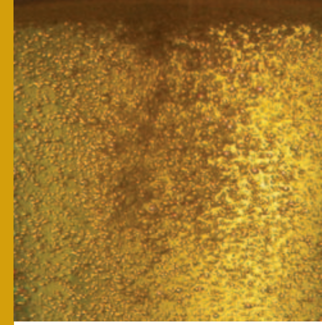

"Fizzics" of Bubble Growth in Beer and Champagne

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Although beer and champagne are mostly enjoyed at leisure, the myriad physical and chemical processes in them are challenging. Furthermore, studying these processes sheds light on explosive volcanic and lake eruptions because bubble growth is a process common to all of them. We model the growth rate of rising bubbles in beer and champagne. Due to different initial gas concentrations, the eruption velocity of champagne is two orders of magnitude higher than that of CO_2-based beer. In N_2-based Guinness beer, bubble growth is slow, leading to smaller bubbles that can be entrained by downward flow; these are often seen as sinking bubbles.

KEYWORDS: bubble growth, bubble ascent, beer, champagne, Guinness

INTRODUCTION

Shake a bottle of champagne and pop it open. The champagne will shoot out in a mini-eruption. Do the same to a bottle of beer. Beer will ooze out more slowly. If a bottle of champagne or beer is opened without perturbation, there will be no eruption, but bubbles will rise and grow, often in regularly spaced "trains" (FIG. 1). In Guinness beer, bubbles rise more slowly and may even sink. The myriad phenomena resulting from the remarkable interplay between gas and liquid have attracted much attention.

Because gas solubility in drinks increases with pressure, the sudden reduction of pressure when a bottle of champagne or beer is opened causes the gas to exsolve, forming bubbles. Shafer and Zare (1991) took high-resolution and high-speed pictures, found that bubble growth rate is roughly constant, and successfully modeled the rising velocity of bubbles from the measured bubble size as a function of time. Liger-Belair (2004) photographed the nucleation, rise, and burst of bubbles in champagne, and determined that nucleation occurs heterogeneously on micrometer-sized, elongated, hollow, and roughly cylindrical cellulose fibers (likely paper or cloth particles) on the glass wall, rather than on scratches or irregularities in the glass itself, as is commonly believed. On the other hand, bubble growth has not been quantitatively modeled from kinetic and fluid dynamic principles. The pursuit of bubble physics is more than pure academic curiosity and pleasure: explosive volcanic eruptions such as the supereruptions described in this issue, lake eruptions such as the 1986 eruption of Lake Nyos that led to 1700 deaths (Kling et al. 1987; Zhang 1996), and possible ocean eruptions (Zhang 2003) are powered by similar gas–liquid interactions (Zhang et al. 1997; Zhang and Kling 2006). Here, we focus on quantifying the growth rate of rising bubbles.

CONVECTIVE BUBBLE GROWTH

Bubble growth in liquid is more than a diffusion problem because the rise of bubbles induces convection that enhances mass transport into the bubbles. In this article, such bubble growth is termed convective bubble growth. Recent theoretical developments (Kerr 1995; Zhang and Xu 2003) provide a method to calculate the convective growth or dissolution rate of a sinking or rising crystal or droplet; the accuracy of the calculation has been verified by experiments to be about ±15% (Zhang and Xu 2003; Zhang 2005). The theory is adapted here (SEE BOX 1) to model convective growth of spherical bubbles (bubbles with a radius of 1 mm are roughly spherical in beer or champagne, based on Clift et al. 1978). The model must include the additional effect of bubble expansion due to pressure decrease as the bubble rises. For bubbles in beer or champagne, the effect is small but is nonetheless incorporated. For bubbles in a magma chamber or in a lake, the effect is significant: even a dissolving bubble can become larger as it rises.

The necessary parameters for the calculation include the viscosity (resistance to flow) of the liquid, and the diffusivity and solubility of the gas in the liquid. We measured viscosity using a calibrated Cannon-Fenske viscometer. The viscosities of (1) Budweiser beer (containing CO_2), (2) White Star Moet & Chandon Champagne (containing CO_2), and (3) Guinness beer (containing N_2) are, respectively, 1.44, 1.67, and 1.40 times that of water. Using the Einstein relation between viscosity and diffusivity, CO_2 diffusivity in Budweiser beer and champagne is assumed to be 1/1.44 and 1/1.67 times that in pure water, and N_2 diffu-

FIGURE 1 A glass (230 mm high) of beer with several "trains" of bubbles. One "train" is enlarged by a factor 2.4 and shown on the right-hand side.

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sivity in Guinness beer is assumed to be 1/1.40 times that in pure water. Because CO_2 and N_2 pressures in beer and champagne are low (<7 bars), pressure-independent Ostwald solubility coefficients (Dean 1985) are adopted.

BUBBLE GROWTH AND VOLUME EXPANSION IN BEER AND CHAMPAGNE

Bubble growth in Budweiser beer has been calculated and compared with the experimental data of Shafer and Zare (1991) (Fig. 2). Budweiser beer contains 2.2 bars of CO_2 (personal communication with the manufacturer). However, bubble growth data obtained by Shafer and Zare (1991) were not for undegassed beer but for beer poured into a glass with loss of the head. Hence, CO_2 pressure should be lower than 2.2 bars, but higher than 1 bar because bubbles still nucleate and grow. We varied CO_2 pressure so that the calculation results matched the experimental data (Fig. 2A), and found that the required CO_2 pressure is 1.63 bars. If the diffusivity of CO_2 in pure water is used (i.e. without applying the correction factor of 1.44 from viscosity), a good match is obtained when the CO_2 pressure in beer is 1.50 bars. The bubble ascent rate has also been calculated using the measured viscosity of beer and matches the experimental data well (Fig. 2B). Note that there is no free parameter in the calculation of the bubble ascent rate. For example, if the viscosity of pure water were used, the theoretical calculation would not match the experimental data.

Bubble growth in champagne (initially containing 6.4 bars of CO_2; Liger-Belair 2004) is expected to be more rapid due to the higher CO_2 content in champagne than in beer. Our

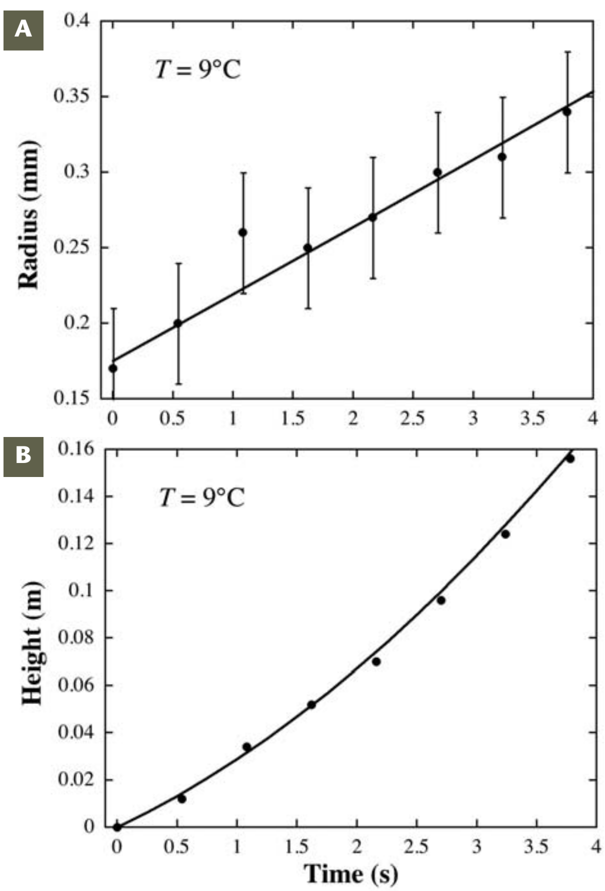

Figure 2 Calculated curves (solid lines) showing bubble radius (**A**) and bubble height (**B**) as functions of time for a glass of Budweiser beer. Compare these with the experimental data (dots) of Shafer and Zare (1991).

calculation shows that the bubble growth rate (da/dt) in undegassed champagne is about 4 times that in undegassed beer, which means that the volume expansion rate of each bubble in champagne is $4^3 = 64$ times that in beer. Assuming a similar bubble nucleation density in beer and champagne, and because the volume of a bottle of champagne is larger than that of a bottle of beer (meaning more bubbles), the total volume expansion rate in champagne is about 100 times that in beer. Because volume expansion powers champagne and beer eruption, the eruption velocity of champagne is 100 times higher than that of CO_2-based beer.

Guinness beer contains about 2 bars of N_2 and 0.014 bars of CO_2 (personal communication with the manufacturer). Although the gas pressure is similar, the concentration of gas in Guinness beer is much lower than in Budweiser beer because the solubility of N_2 is only 1/65 times that of CO_2.

Box 1 **Calculation of Convective Bubble Growth Rate**

Due to convection, there exists a thin boundary layer next to a bubble, with effective thickness δ, across which mass is transported by diffusion (Levich 1962). The diffusive mass flux into the bubble is $D(C_\infty - C_0)/\delta$, where D is the diffusivity of the dissolved gas in the liquid, and C_0 and C_∞ are respectively the solubility (concentration in the interface liquid at saturation) and initial concentration of the gas in the liquid. Hence, dn/dt (where n is the number of moles of gas in a bubble and t is time) equals surface area ($4\pi a^2$, where a is bubble radius) multiplied by the flux:

$$dn/dt = 4\pi a^2 D(C_\infty - C_0)/\delta. \quad (1)$$

The critical unknown is δ, which is obtainable through a relation between three dimensionless numbers, the Sherwood number ($Sh = 2a/\delta$), the Peclet number ($Pe = 2aU/D$, where U is bubble ascent velocity), and the Reynolds number ($Re = 2aU\rho/\eta$, where ρ and η are liquid density and viscosity). The calculation involves the following steps:

(a) Given initial size and depth, calculate pressure P inside the bubble (Proussevitch et al. 1993):

$$P = P_{atm} + \rho g h + 2\sigma/a + 4\eta u/a, \quad (2)$$

where P_{atm} is the atmospheric pressure, g is acceleration due to Earth's gravity, h is the depth of the bubble, σ is surface tension, and u is the bubble growth rate (da/dt). The last two terms in Equation 2 are usually negligible.

(b) Calculate n (ideal gas law):

$$n = (4\pi a^3/3)P/(RT), \quad (3)$$

where R is the gas constant, P is from Equation 2, and T is temperature in Kelvin.

(c) Calculate U: For $Re \le 0.1$, $U = 2ga^2\Delta\rho/(9\eta)$ (Stokes' law), where $\Delta\rho$ is the density difference between liquid and bubble. If $Re > 0.1$ (Re ranges from 4 to 22 for bubbles in Fig. 2), U can be obtained by solving three unknowns (U, Re, drag coefficient C_D) from Clift et al. (1978):

$$Re = 2aU\rho/\eta, \quad (4)$$

$$C_D = \frac{24}{Re}(1 + 0.15Re^{0.687}) + \frac{0.42}{1 + 42500Re^{-1.16}}, \quad (5)$$

$$U = [8ga\Delta\rho/(3\rho C_D)]^{1/2}. \quad (6)$$

The above formulation treats bubbles as rigid, as verified by Shafer and Zare (1991).

(d) Calculate $Pe = 2aU/D$.

(e) Calculate Sh (Zhang and Xu 2003):

$$Sh = 1 + (1 + Pe)^{1/3}\left(1 + \frac{0.096Re^{1/3}}{1 + 7Re^{-2}}\right). \quad (7)$$

(f) Calculate $\delta = 2a/Sh$ (definition of Sh).

(g) Calculate dn/dt from Equation 1. For a given Δt, new n, new h, new P, and new a can be obtained. Then da/dt can be calculated.

Hence, bubble growth rate in undegassed Guinness beer is much lower, only about 1/50 that in undegassed Budweiser beer. Therefore, once released from a widget, the bubbles do not grow much at all in Guinness beer.

The rising velocity of bubbles depends strongly on the size of the bubbles. For example, a bubble with a radius of 0.5 mm rises in beer at 90 mm/s, but a bubble with a radius of 0.03 mm rises at only 1.0 mm/s. This is why in FIGURE 2, although bubble radius varies linearly with time, bubble speed increases with time. Because of their small size, the bubbles in Guinness beer rise slowly and hence can be entrained by downward flow if the downward flow velocity exceeds the small velocity of rising bubbles, which explains why in Guinness beer bubbles are often observed to sink.

The growth and rise of non-interacting bubbles are the focus of this article, but the growth and rise of interacting bubbles require more complex models. Furthermore, many bubbles in liquid can rise as a bubble plume. Bubbles can deform, oscillate, break up, and coalesce. The half-life of foam formed by collecting bubbles varies from beer to beer and from beer to champagne. The quantitative understanding of the rich phenomena will require much more work. Until then, enjoy your drink. Cheers!

ACKNOWLEDGMENTS

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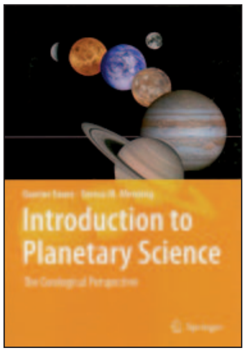
INTRODUCTION TO PLANETARY SCIENCE: THE GEOLOGICAL PERSPECTIVE[1]



Astronomy is rightfully abdicating much of the solar system to geology, as we learn more and more about the geological workings of planets and small bodies. This shift of a substantial quantity of scientific real estate is reflected in the appearance of planetary geoscience courses at many colleges and universities. The preface of this new textbook indicates that it is intended for use in capstone courses taken by senior undergraduate Earth science majors and possibly beginning graduate students. Until now, there has been no appropriate text available.

Introduction to Planetary Science: The Geological Perspective provides some historical background on solar system exploration, especially good sections on stellar evolution, nucleosynthesis, and orbital mechanics, and survey chapters on the solar nebula, the Sun, meteorites, and impact craters. Global-scale processes on the Earth are discussed very well (after all, Earth is a planet too). The terrestrial planets, the Earth's Moon, asteroids, the giant planets and some of their moons, Pluto–Charon and Kuiper Belt objects, and comets are all described in turn, as the chapters march through the solar system in order of increasing heliocentric distance (an organization that is logical and perhaps inevitable, but nonetheless feels encyclopedic). The book ends with interesting discussions of the origin and future of life on Earth and of the successful search for planets around other stars.

The authors, Gunter Faure and Teresa M. Mensing, have produced a book that is remarkably up to date, nicely illustrated, and written in an engaging style. An especially effective touch is that each chapter ends with one or more science briefs, introducing students to especially interesting topics in greater detail. I found no errors, except that refractory compounds in the nebula are described as having high melting temperatures rather than condensing at high temperatures from gas to solid form. Despite its strong points, and there are many, the readers of *Elements* may share some of my concerns. Contrary to the book's subtitle, its geologic perspective is not strong enough for my taste. Planetary mineralogy, petrology, and geochemistry are topics largely missing, although abundant data and interpretations are available for asteroids (meteorites), the Moon (lunar samples and orbital remote sensing), and Mars (meteorites, rover missions, and orbital data). The book contains few descriptions of the imaging, remote sensing, and geophysical techniques that have transformed planets into worlds shaped by familiar geologic processes. Planetary geomorphology fares much better, and there is little to criticize there, although additional information on planetary stratigraphic frameworks, crustal structures, and the methods of planetary geologic mapping would be of interest to geology students. The book's level is also uneven, given that the target audience is advanced geology majors; one might expect a capstone course to use mathematics of a higher level than rudimentary algebra, and might question whether explanations of the scientific method and Bowen's reaction series are necessary.

Those criticisms aside, the book presents an abundance of fascinating information about our cosmic neighborhood, in a form that is readily accessible to students majoring in Earth science. This text will significantly improve teaching and learning about planetary geoscience, and I will be using it for my own undergraduate course, supplemented with other readings.

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[1] Faure G, Mensing TM (2007) Introduction to Planetary Science: The Geological Perspective. Springer, Dordrecht, The Netherlands, 526 pp, ISBN-13 978-1-4020-5233-0, 79,95 Euros