The bubble bursts

1989 Phys. Educ. 24 147

(http://iopscience.iop.org/0031-9120/24/3/306)

Phys. Educ. **24** (1989). Printed in the UK

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The explosion of soap films in the form of hemispherical bubbles resting on cellulose paper

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A simple method of recording the explosion of soap film hemispheres under a variety of controlled experimental conditions is described, together with ways of describing the ensuing droplet patterns quantitatively.

Soap films and soap bubbles have always attracted the human mind due to the brilliance of their colours, the beauty of the particular geometrical forms which can be created and their fragile nature. Leonardo da Vinci was among the first scientists who devoted time to a more systematic study of the underlying phenomenon of surface tension and since then a number of other scientists such as Laplace, Gibbs and Dewar, to mention a few, have been attracted to the field and have contributed to our understanding of the nature and behaviour of these systems. References to contributions from these and later workers in this field are collected in the textbook by Isenberg (1978) which includes an extensive amount of information gathered over the years on soap films.

In using soap films and bubbles for teaching purposes (Rämme 1988) I happened to drop a soap bubble onto an ordinary sheet of paper. The soap film survived the shock and created a hemisphere, which of course spontaneously exploded after a short time. This event was the beginning of my interest to study and learn more about the bursting of soap bubble hemispheres under a variety of experimental conditions. In this article I will present a few of these beautifully simple experiments and give some experimental details and results.

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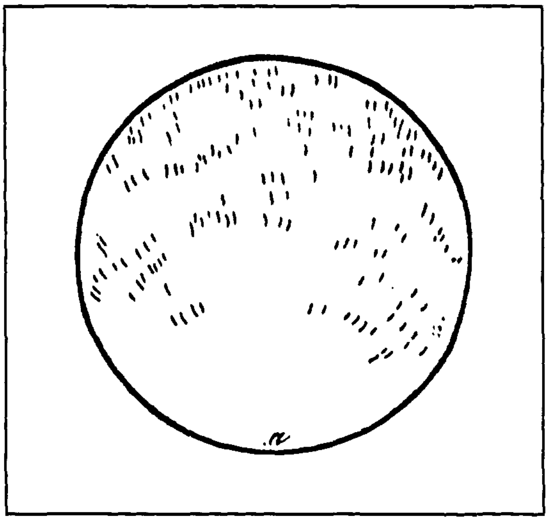


Figure 1 The droplet pattern generated on a paper surface from the rupture of a planar soap film in a rectangular wire framework positioned a few millimetres from the paper. The point of rupture is marked α. *(Reproduced from the book by Plateau (1873))*

The rupture of a planar soap film, generated by withdrawing a wire framework from a soap solution, was first investigated over a century ago (Plateau 1873). The soap film was placed close to a suitable paper surface, punctured and then the created droplet pattern was observed on the paper (figure 1). A series of ordered arrays of droplets was obtained and the structure was interpreted in the following way. When the soap film ruptures, a liquid rim is formed around the bursting point. Due to the force of surface tension acting on the film and reducing its area, the rim recedes and the hole in the film expands. More liquid is accumulated in the rim and finally a point of instability of the liquid cylinder is reached and it spontaneously breaks up into a number of droplets. These are ejected tangentially in the same direction as the receding film is moving and create an ordered array of droplets on the

0031-9120/89/030147 + 07 $02.50

surface of the paper. The process is repeated as a new rim is formed and another series of droplets produced at a specific distance from the first one. The excess pressure inside a bubble of 5 cm diameter was reported to be of the order of only 0.5 mm of water and therefore the release of this pressure when a hole is made in the soap film has only a negligible effect on the course of the explosion.

More recently a deliberate controlled bursting of a vertically suspended planar soap film was thoroughly investigated by means of photographs taken in the light of sequential submicrosecond flashes (McEntee and Mysels 1969). The receding rim could then be observed on the photographs and its maximum velocity was found to be of the order of 5 cm ms^{-1} or 180 km h^{-1}, decreasing with increasing film thickness.

Experimental details

The procedure utilised to generate and puncture the hemispheres under controlled conditions is shown in a series of pictures given in figure 2. The hemisphere was produced by blowing through a plastic pipe with an orifice of 1 cm diameter. It was fixed in position typically 5 cm above the surface of a glossy sheet of paper. Air was supplied in an easily controlled form by using a urine bag. These plastic bags are convenient to use in handling gases for teaching purposes (Norrild 1983).

The inflow of air was interrupted as soon as the expanding bubble touched the surface of the paper (figure 2(*a*)). From the moment of contact, the bubble is physically drawn to the paper. Its diameter continues to expand (figure 2(*b*)) and finally it detaches from the pipe and creates a trembling

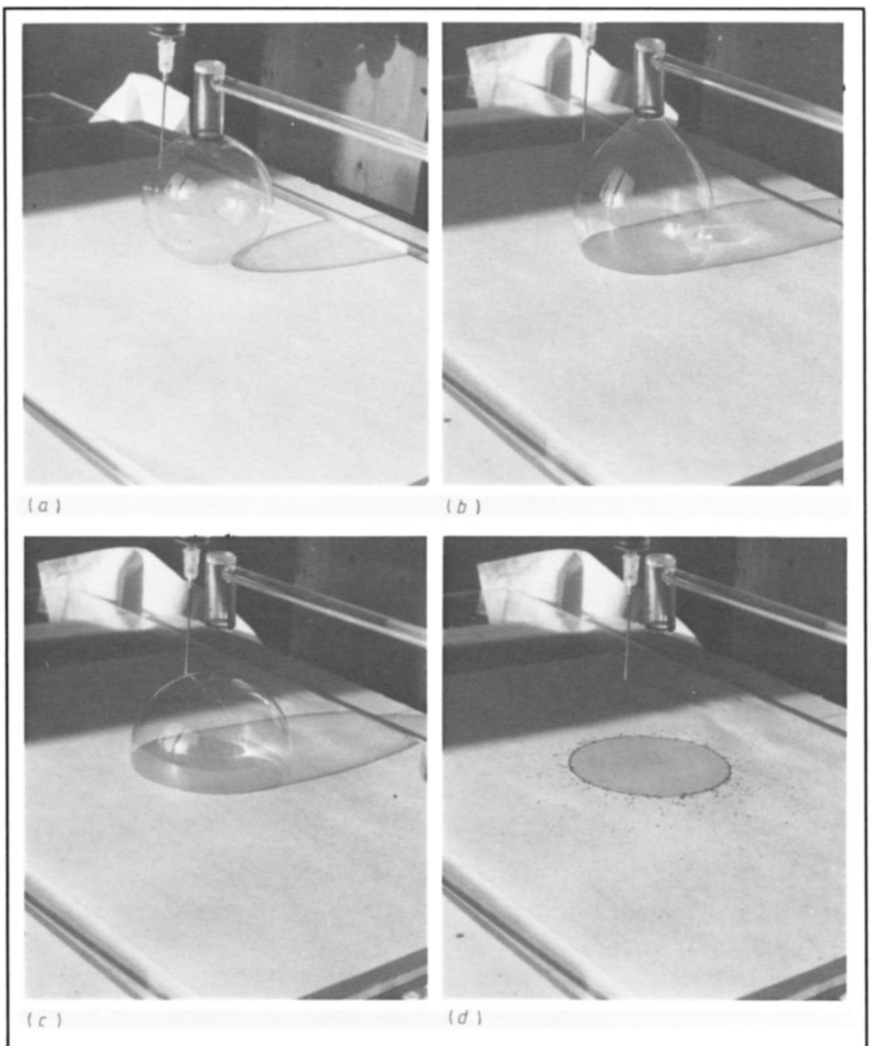


Figure 2 A sequence of pictures showing the technique used to generate and deliberately puncture soap bubble hemispheres under controlled experimental conditions

hemisphere, rapidly coming to rest (figure 2(*c*)). The paper surface inside the periphery of the hemisphere becomes completely wetted by the lower part of the collapsing bubble.

The experimental arrangements were such that the pipe could reproducibly be dipped into the soap solution in every experiment, thus permitting the same amount of solution to be transferred to the orifice. The experimental procedures allow the diameter of the hemisphere to be reproduced within 2%.

In order to make the droplet pattern from the bursting soap film visible on the paper, the soap solution was dyed by adding a small amount of Congo red dye. The result of a spontaneous or deliberately caused rupture of the soap film then manifested itself as a pattern of red spots of different sizes distributed over the surface of the paper (figure 2(*d*)). The pattern can be transferred advantageously to a Xerox transparency for suitable treatment. The smallest droplets can be excluded from the distribution simply by decreasing the sensitivity of the Xerox apparatus while copying. This can greatly simplify the classification of droplets by size. Several interesting features appear, the result being dependent upon such factors as the choice and properties of the soap solution, the nature of the supporting surface, where and when the rupturing process is performed, etc.

A controlled deliberate bursting of the soap film was obtained by using a microsyringe containing alcohol. Gently touching the tip of the needle onto the film surface was sufficient to burst the film. The syringe was mounted in a stand and could be moved in a vertical direction. The distance from the surface of the paper to the point of rupture was determined accurately by means of an attached scale.

Results

In the first series of experiments the soap solution was prepared according to Kay (Walker 1987) and consisted of 1.4 g of triethanolamine, 100 g of glycerine and 2 g of oleic acid. A hemispherical soap bubble of 60 mm diameter blown with this solution

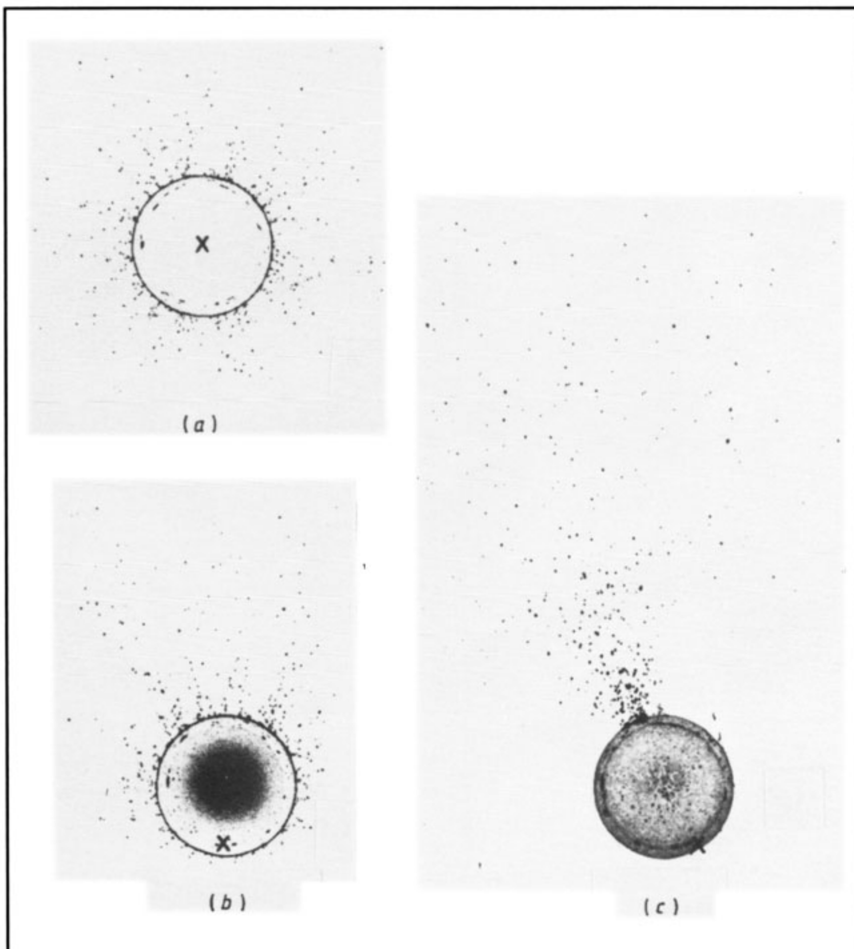


Figure 3 The droplet pattern created after the bursting of similar size soap film hemispheres. The point of rupture is marked by a cross

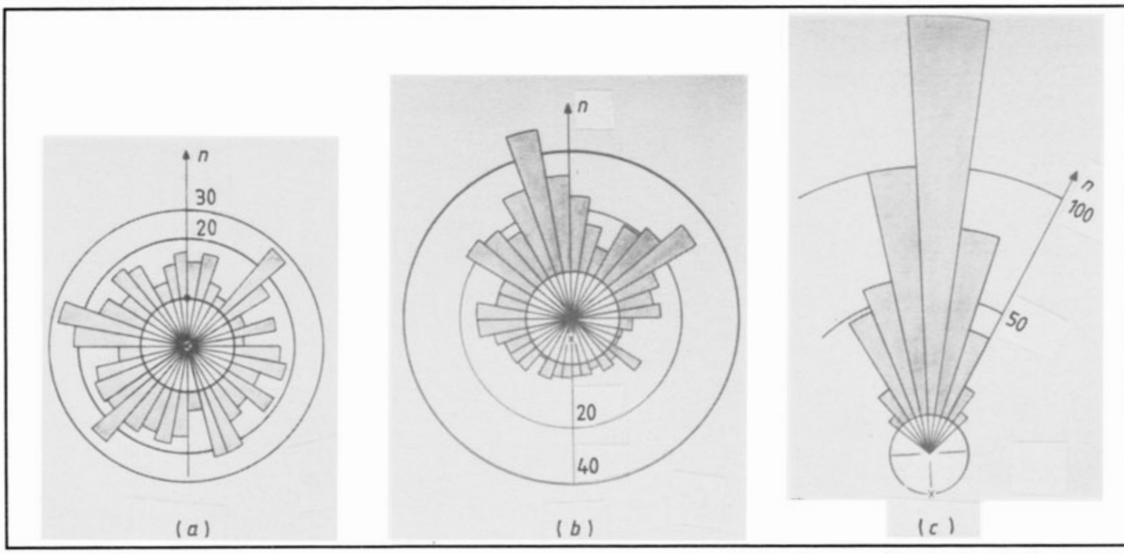


Figure 4 Sector diagrams showing the number n and the distribution of droplets outside the borderline of hemispheres punctured at points marked by a cross shown in figure 3

was found to weigh 10.0 mg. The density of the soap solution was determined to be $1.20 \times 10^3\ \mathrm{kg\,m^{-3}}$. Thus the liquid volume of the hemisphere is $8.3\ \mathrm{mm^3}$. By means of the volume and the area of $56.5 \times 10^2\ \mathrm{mm^2}$ of the hemisphere a film thickness of 0.0015 mm can be derived. Accordingly, about 700 similar soap films would have to be piled on top of each other to produce a film just 1 mm thick!

Figure 3(a) shows the droplet pattern from a soap bubble hemisphere with a 60 mm diameter, which has been punctured at the centre, 30 s after coming to rest on the surface of the paper. The droplets generated are scattered symmetrically in all directions outside the borderline of the hemisphere. By looking more carefully at the distribution we can observe sequences of droplets similar to the form of solar flares extending from the borderline between the hemisphere and the surface of the paper. The diameter d of the spots on the surface of the paper, reflecting the size of the droplets, vary between 0.1 and 1.0 mm. Some of the droplets are ejected as far as 40 cm from the centre of the hemisphere.

A total number of typically 500 droplets is created in an explosion under these circumstances. The total surface area of these droplets is $390\ \mathrm{mm^2}$, using an average diameter of 0.5 mm, in comparison with the surface area of the hemisphere which is twice the area of the half-sphere or $113 \times 10^2\ \mathrm{mm^2}$. The surface energy is directly proportional to the surface area, the constant of proportionality being the surface tension. Thus only about 4% of the available surface energy of the hemisphere remains on the generated droplets. This is in agreement with the results of Liebman *et al* (1968) who estimated that more than 40% of the surface energy in a soap film is converted to kinetic energy of the film's free edge.

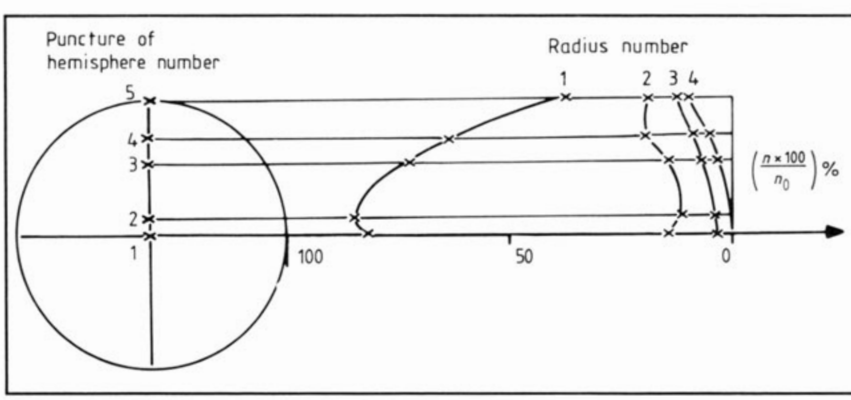


Figure 5 Relative number of droplets from the explosion of five similar size soap film hemispheres between successive concentric circles outside the periphery of the hemisphere separated by the distance r, the radius of the hemisphere

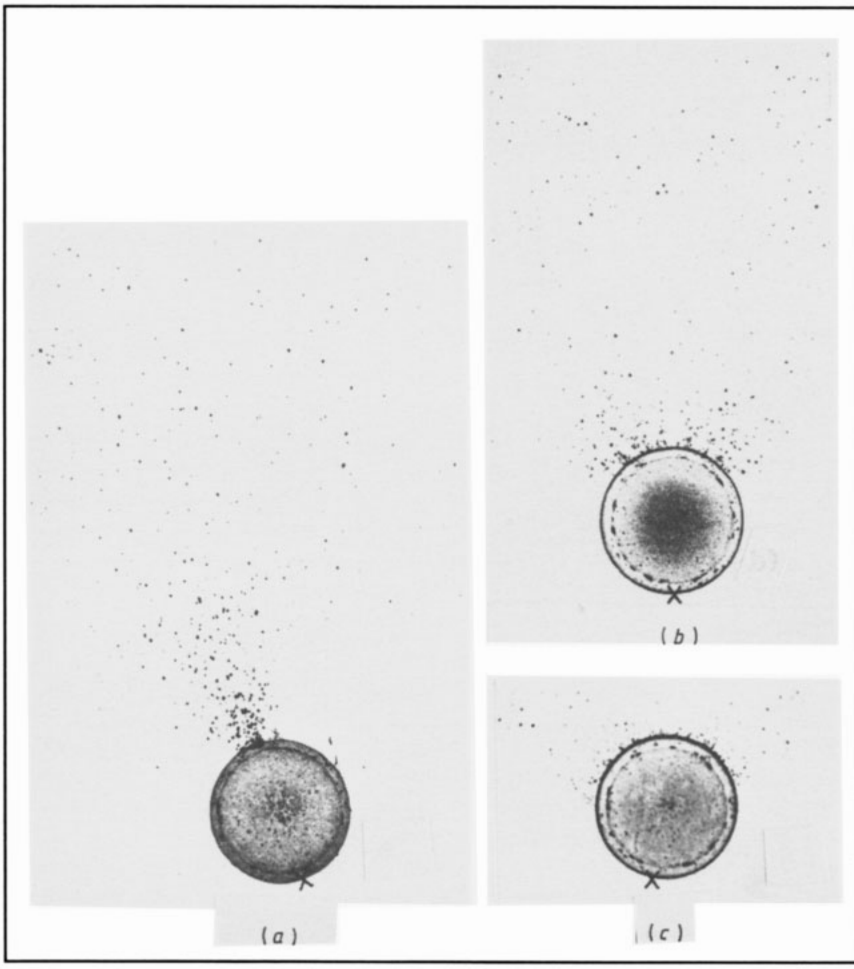


Figure 6 Effects of aging soap film on the droplet pattern of three similar size soap film hemispheres.
(*a*) Punctuated after 15 s, (*b*) 3 min and (*c*) 9 min

about 50% is attributed to internal viscous forces, and the rest, a few per cent, remains as surface energy.

The distribution pattern of droplets from a hemisphere of the same size as shown in figure 3(*a*), which has now been punctured half-way between the centre and the borderline, is reproduced in figure 3(*b*). The droplets are found to be concentrated outside the periphery of the hemisphere on the side opposite the point of rupture. As the puncture is performed further away from the centre, the droplets are collected within a more narrow sector.

Figure 3(*c*) depicts the extreme case when the soap bubble was punctured close to the point of contact with the surface of the paper. Now more than 80% of the liquid droplets are collected within a narrow angle of only 30°. Consequently, the aperture covers only about 10% of the total length of the periphery of the hemisphere. It was further observed that a spontaneous rupture of the soap film produced that kind of pattern which makes it evident that the film usually bursts somewhere along the borderline between the hemisphere and the surface of the paper.

In order to discuss the quantitative aspects of the distribution of droplets, I will give some examples of possible representations.

The first method is presented in figure 4 where the distribution of droplets from the explosion of three hemispheres of similar size is presented as sector histograms. The total number of individual droplets detected has been counted within successive sector angles of 10° aperture and plotted radially, using the periphery of the hemisphere as the zero line.

The next method gives the distribution as relative number of droplets, in per cent, confined between successive concentric circles which are separated by the distance r, the radius of the hemisphere. The results from the bursting of five hemispheres of similar size, punctured at points across, are summarised in figure 5. The diagram shows for example that when a soap bubble is punctured at position 2, about 80% of the total number of ejected droplets is located within the first radius outside the periphery,

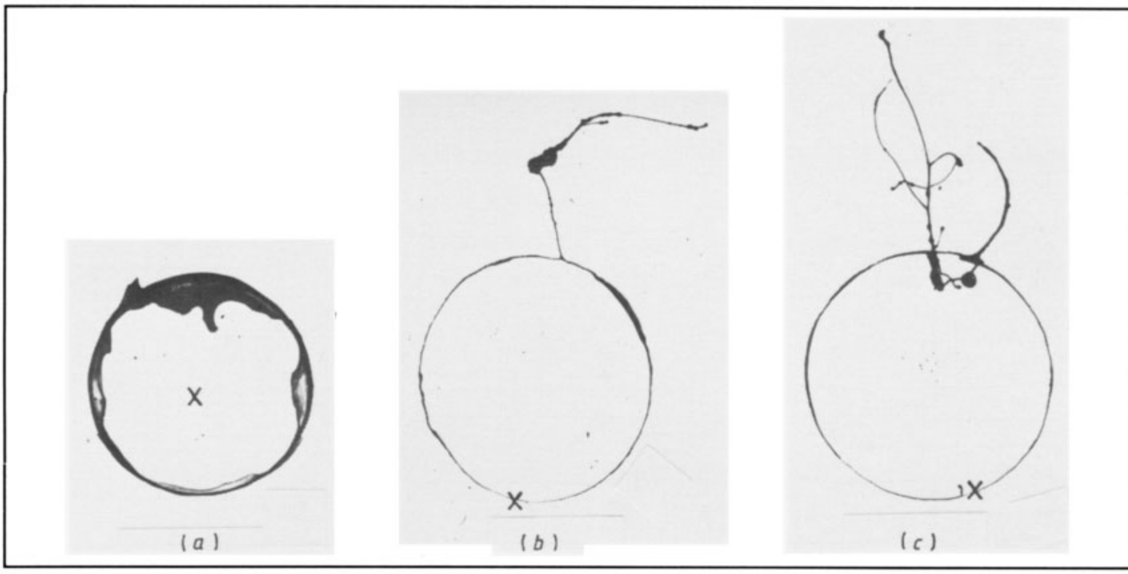


Figure 7 Examples of the kind of pattern formed by the explosion of hemispherical bubbles prepared from a soap solution containing polyvinylalcohol. The point of rupture is indicated by a cross

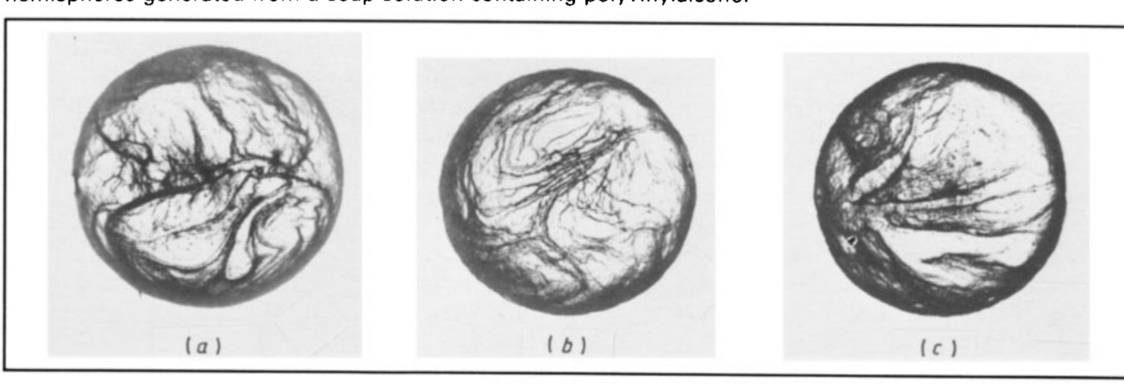
but only 35% when the rupture is initiated at position 5, the periphery. Moreover, no droplets are found outside the fourth radius of the periphery when the hemisphere is punctured at the centre, and about 20% if the rupture occurs at the periphery.

Finally, the distribution was also classified according to the number of different size droplets by measuring the spot diameters on the paper. It was typically found that roughly 30% of the total number of droplets had a diameter of less than 0.2 mm, 50% between 0.2 and 0.5 mm and 20% between 0.5 and 1.0 mm.

In another series of experiments, using the same soap solution, the effect of aging of the soap film on the rupture process was investigated. Hemisphere bubbles of similar size were deliberately ruptured after 15 seconds 3 minutes and 9 minutes respectively. All the soap films were punctured close to the point of contact with the supporting paper surface. The droplet patterns obtained are displayed in figure 6. The number of droplets formed increases considerably with increasing lifetime and thinning of the film and their size decreases in a corresponding degree. The angle of scattering also increases with prolonged lifetime of the film. Thus, the droplets formed in the explosion of a freshly prepared soap film are ejected within a narrow angle of 30° (figure 6(*a*)), while the spread covers a much wider angle of about 180° when the film is destroyed after nine minutes (figure 6(*c*)).

Some experiments were also conducted with a soap solution containing 3% polyvinylalcohol. The presence of polymeric material increases the viscosity and the surface film becomes tough and skin-like during the aging process. If a hemispherical bubble of this kind is punctured a short time after it has

Figure 8 Some examples of the kind of structure which is obtained after the collapse of soap film of aged hemispheres generated from a soap solution containing polyvinylalcohol



been blown, no droplets are formed or scattered. All the material in the liquid film eventually contracts to a 'string' which is ejected in a direction opposite to the side of the point of rupture. Figure 7 gives some typical examples of the kind of structures observed when the hemisphere has been punctured (*a*) at the centre, (*b*) and (*c*) at a point of contact between the hemisphere and the surface of the paper. If on the other hand the film is allowed to dry for some minutes before being punctured, the action of a needle only makes a hole in the soap film. Air leaks out and the film slowly collapses onto the surface of the paper, creating a characteristic beautiful pattern. Some examples of the kind of structures produced are depicted in figure 8. The pattern observed is a remnant of the liquid streams and movements which occurred in the freshly prepared film being preserved as the aging and solidification process proceeds.

Summary

The experiments describe a simple technique for observing the patterns created by the explosion of soap film hemispheres under controlled experimental conditions. Further experiments are in progress with the aim of studying the ejection process in more detail by catching the droplets before they reach the supporting paper surface, as has been the case in these experiments.

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