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The fluid mechanics of BUBBLY DRINKS

Roberto Zenit and
Javier Rodríguez-Rodríguez

Although quenching one's thirst may be the primary appeal of soda pop or a cold beer, there's a lot of physics in the drinks' two-phase flow.

In most cases, the bubbles in a drink are the result of carbonation. The amount of carbon dioxide gas that dissolves in the liquid is proportional to pressure. And if the pressure is suddenly reduced, such as when a bottle of beer is opened, the gas quickly comes out of solution and forms bubbles that rise to the surface, only to burst after a brief instant or to aggregate into a frothy head of foam.

That's just the start of what happens to carbonated drinks opened to air; many processes occur before the first refreshing sip. In this article we discuss the bubbles' birth, motion, stability, and fascinating connections to a range of other phenomena that lie beyond the need for refreshment.

Perhaps the first question worth asking is, Why do we like bubbly drinks? A scientific answer has proven elusive. Carbonation, it turns out, triggers the same pain receptors in the deep brain that are activated by tasting spicy food.¹ Curiously, when carbonated water is fed to other animals, such as mice, dogs, and horses, the animals refuse to drink it. But humans appear to enjoy the mildly irritating effects. Water, CO₂, and saliva enzymes react to produce small amounts of carbonic acid, the substance thought to be behind the tingly sensation. The bubbles themselves are known to alter a drink's

perceived flavor, at least in the case of soda: The smaller the bubbles, the faster they dissolve to produce carbonic acid.

Manufacturers usually adjust the gas content in their drinks to please the consumers' palate; sweet drinks often contain more gas than savory ones do. To understand the bubbles' influence on taste, researchers have tested

the effect of their size distribution.² The results were puzzling: The presence of bubbles was not required to experience the carbonation bite, and yet they did modulate the flavor. No one has a clear picture of how or why.

Origins

Carbonation can occur naturally or artificially. Better known for the discovery of oxygen, Joseph Priestley invented carbonation in 1772, when he discovered that air could be dissolved in water at high pressures. The original intention was to maintain potable water for consumption in ships. Even then, the most relevant result was the bubbly drink's "distinct freshness," as Priestley put it.

Carbonation can also occur by fermentation. When yeast eats simple sugars, it primarily excretes ethanol and CO₂. If

BUBBLY DRINKS

the process occurs in a closed container, the pressure rises as the amount of CO_2 increases. In turn, as the pressure rises, the gas dissolves. Although beer making dates back thousands of years,³ it is unclear how bubbly beer could have been originally—old ceramic containers were most likely unsealed. Sparkling wine was discovered later—in the 17th century—and its carbonation comes from a secondary fermentation inside the bottle.

The presence of alcohol and other molecules during fermentation, such as proteins and enzymes, makes the physical description even more interesting. They affect the liquid's surface tension, viscosity, density, and other properties, which in turn affect the formation, motion, and surface stability, or lifetime, of the bubbles. No less important is the bubbles' ability to accelerate the absorption of alcohol in the body and thus the rapidity of intoxication.⁴

Alcoholic or not, bubbly drinks are full of physics. Figure 1 illustrates the processes that occur when a carbonated drink is poured into a tall glass. If the liquid is poured shortly after the bottle is opened, the birth of bubbles is visible inside the liquid and on the surface of the glass. Streams of bubbles continuously form and induce convection that affects their production rate and motion. As they grow, the bubbles rise and eventually reach the surface. Once there, depending on the properties of the liquid, the bubbles either burst or float.

The bubbles also make noise. As resonant objects, they ring at particular frequencies that depend on their size and the mechanical properties of the liquid and gas. Indeed, researchers have tested how to “hear” the size distribution of the bubbles, which ring as they rise. (See the Quick Study by Kyle Spratt, Kevin Lee, and Preston Wilson, *PHYSICS TODAY*, August 2018, page 66.)

The birth and early life of bubbles

The behavior of bubbles in carbonated drinks is determined primarily by two physicochemical laws. The first one is Henry's law: The concentration C_s of dissolved gas at a liquid–gas interface is proportional to the gas's partial pressure as $k_H p_g$, where k_H is the so-called Henry's constant (although its value actually depends on temperature). Usually termed the saturation concentration, C_s has an important implication. If a liquid has been pressurized with CO_2 or some other soluble gas for sufficient time, it will contain more gas in solution than the liquid is able to store at a lower atmospheric pressure. The liquid is said to be supersaturated at ambient pressure.

Beer is typically bottled at a pressure of about 3 atm whereas champagne is usually bottled at 6 atm. Since Henry's constant for CO_2 in water at 12 °C is 1.9 g/L · atm, a beer bottle contains between 5–6 g/L, whereas a champagne bottle contains about 11 g/L. Were those gases kept at standard pressure and temperature (25 °C at 1 atm), they would occupy 3 L and 5.6 L of CO_2 respectively. Compare those volumes with the gas content

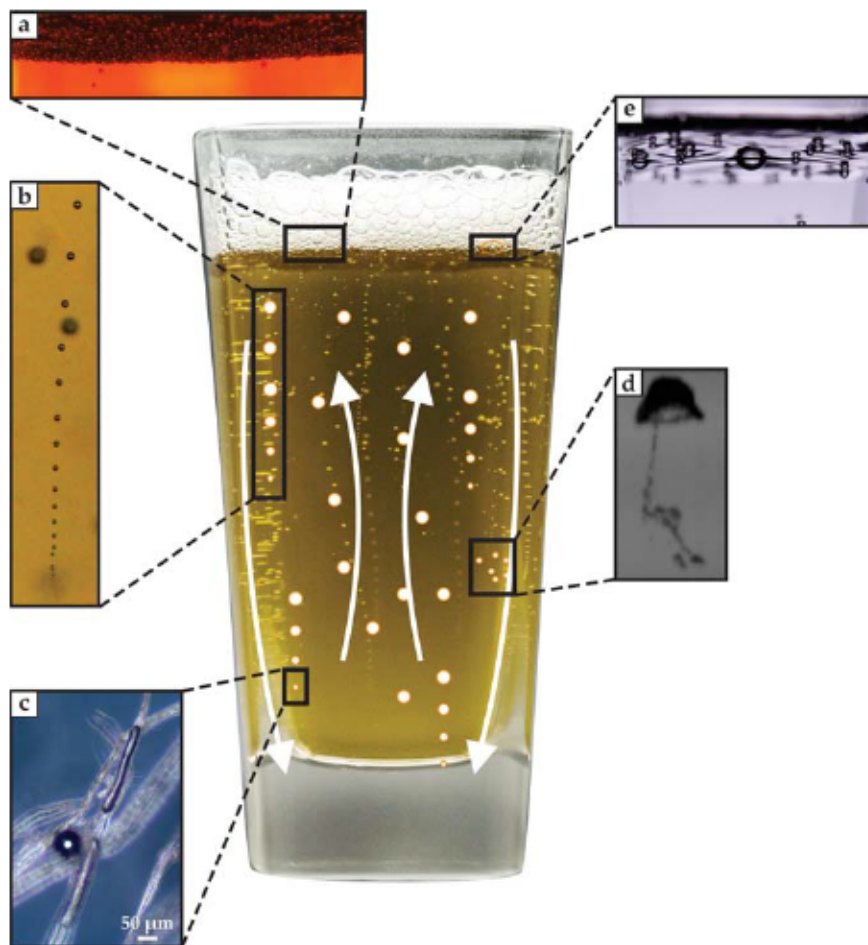


FIGURE 1. A GLASS OF BEER, DECONSTRUCTED. (a) At the beer's surface sits a head of foam. (b) A trail of bubbles rises from a nucleation site along the glass wall. The rising of bubbles from different nucleation sites induces a global circulation (sketched here with white arrows). (c) Cellulose fibers serve as nucleation sites; gas cavities inside the fiber are clearly visible. (d) A 3-mm-wide mushroom-shaped bubble plume arises from the implosion of a millimeter-sized bubble when a beer bottle is gently tapped. (e) Surface bubbles seen from below are nearly on edge. (Panels a and b courtesy of Rodrigo Viñas, TresArt Collective.)

corresponding to saturation at ambient pressure, $C_s \approx 1.9$ g/L, which would occupy only 1 L.

The second law is Fick's law of molecular diffusion. Analogous to Fourier's law of heat conduction, Fick's law states that in the presence of a concentration gradient, a mass flux is established that's proportional to the gradient but in the opposite direction. The proportionality constant is the diffusivity D of CO_2 in water—about 2×10^{-9} m²/s.

When a bottle of liquid with pressurized CO_2 is opened at ambient pressure, Henry's law dictates that any gas cavity inside it will immediately adopt the saturation concentration at ambient pressure. In response to the concentration gradient, molecular diffusion induces a net flux of gas toward the cavity that makes it grow as a bubble.

In the case of a spherical, isolated bubble, the two laws can be combined into the Epstein–Plesset equation,⁵ a building block for more elaborate models of gas–liquid mass exchange. If surface tension is neglected, the equation reads

$$\frac{dR}{dt} = D\Delta\zeta \left(\frac{1}{R} + \frac{1}{\sqrt{\pi Dt}} \right),$$

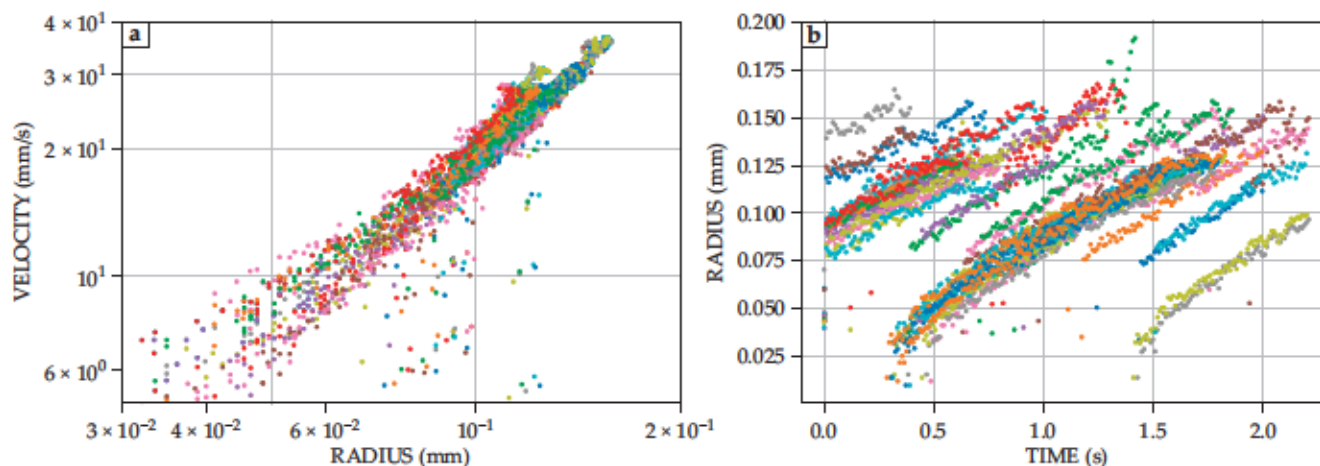


FIGURE 2. RISING VELOCITY AND RADIUS of carbon dioxide bubbles in beer. (a) Bubbles are produced in the bulk liquid by a focused laser pulse to prevent, among other effects, any nucleation of bubbles on nearby walls. The index of the power-law relation between the bubbles' velocity v and radius R is close to $\frac{1}{3}$. That's smaller than the value of 2 derived theoretically, assuming zero Reynolds number. (b) The radii of individual (color-coded) bubbles shown in panel a increase in time. Except for small sizes (less than 50 μm radius), the bubble growth rate is fairly constant for all the bubbles, regardless of size. Experiments were done in a lager beer with a bottling pressure of 5 atm. (Data courtesy of Almudena Casado.)

where Λ is the Ostwald constant, the volume of liquid that can be saturated with a given volume of gas; ζ is the supersaturation level; and R is the bubble radius. The equation predicts that the size of a gas bubble grows by diffusion as the square root of time t . Gas cavities form as the glass is being filled and survive either by attaching to crevices on the glass, which pin and thus stabilize them, or by becoming trapped by impurities, such as cellulose fibers from barley or hops.⁶

When cavities become large enough for their buoyancy to detach them from such nucleation sites, they start to rise, usually leaving behind a smaller cavity to repeat the cycle. The repetition accounts for the trail of bubbles commonly observed in beer and champagne glasses. Once in the trail, new bubbles rise with a speed that increases with their radius. During that rise, the relative velocity between a bubble and the surrounding liquid enhances the mass transfer from the liquid phase to the gas phase, and the bubble actually grows faster than the predicted square root of time.

Indeed, the radius of a bubble rising in a supersaturated liquid grows at a constant rate, independent of its size,⁶ as shown in figure 2. The upward motion is driven by the competition between buoyancy, which scales with the bubble's volume, and viscous drag. The constant growth rate can be explained by the fact that the bubble motion is faster than the rate at which CO_2 diffuses into the water. For a small bubble of CO_2 in water, and thus for a small Reynolds number—the ratio of inertial to viscous forces—it can be shown that

$$\frac{dR}{dt} \sim \Lambda \zeta \left(\frac{\rho g D^2}{\mu} \right)^{1/3},$$

where ρ is the density, g is the acceleration of gravity, and μ is the viscosity. In the equation dR/dt is independent of R and typically has a constant value of tenths of millimeters per second for bubbles found in drinks. That's the reason bubbles inflate as they rise—not because of any change in hydrostatic pressure, which would only be about 1% of the ambient pressure in a glass 10 cm tall.

Similarly, a bubble sitting at a solid surface in a container grows more quickly if the liquid is flowing inside the container.

That creates feedback between the bubble's growth and the circulation induced in the glass after the drink is poured. More specifically, the flow near the glass walls promotes faster bubble growth. And as the bubbles rise, their momentum sustains the circulatory motion until a substantial part of the dissolved CO_2 is lost.

Eventually that chain of events degasses beer or sparkling wine left open to ambient conditions. By itself, diffusion would take an extremely long time to degas a carbonated drink—roughly H^2/D , where H represents the height of the liquid. For a glass 10 cm tall, the calculation yields 5×10^6 seconds, or about 2 months.

In 2005 Gérard Liger-Belair, a professor of chemical physics at the University of Reims Champagne-Ardenne, pointed out that CO_2 bubbles actually take much less time to exsolve from a drink. Although the gas that bubbles transport to the surface is just 20% of the total volume,⁶ the rising motion produces a global circulation that ultimately enhances the advection, as illustrated in figure 1.

The degassing of a carbonated beverage can be further accelerated if the bottle is gently tapped. Four years ago, one of us (Rodríguez-Rodríguez) and coworkers showed that the impact creates a pressure wave that triggers the formation of dense bubble clouds, each consisting of about a million microbubbles.⁷ Those bubble clouds are much more effective than individual bubbles in generating a convective motion inside the bottle. Indeed, experiments have revealed the existence of bubbly plumes—akin to the mushroom clouds formed during an explosion—that promote mixing and thus degassing from a liquid.

Similar phenomena occur in chemical reactors when the products of a reaction are lighter, or warmer, than the reactants. They can likewise produce gas-driven eruptions known as limnic eruptions. The eruptions occur in lakes where the bottom becomes supersaturated with CO_2 because of geological or biological activity. Carbonated water is heavier than fresh water, which stabilizes the accumulation of substantial amounts of gas. For reasons not yet fully understood, some of the supersaturated water rises to a shallower depth where bubbles can nucleate and grow. The growth can then create a plume that, on reaching the free surface, establishes a bubble-laden conduit

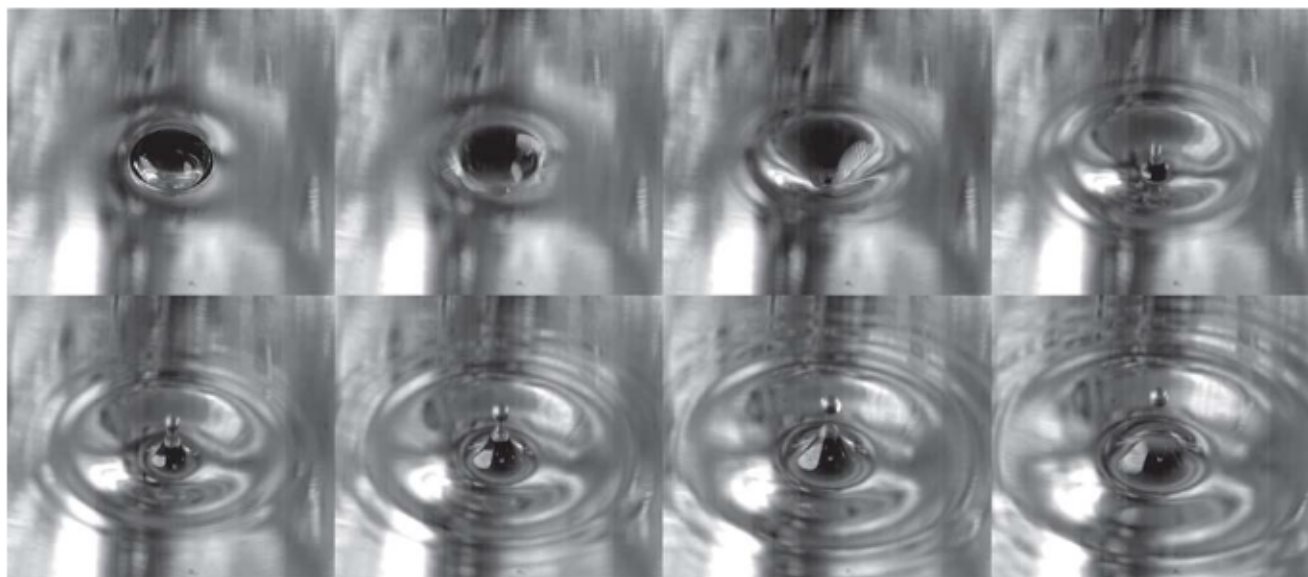


FIGURE 3. A BUBBLE BURSTS on the surface of mineral water. As the 2-mm-diameter CO₂ bubble (top left) ruptures, the torn film retracts and leaves behind a curved cavity at the liquid surface. The surface rebounds because of surface tension and produces an upward-moving jet. A moment later the jet fragments in midair into a smaller droplet. For the video sequence, shown at 5 frames per second, see the hyperlink in the online version of this article. (Images taken by Bernardo Palacios, National Autonomous University of Mexico.)

that continues degassing the bottom of the lake until the amount of dissolved CO₂ becomes too low to further support the plume. That sequence of events happened in 1986 in Cameroon's Lake Nyos, when a limnic eruption suddenly released up to 300 000 tons of CO₂. More than 1700 people and 3500 livestock suffocated in nearby towns and villages.

The importance of bubble growth and rise in a supersaturated liquid in geology goes beyond limnic eruptions. The sudden exsolution of volatile elements in magma, for instance, is known to strengthen the intensity of certain kinds of volcanic eruptions. As pointed out by volcanologists Katharine Cashman and Stephen Sparks, the mechanism is akin to the dramatic reaction that occurs when Mentos are dropped in a bottle of Diet Coke.⁸

Distant seismic events also may trigger autocatalytic bubbly plumes that themselves produce volcanic or geyser-like eruptions. There's considerable evidence gathered over more than a century that volcanoes and geysers erupt in direct response to and in the days following a strong earthquake. Could the self-accelerating exsolution of gas observed in a beer bottle be behind those geological phenomena as well? (See the article by David Hill, Fred Pollitz, and Christopher Newhall, *PHYSICS TODAY*, November 2002, page 41.)

To burst or not to burst

Unless you are drinking soda pop on the International Space Station—a scenario discussed in the box on page 49—the bubbles you see appear will rise due to their buoyancy. When a bubble reaches the surface, a liquid film forms on the bubble's exposed side. Depending on the stability of the film, that surface bubble can remain afloat for some time. In a pure fluid, it may burst in a few milliseconds, whereas if surfactants are present, it's more likely to persist for hours. Curiously, a bubble's lifetime is also related to the amount of alcohol in a drink—as recently shown for the case of mescal.⁹

How long a bubble survives has relevance for more than

just drinks. Longevity is determined by the draining dynamics of the film, which progressively thins due to gravity until it ruptures. To appreciate why a bubble bursts, consider one sitting on a surface. Its shape is determined by the balance between its buoyancy and surface tension σ . For a bubble of radius R , those forces can be quantified by the Bond number, Bo , which equals $\rho g R^2 / \sigma$. The Bond number compares the size of a bubble with the capillary length, $\sigma / (\rho g)$, a characteristic length scale for a fluid interface subject to gravity.

For a small bubble in water, the value of Bo is small (approximately 0.1) because surface tension dominates gravitational effects. Hence the bubble would remain mostly immersed in the liquid and remain primarily spherical. On the other hand, larger bubbles (with correspondingly larger values of Bo), will protrude above the surface.

Film thinning and rupture is subtly more complicated than the extent to which a bubble holds its shape or becomes deformed. It is understood to be dictated by the balance between gravity, viscosity, and surface tension, but a detailed modeling of the process is difficult. To the usual mass and momentum conservation equations at the bubble's interface, one must add the stress and pressure distributions associated with the variations of surface tension along the film.

In 1999 Peter Howell modeled the dynamics of the process analytically and obtained an expression for the ratio of the film's instantaneous thickness h to its initial thickness h_0 in the limit of small Bo :¹⁰

$$\frac{h}{h_0} = \left(1 + \frac{16 t \rho g R / \mu \sqrt{h_0 / R}}{Bo^{3/2}} \right)^{-2}.$$

In that approximation, the bubble ruptures when h narrows to about 10 Å. For a millimeter-sized bubble, the corresponding rupture time would be roughly 10^{-4} seconds.

That lifetime is much shorter than what's typically observed in a glass of beer or soda because the calculation neglects the effect of impurities such as surfactants. Those molecules, which

often have a head and a tail, accumulate at the surfaces of pure liquids such as water and produce several important effects. One is that they can reduce the surface tension. Soap is a classical example; it can reduce the surface tension of water by up to a factor of three. Another is that surfactant molecules tend to immobilize the surface and make it behave like a solid, which significantly slows the drainage and rupture time. (See the Quick Study by Doug Durian and Srini Raghavan, *PHYSICS TODAY*, May 2010, page 62.)

Alcohol also reduces the surface tension. In beer, certain proteins that are released from ruptured yeast cells during fermentation act as surfactants.¹¹ As a result, beer bubbles typically survive for minutes. What's more, the alcohol and water in a drink evaporate at different rates, which produces gradients in surface tension at the surface of the bubbles. The gradients induce upward-moving, so-called Marangoni flows that further delay the rupture process. The effect has been studied in detail for alcoholic drinks and produces what are known as "tears of wine": the Marangoni flow pushes fluid up, whereas gravity pulls it down and causes continuous tearing.

Jets and fizz

When a bubble finally bursts, the film tears, rapidly retracts, and leaves behind a curved cavity at the liquid's surface, as shown in figure 3. The surface tension tries to flatten the surface, whose shape quickly changes from convex to concave and produces an upward jet that breaks up in midair. The smaller the bubble, the faster the jet. Both the tearing film and the fragmentation of the jet lead to the formation of small aerosol droplets. That process is behind aerosols produced by ocean spray, which exert a significant effect on climate. (See the article by David Richter and Fabrice Veron, *PHYSICS TODAY*, November 2016, page 34.) On the microscale, aerosols can influence the emission of odors, which in turn affect the perception of flavor.¹²

If the production rate of bubbles is faster than their lifetime on the surface, the bubbles accumulate to create a foam head. That region of densely packed bubbles is an important feature of many drinks. Not only do the bubbles release odors, they also make for a creamy mouthfeel. The thickness of the foam layer depends on the liquid's properties—viscosity and density among them—and, as many of us know, on the skill of the pourer. If beer is poured too quickly, for instance, air becomes entrained into it. Those air cavities become nucleation sites that increase the production rate of bubbles.

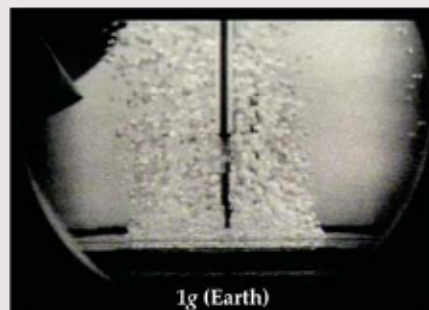
If the lifetime of the bubbles is not affected, the thickness of the foam layer sometimes increases only to overtop the rim of the glass and spill the bubbly treasure. How much foam is desirable? That depends on whom you ask. A recent study suggests that a layer of foam reduces the sloshing in a vibrating container;¹³ so if you prefer not to spill your beer while walking, it is better to pour it with a head.

In addition to adding appeal to a drink, foam has important functions in many other contexts.¹⁴ Figure 4 depicts just a few of them. Among the important properties of foam are its stability, the distribution of the bubbles, and its mechanical properties. Foam can behave like an elastic material with a bulk, shear-dependent viscosity. And its thermal conductivity is small, a property that makes the material an excellent insulator. (Indeed, some beers served in Los Angeles's Dodger Stadium are prepared with additional "artificial" foam that slows the degassing and keeps them cool.)

In fact, most modern insulating materials are foam-based products. For biological systems, water-soluble proteins can significantly prolong a foam's lifetime. Some fishes and amphibians create foam nests in which to deposit and hatch their eggs; the foams reduce temperature fluctuations and provide an oxygen-rich environment.¹⁵ For the food industry, foam adds texture to otherwise unappealing products,¹⁶ and the proteins in egg whites can extend the foam's lifetime for weeks.

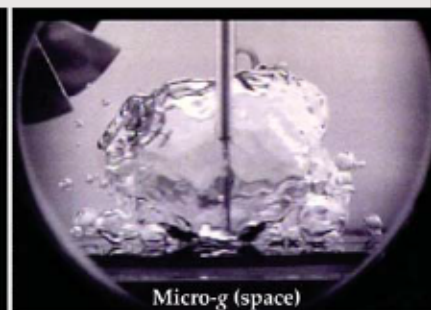
BUBBLES IN MICROGRAVITY

In the absence of gravity, bubbles that form in a carbonated liquid are not buoyant. They make no trails for the surface but instead remain where they are formed. (See the video link in the article's online version for a comparison of bubbles created by a spark inside carbonated water under normal ground-test conditions and under microgravity conditions.¹⁹) Nevertheless, the bubbles can grow to enormous sizes inside the liquid and eventually produce a frothy liquid with a much larger gas-volume fraction than their earthbound equivalents. The photographs illustrate (left) a cloud of microbubbles that formed as water was heated to the boiling point at Earth's surface and (right) a single bubble that grew as large as the container at boiling temperature in the microgravity environment of the



International Space Station; g refers to the acceleration of gravity. (For details, see V. K. Dhir et al., *Microgravity Sci. Technol.* **24**, 307, 2012.)

Not surprisingly, food scientists have made efforts to produce carbonated soda for astronauts. In 1985 modified cans of Coca-Cola and Pepsi rode aboard the space shuttle *Challenger* on its STS-51F mission. And on at least one other occasion, a soda dispenser also made it into orbit



on the space shuttle *Discovery's* STS-63 mission in 1995. Aside from the change in flavor, though, the bubbly soda became problematic when consumed. Unable to escape the liquid in the digestive system, the gas would produce painful bloating of the astronauts' stomach and intestines. For relief, one could only burp, but in the microgravity environment the burp was often wet, much like the experience of acid reflux.



FIGURE 4. FINDING FOAM. (a) Sprayed on the interior of a narrow boat, foam improves thermal insulation. (Photo courtesy of Isothane.) (b) Foam nests made by Siamese fighting fish provide eggs and newborn with an oxygen-rich environment and protection from thermal fluctuations. (Photo by ZooFari, CC BY 3.0.) (c) The texture of chocolate mousse comes from its bubbles. (Photo by Lu, CC BY 2.0.) (d) Sea foam is blown ashore on the California coast. (Photo by Brocken Inaglory, CC BY-SA 3.0.)

The best example of edible foam is chocolate mousse, deliciously shown in figure 4c. Lastly, the foam on the surface of seawater usually contains dissolved organic matter,¹⁷ though it sometimes indicates pollution or contamination. Whatever composes ocean foam, the tracking of it as whitecaps—a widely used tool to measure wind speed over the ocean via satellite imaging—would be impossible if the foam were not sufficiently stable.

Whatever your field, we hope that the next time you sit before your favorite bubbly drink you will look at it with a new perspective—as a laboratory of myriad, fascinating phenomena, with length scales ranging from tens of microns (the nucleation sites) to tens of centimeters (the container).

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