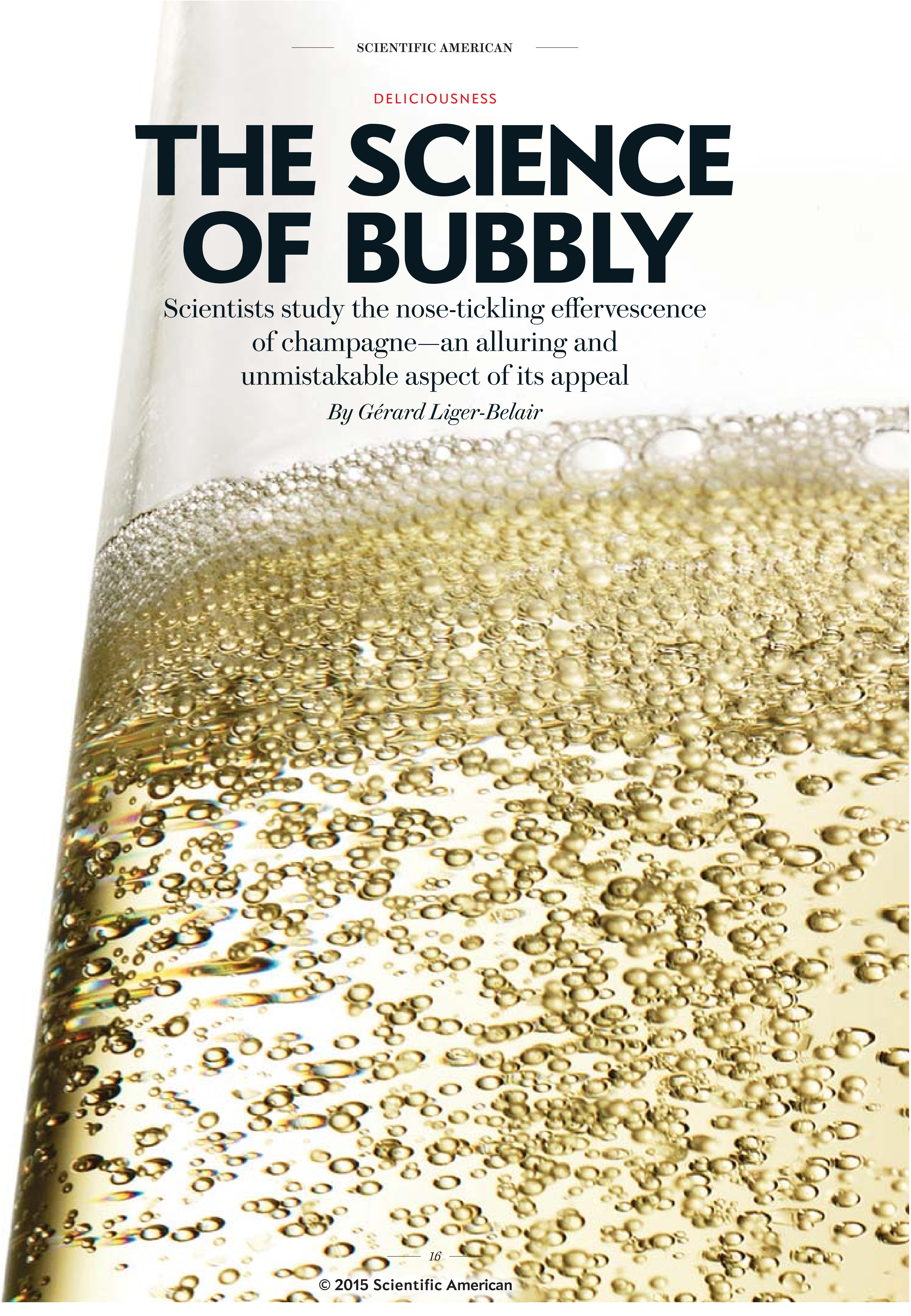
DELICIOUSNESS

THE SCIENCE OF BUBBLY

Scientists study the nose-tickling effervescence of champagne—an alluring and unmistakable aspect of its appeal

By Gérard Liger-Belair



POP OPEN A BOTTLE OF CHAMPAGNE AND POUR YOURSELF A GLASS. TAKE A SIP. THE elegant surface fizz—a boiling fumarole of rising and collapsing bubbles—launches thousands of golden droplets into the air, conveying the wine's enticing flavors and aromas to tongue and nostrils alike. A percussive symphony of diminutive pops accompanies the tasty mouthful, juxtaposing a refreshing carbonated chill and a comforting alcoholic warmth. Such is the enchantment of bubbly, the classic sparkling wine of northeastern France's Champagne district, a libation that has become a fixture at festive celebrations worldwide. Among the hallmarks of a good champagne are multiple bubble trains rising in lines from the sides of a poured glass like so many tiny hot-air balloons. When they reach the surface, the bubbles form a ring, the so-called *collerette,* at the top of a filled flute. Although no scientific evidence correlates the quality of a champagne with the fineness of its bubbles, people nonetheless often connect the two. Because ensuring the traditional effervescent personality of champagne is big business, it has become important for vintners of sparkling wines to achieve the perfect *petite* bubble. More than a decade ago several research colleagues from the University of Reims Champagne-Ardenne and Moët & Chandon and I decided to examine the behavior of bubbles in carbonated beverages. Our goal was to elucidate the roles of each of the many parameters that come into play in bubbling. Close observations of glasses filled with sparkling wine, beer and soda revealed their visually appealing outgassing to be surprisingly complex. In the years since, we have learned a great deal about the three main phases of a bubble's life: its birth, ascent and dramatic demise.

On the rise: The short but spectacular ascent of champagne bubbles to the top of a glass embodies a complex physicochemical system that is both more functional and more picturesque than one might expect.

BUBBLE GENESIS

IN CHAMPAGNE, sparkling wines and beers, carbon dioxide (CO_2) is the principal agent that produces gas bubbles, which form when yeast ferments sugars, converting them into alcohol and carbon dioxide molecules. Industrial carbonation is the source of the fizz in soda drinks. After bottling or canning, the carbon dioxide dissolved in the liquid comes into equilibrium with the gas in the space directly under the cork, cap or tab.

When the container is opened, the pressure of the gaseous carbon dioxide above the liquid falls abruptly, breaking that equilibrium. As a result, the liquid becomes supersaturated with carbon dioxide. To regain thermodynamic balance with the CO_2 in the atmosphere, carbon dioxide must leave the fluid. When the beverage is poured into a glass, two mechanisms enable dissolved carbon dioxide to escape: diffusion through the free surface of the liquid and bubble formation.

Before molecules of gas can coalesce into embryonic bubbles, however, they must push their way through the liquid, the molecules of which are strongly linked by van der Waals forces (dipole attraction). Bubble formation is limited by this energy barrier; the supersaturation that occurs in carbonated beverages is not strong enough to overcome it alone.

In weakly supersaturated liquids, including champagne, sparkling wines, beers and sodas, bubbles thus form only when preexisting gas cavities are large enough to overcome the nucleation energy barrier. The cavities must be big because the curvature of the gas/liquid interface leads to an excess of pressure inside the gas pocket that is inversely proportional to its radius. The smaller the bubble, the greater the overpressure within it. CO_2 simply cannot diffuse into bubbles smaller than a critical size. In newly opened champagne, the critical radius is microscopic—around 200 nanometers.

To observe "bubble nurseries" in detail, we aimed a high-speed video camera fitted with a microscope objective lens at the bases of hundreds of bubble trains. Contrary to general belief, these nucleation sites are not located on irregularities on the glass surface, which are much smaller than the critical radii of curvature required for bubble formation. Bubble nurseries, it turns out, arise on impurities *attached* to the glass wall. Most are hollow cellulose fibers that fell out of the air or were left behind as the glass was wiped dry. The geometries of these fiber particles prevents them from being wet completely by the beverage. They are thus able to entrap gas pockets when a glass is filled [*see bottom inset on opposite page*].

A bubble forms when dissolved carbon dioxide molecules migrate into one of these minute gas pockets. Eventually it grows to macroscopic size, yet initially it remains rooted to its nucleation site by capillary forces. Finally the bubble's increasing buoyancy causes it to detach, and a new bubble can form in its place. The process repeats until too little dissolved CO_2 remains to make bubbles.

My colleagues and I use a stroboscope to measure the number of bubbles produced per second at each nucleation site. When the frequency of the flash equals that of bubble production, the bubble train appears frozen.

Because bubble growth depends also on the concentration of dissolved carbon dioxide content, bubble formation frequencies vary from one carbonated beverage to another. In champagne, for example, the most active nucleation sites emit up to about 30 bubbles per second. The gas content of beer is about a third that of champagne, and beer bubble nurseries produce bubbles only about a third as fast.

BUBBLE ASCENT

AFTER A BUBBLE is released from its nursery, it grows as it rises to the surface [*see middle inset on opposite page*]. Carbon dioxide molecules continuously diffuse from the liquid into the bubble as it floats along. As bubbles expand, they become more buoyant, so they accelerate upward and separate from one another.

Bubbles in beers and sparkling wines are more than just pockets of gas because these beverages are not pure liquids. In addition to water, alcohol and dissolved carbon dioxide, the drinks contain proteins, glycoproteins, and other organic compounds that can behave like detergents, also known as surfactants.

Surfactant compounds combine water-soluble and water-insoluble parts. The surfactants come out of solution and encircle bubbles, aiming their hydrophobic ends into the gas and sticking their hydrophilic ends into the liquid.

The surfactant coating changes how a bubble plows its way through the liquid after it detaches. The shieldlike coat stiffens the bubble, which makes it encounter greater resistance from the liquid, compared with a more flexible, surfactant-free sphere. In addition, surfactant molecules encountered during ascent gradually collect on the bubble surface, making it more rigid still. The hydrodynamic drag experienced by a rising bubble of fixed radius thus increases progressively; the bubble slows to a minimum velocity when the gas/liquid interface becomes almost totally contaminated by surfactants.

That is not necessarily true for bubbles that expand as they rise, however. A growing bubble adds surface area, which offers more space to adsorb surfactants. Swelling bubbles are consequently subject to opposing effects. If the expansion rate overcomes the speed with which surfactants stiffen the surface, a bubble "cleans" its interface constantly because the ratio of the surface area covered by surfactants to that free from surface-active agents decreases. If this ratio instead increases, the bubble surface becomes inexorably contaminated by a surfactant monolayer and grows rigid.

My co-workers and I measured the drag coefficients of expanding champagne and beer bubbles during their journeys up to the surface and then compared our data

IN BRIEF

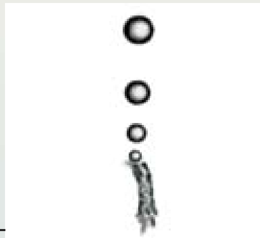
A million bubbles, roughly speaking, appear when you pour a glass of sparkling wine. Bubbles like these are what give beer, champagne and soda their pleasing fizz.

The life cycle of a bubble in a carbonated beverage is more complex than you might think. The bubbles are born, for example, from bits of dust. They are initially a mere 200 nanometers across.

As bubbles rise, gas continually diffuses into them, so the bubbles expand. But soaplike compounds in the liquid coat the bubbles, stiffen their walls and add drag that slows their ascent.

A bubble dies a spectacular death as it bursts and jets aromatic aerosols into the nose and palate of the drinker. The sting and smell of the fizz enhance the flavor of the beverage.

Champagne Bubbles



GROWING BUBBLES: The brief existence of a champagne bubble begins on a tiny mote of cellulose left clinging to the sides of a glass after it is wiped dry. When the sparkling wine is poured, a submicron-diameter gas pocket forms on the cellulose fiber. Dissolved carbon dioxide under pressure enters this small cavity and eventually expands it so much that buoyancy causes it to separate from the nucleation site (*bottom inset*). During its journey to the surface, the bubble continues to swell as more carbon dioxide makes its way in (*middle inset*). Simultaneously, aromatic flavor molecules in the beverage attach themselves to the gas/water membrane, a phenomenon that slows the bubble's ascent by boosting its drag. Soon after emerging at the surface, the flavor-carrying gas capsule collapses on itself and shoots a bit of the wine into the air (*top inset*), thus enhancing the champagne's smell and savor.

HOW MANY BUBBLES IN THAT GLASS? Many champagne drinkers have idly mulled this question, but researchers have recently attempted to answer it scientifically by using models that include both the dynamics of bubble ascension and mass transfer equations. As one might expect, the number of bubbles likely to form per glass depends on both the wine and the glass itself. Pour 100 milliliters of champagne straight down the middle of a vertical flute like the one at the left, and you will probably see a million bubbles form in the wine, if you can refrain from drinking it. Champagne served more gently by pouring down the wall of a tilted flute—a technique that better preserves the dissolved carbon dioxide—will probably yield tens of thousands more bubbles before it goes flat.

SHOW ME THE BUBBLES: Champagne is best served in a long-stemmed flute—a slender glass with a tulip- or cone-shaped bowl containing six ounces or more, wine experts say. The tall, narrow configuration of the flute extends and highlights the flow of bubbles to the crown, where the restricted open surface area concentrates the aromas carried up with the bubbles and released by their collapse. The slender stemware also prolongs the drink's chill and helps to retain its effervescence.

The flute is better suited for drinking sparkling wine than the "champagne" coupe, the short-stemmed, saucer-shaped glasses that were once so fashionable (*bottom of box on next page*). Legend has it that these glasses were originally modeled on the celebrated breasts of Marie Antoinette, queen of France in the late 18th century. Although it is still popular, the coupe was never designed for drinking champagne and thus does not allow the taster to fully enjoy its qualities, according to wine connoisseurs. Shallow and wide-brimmed, coupe glasses tend to be unstable and too likely to spill, and they fail to keep the wine as cold as tall wine flutes do. Further, coupes do not present the elegant bubble trains to best advantage.

To open a bottle of champagne, hold it with the cork pointed at a 45-degree angle upward, away from you or anyone else. Hold the cork and gently turn the bottle in one direction. Rather than popping off with a bang, the cork should come off with a subdued sigh. A loud pop wastes bubbles; as the saying goes, "The ear's gain is the palate's loss." —*G.L.-B.*

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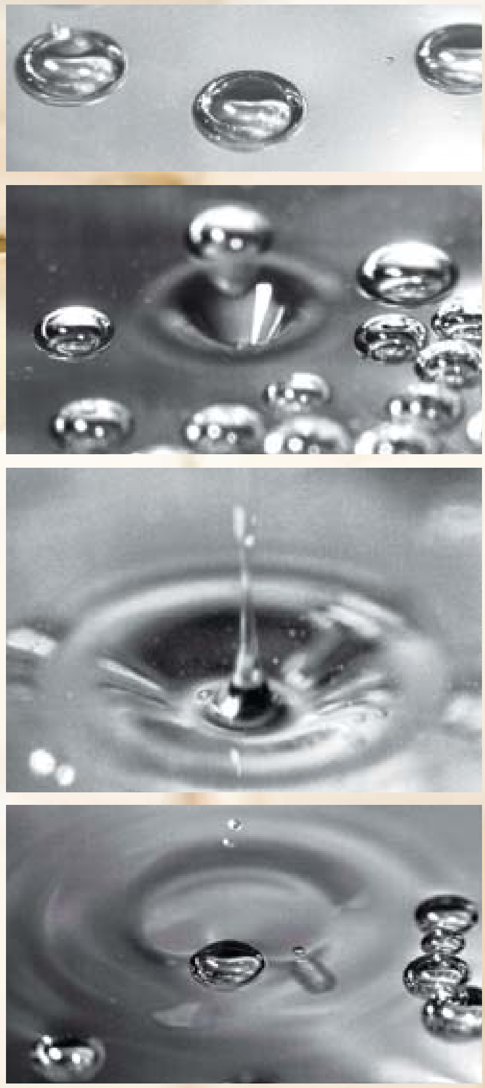
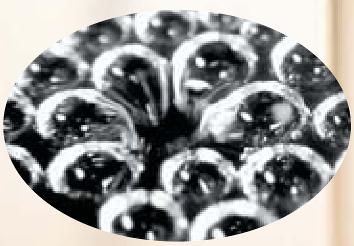
Death of a Bubble

POP GOES THE BUBBLE: The collapse of a champagne bubble begins nearly as soon as it breaches the surface of the beverage (*sequence at right*). In the second image, the thin liquid film that constitutes the emerged part of the bubble has just ruptured. During this extremely brief event, the shape of the bubble—nearly a millimeter wide—remains intact. The collapse of the cavity gives rise to a high-speed liquid jet that flies above the surface (*third image*). Because of its own velocity, this jet becomes unstable, forming a capillary wave that breaks up the flow into droplets. Hundreds of bubbles are bursting every second after pouring, so the liquid surface is literally spiked with cone-shaped structures, which are unfortunately too short-lived to be seen with the naked eye.

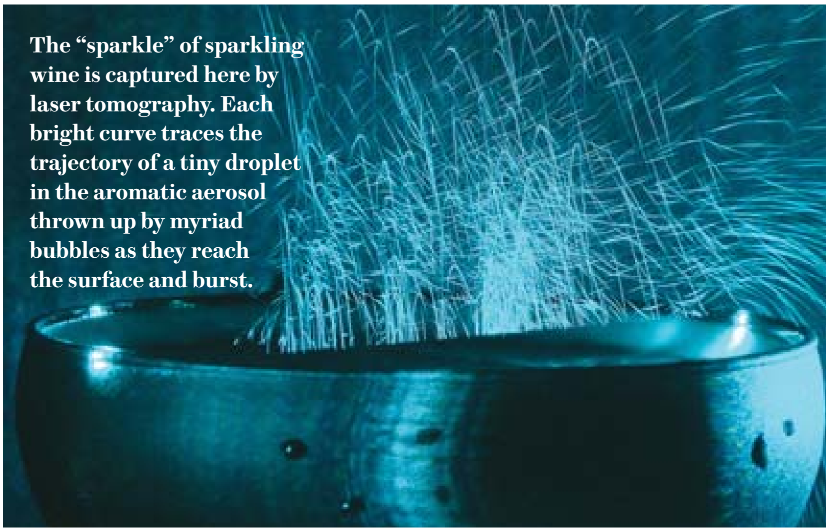




BUBBLE FLORETS: Because surface bubbles collapse so rapidly (in less than 100 microseconds), few photographs capture the process. But clusters of champagne bubbles form visually appealing flower-shaped structures (*left*) when they are deformed by the sucking force created by a nearby popped bubble. The bubble caps adjacent to the bubble-free central zones are stretched into teardrop shapes pointed toward the empty cavities.

THINKSTOCK (*wineglass*); COURTESY OF GÉRARD LIGER-BELAIR (*top left, top right* and *bottom right*); FROM "RECENT ADVANCES IN THE SCIENCE OF CHAMPAGNE BUBBLES," BY GÉRARD LIGER-BELAIR ET AL., IN *CHEMICAL SOCIETY REVIEWS*, VOL. 37, NO. 11; JULY 2008 (*bottom left, two at middle right and opposite page*) with values found in the scientific literature of bubble dynamics. We concluded that beer bubbles act very much like rigid spheres. In contrast, bubbles in champagne, sparkling wines and sodas present a more flexible interface during their ascent. This is not overly surprising, because beer contains much higher quantities of surfactant macromolecules (on the order of several hundred milligrams per liter) than does champagne (only a few mg/L). Furthermore, because beer contains less gas, beer bubbles grow slower than champagne bubbles do. As a result, the cleaning effect caused by a beer bubble's expansion may be too weak to avoid rigidification of its gas/liquid interface. In champagne, sparkling wines and sodas, bubbles grow rapidly, and the concentration of surfactants is too low to make them rigid.

A NEW VIEW



The "sparkle" of sparkling wine is captured here by laser tomography. Each bright curve traces the trajectory of a tiny droplet in the aromatic aerosol thrown up by myriad bubbles as they reach the surface and burst.

BUBBLE COLLAPSE

IN THE SEVERAL SECONDS after its birth and release, a bubble travels the few centimeters to the beverage's surface, eventually ballooning to a diameter of about one millimeter. Like an iceberg, a gas bubble at the top of a drink emerges only slightly from the surface; most of its volume remains below. The emerged part, the bubble cap, is a hemispherical liquid film that gets progressively thinner as liquid drains down the sides. When the cap thins to a critical thickness, it becomes sensitive to vibrations and thermal gradients, which finally cause it to burst. In 1959 two physicists, Geoffrey Ingram Taylor of the University of Cambridge and Fred E. C. Culick of the California Institute of Technology, showed independently that surface tension causes a hole to appear in the bubble cap and that the hole widens very quickly. For bubbles a millimeter across, disintegration takes only 10 to 100 microseconds [*see box on opposite page*].

After the bubble cap breaks, a complex hydrodynamic process ensues, causing the collapse of the submerged part of the bubble. For an instant, an open cavity remains in the liquid surface. Then the inrushing sides of the cavity meet and eject a high-speed liquid jet above the free surface. Because of its high velocity, this jet becomes unstable, developing a capillary wave (the Rayleigh-Plateau instability) that fragments it into droplets called jet drops. The combined effects of inertia and surface tension give the detaching jet drops a variety of often surprising shapes. Finally they take on a quasi-spherical shape. Because hundreds of bubbles are bursting each second, the beverage surface is spiked with transient conical structures, which are too short-lived to be seen with the unaided eye.

AROMA AND FLAVOR RELEASE

BEYOND AESTHETIC considerations, bubbles bursting at the free surface impart what merchants call "feel" to champagne, sparkling wines, beers and many other beverages. Jet drops are launched at several meters per second up to a few centimeters above the surface, where they come in contact with human sense organs. Nociceptors (pain receptors) in the nose are thus stimulated during tasting, as are touch receptors in the mouth when bubbles burst over the tongue; this bursting also yields a slightly acidic aqueous solution.

In addition to mechanical stimulation, bubbles collapsing at the surface are believed to play a major role in the release of flavors and aromas. Fatty acids and other aromatic compounds in carbonated beverages act as surfactants, so they latch onto rising bubbles, and then molecules concentrate at the surface of the beverage. The aerosol spray created by the bursting of myriad bubbles consists of clouds of tiny droplets. My research group has used ultrahigh-resolution mass spectrometry to analyze the aerosols, and we showed that they contain high concentrations of compounds known to be aromatic or the precursors of aromas. This discovery supports the idea that rising and collapsing bubbles act like an escalator to continuously lift delicious aromas from the glass to the nose and the palate. SA

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MORE TO EXPLORE

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How Many Bubbles in Your Glass of Bubbly? Gérard Liger-Belair in *Journal of Physical Chemistry B,* Vol. 118, No. 11, pages 3156–3163; 2014.

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