this limit, we expect the dynamics to follow the same rules as the water sheets or bells studied by Savart, Boussinesq and Rayleigh. A balance between surface tension forces and the inertia of the displaced liquid leads to a constant Taylor–Culick velocity, $V_c = \sqrt{2\gamma/\rho h_0}$, where γ and ρ are the surface tension and the density of the liquid, respectively, and h_0 is the thickness of the film (Rio & Bianco 2014).

Our childhood experience teaches us that the addition of minute quantities of soap provides fragile bubbles with some stability. The added surfactant molecules have antagonist extremities: one end is hydrophilic (e.g. an ionic head), while the other is hydrophobic (e.g. a hydrocarbon chain). Due to their amphiphilic properties, these molecules tend to be absorbed by water/oil or water/air interfaces. Once at the interface, they behave like a two-dimensional gas, which results in surface pressure. As a consequence, the measured surface tension decreases. Typically, accounting for the modification in surface tension is sufficient to describe the rupture of soap films. However, the effects of surfactant molecules are far more subtle than a simple change in surface tension. As illustrated in figure 1, the presence of surfactant limits the thinning of the film and provides a pulling force that balances the weight of the liquid. In addition, surfactant molecules induce spring-like behaviour in the interface. If the interfacial area is stretched, the surface concentration of surfactant molecules decreases and the surface tension rises (conversely, the surface tension decreases if the interface is compressed). This effect is rationalized in terms of surface elasticity, $E = 1/A(\partial\gamma/\partial A)$. If the surfactant molecules are soluble, they progressively diffuse towards (or away from) the interface, and the surface tension eventually recovers its initial value γ_{eq} after a step deformation, depending on their solubilities and associated time scales. Surfactants thus induce a complex and nonlinear interfacial rheology with an important impact in foam processing (Fuller & Vermant 2012).

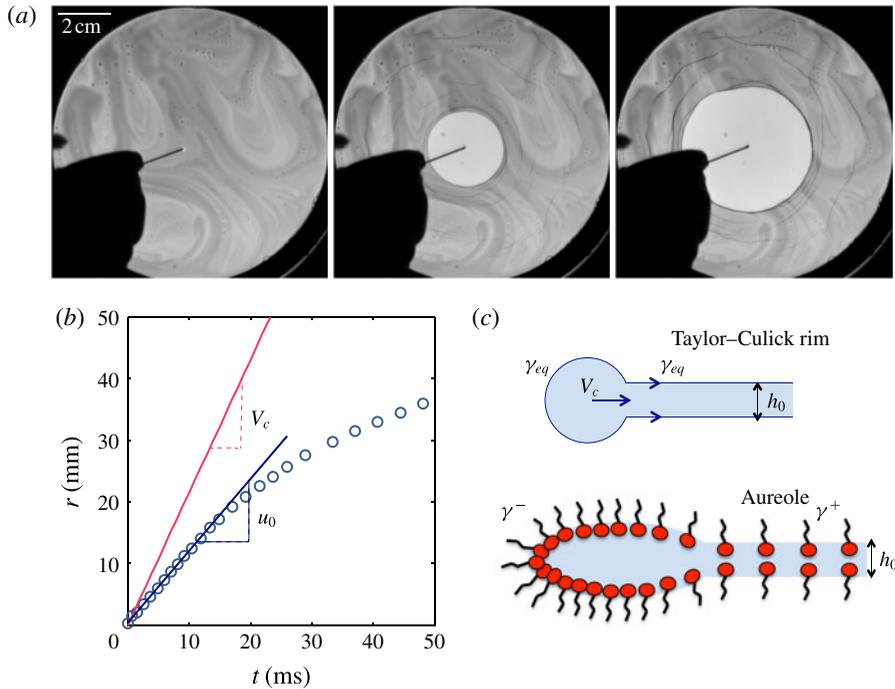


FIGURE 2. (a) Image sequence of the rupture of an elastic soap film. The interval between images is 15 ms. Circular patterns reminiscent of faults appear beyond a critical radius of the hole. (b) The radius of the hole as a function of time. The opening velocity u_0 (blue line) is initially constant but significantly deviates from Taylor–Culick velocity V_c (red line). (c) In Taylor and Culick’s description, the liquid removed from the hole accumulates in a rim of circular section. Conversely, an aureole shape is observed in the present situation. The circular patterns appear as the front of the aureole reaches the frame supporting the film. From Petit, Le Merrer & Bianco (2015).

In their recent experiments using solutions with strong surface elasticity, Petit *et al.* (2015) explored the role of surface rheology in the bursting dynamics of soap films. In the typical experiment presented in figure 2, the opening velocity u_0 is initially constant, as expected but its amplitude is significantly lower than predicted by Taylor & Culick. Following Frankel & Mysels (1969), the authors interpret this deviation as an effect of surface elasticity and show that their experimental data can be represented in a universal plot $u_0/V_c = f(E_0/\gamma_{eq})$, which is determined numerically. As well as the dynamics, the profile of the opening rim is also very peculiar. Contrary to Taylor and Culick’s description, where the liquid from the opening hole is collected in a circular rim, ‘aureole’ patterns are observed in the present experiments. Surfactant molecules accumulate in the inner part of the rim and induce a gradient of surface tension along the rim. Consequently, the profile of the rim becomes more elongated as the hole propagates. Intriguing circular patterns are finally observed when the front of the aureole reaches the rigid frame holding the film. Are they cracks, faults or buckles? While their exact nature remains a mystery, their origin probably relies on radial compressive strains of the soap film.

3. Future: towards interfacial rheology?

The intriguing patterns observed in the recent study by Petit *et al.* should motivate further investigations combining traditional fluid mechanics with the tools from thin sheet mechanics. These patterns may indeed be reminiscent of the localized folds observed in floating sheets under compression by Pociavsek *et al.* (2008). As well as exciting physics, this study also opens up interesting applications in interfacial rheology. Indeed, the short time scales involved in the rupture of a soap film (typically a few milliseconds) promote elastic effects under high strains. The simple observation of bursting soap films may thus lead to innovative video-rheology techniques, as has been proposed for liquid droplets impacting small targets (Rozhkov, Prunet-Foch & Vignes-Adler 2010). As a recent very interesting example, Timounay, Lorenceau & Rouyer (2015) have studied the opening of soap films laden with solid particles.

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