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The complexity of aerosol production from bubble bursting

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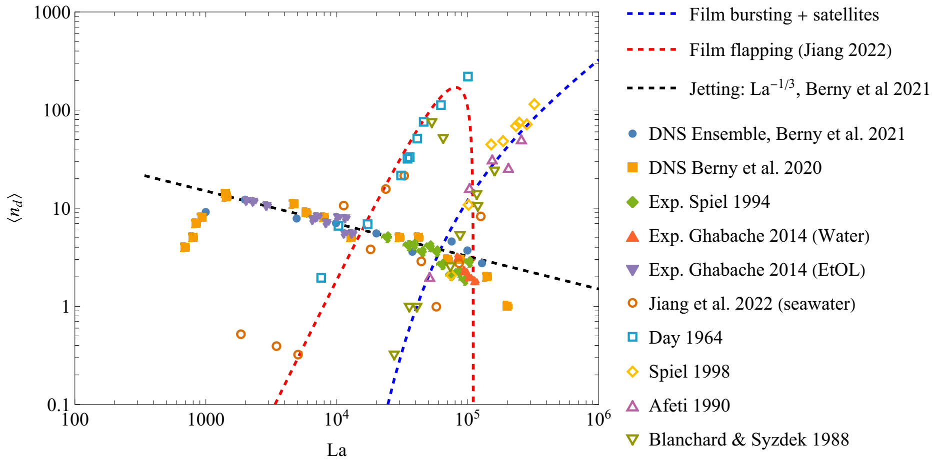

Fig. 1. Number of droplets produced per bubble, according to their attribution to film flapping, film bursting, or jetting by different authors.

Jiang et al. (1) address the fundamental question of the origin of submicron primary sea salt aerosols by proposing the mechanism of film flapping in bubble bursting. To support that, they report detailed experimental measurements of aerosols produced by controlled-size bubble swarms. First, instead of the equivalent bubble volume radius R, Jiang et al. use the bubble cap radius (approximately twice R, for most of the relevant size range) calculated according to Toba (2). However, comparing the average number of particles $<n_d>$ produced per bubble, Jiang et al. mix their data with other works that use the equivalent radius R (ref. 1, figure 3B). The correct comparison is shown here in Fig. 1 using the Laplace number $La = \rho\sigma R/\mu^2$ (ρ, σ, and μ are the liquid density, surface tension, and viscosity).

That comparison collapses much better prior data with Jiang et al.'s (1) (see ref. 1, SI Appendix), and emphasizes the success of Jiang et al.'s proposal in explaining the puzzle of Blanchard and Syzdek (3) in the region for $La > 10^4$ where the jetting mechanism is subdominant. Two observations are as follows:

(i) For $La < 10^4$, Jiang et al. (1) correctly state that their 73-, 137-, and 199-micron bubbles would produce daughter bubbles whose jet droplets would yield particles of 24, 52, and 83 nm, respectively. However, in contrast with the general inconsistency claimed by Jiang et al. for jet droplets, these values agree with their experimental peaks at about 35, 50, and 80 nm (ref. 1, figure 2).

(ii) Fig. 1 shows additional published data for bubble jetting. Since Jiang et al. (1) cannot experimentally discriminate the mechanism producing their aerosols, their measurements should reproduce the number of jet droplets that others report for $La < 10^4$ (4–6). However, Jiang et al.'s values for $La < 10^4$ are at least 30 times smaller. This major experimental inconsistency suggests a possible underperformance of their scanning mobility particle sizer and aerodynamic particle sizer equipment or the inadequate measurement of bubble sizes actually bursting at the water surface. In effect, complex mechanisms involving water supersaturation with air, bubble coalescence, and daughter formation at the water surface (6–8) cannot be ruled out. Hence, the bubble size distribution actually bursting at the surface (7, 8) for their $La > 10^4$ range may contain an indeterminate but significant fraction of bubbles in the actual range $La < 10^4$.

These considerations and the latest model of ref. 9 suggest that a sparse-sized submicrometer jet droplet population should be expected along the whole bubble size range reported by Jiang et al. (1), which is, indeed, consistent with their measurements. However, they exclusively attribute their measurements to film flapping. Furthermore, given that the molecular mean free path in air at atmospheric pressure is about 143 nm, extrapolating to bubbles with $R < 0.2$ mm ($La < 10^4$, with a film thickness less than 10 nm), the same flapping mechanism observed at larger scales might be difficult to justify.

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The author declares no competing interest.

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1. X. Jiang, L. Rotily, E. Villermaux, X. Wang, Submicron drops from flapping bursting bubbles. *Proc. Natl. Acad. Sci. U.S.A.* **119**, e2112924119 (2022).
2. Y. Toba, Drop production by bursting of air bubbles on the sea surface (II) Theoretical study on the shape of floating bubbles. *J. Oceanogr. Soc. Jpn* **15**, 121–130 (1959).
3. D. C. Blanchard, L. D. Syzdek, Film drop production as a function of bubble size. *J. Geophys. Res.* **93**, 3649–3654 (1988).
4. E. Ghabache, T. Séon, Size of the top jet drop produced by bubble bursting. *Phys. Rev. Fluids* **1**, 051901 (2016).
5. A. Berny, L. Deike, T. Séon, S. Popinet, Role of all jet drops in mass transfer from bursting bubbles. *Phys. Rev. Fluids* **5**, 033605 (2020).
6. A. Berny, S. Popinet, T. Séon, L. Deike, Statistics of jet drop production. *Geophys. Res. Lett.* **48**, e2021GL092919 (2021).
7. B. Néel, L. Deike, Collective bursting of free-surface bubbles, and the role of surface contamination. *J. Fluid Mech.* **917**, A46 (2021).
8. B. Néel, M. Erinin, L. Deike, Role of contamination in optimal droplet production by collective bubble bursting. *Geophys. Res. Lett.* **49**, e2021GL096740 (2022).
9. A. M. Gañán-Calvo, J. M. López-Herrera, On the physics of transient ejection from bubble bursting. *J. Fluid Mech.* **929**, A12 (2021).