Ice Nuclei Production in Volcanic Clouds

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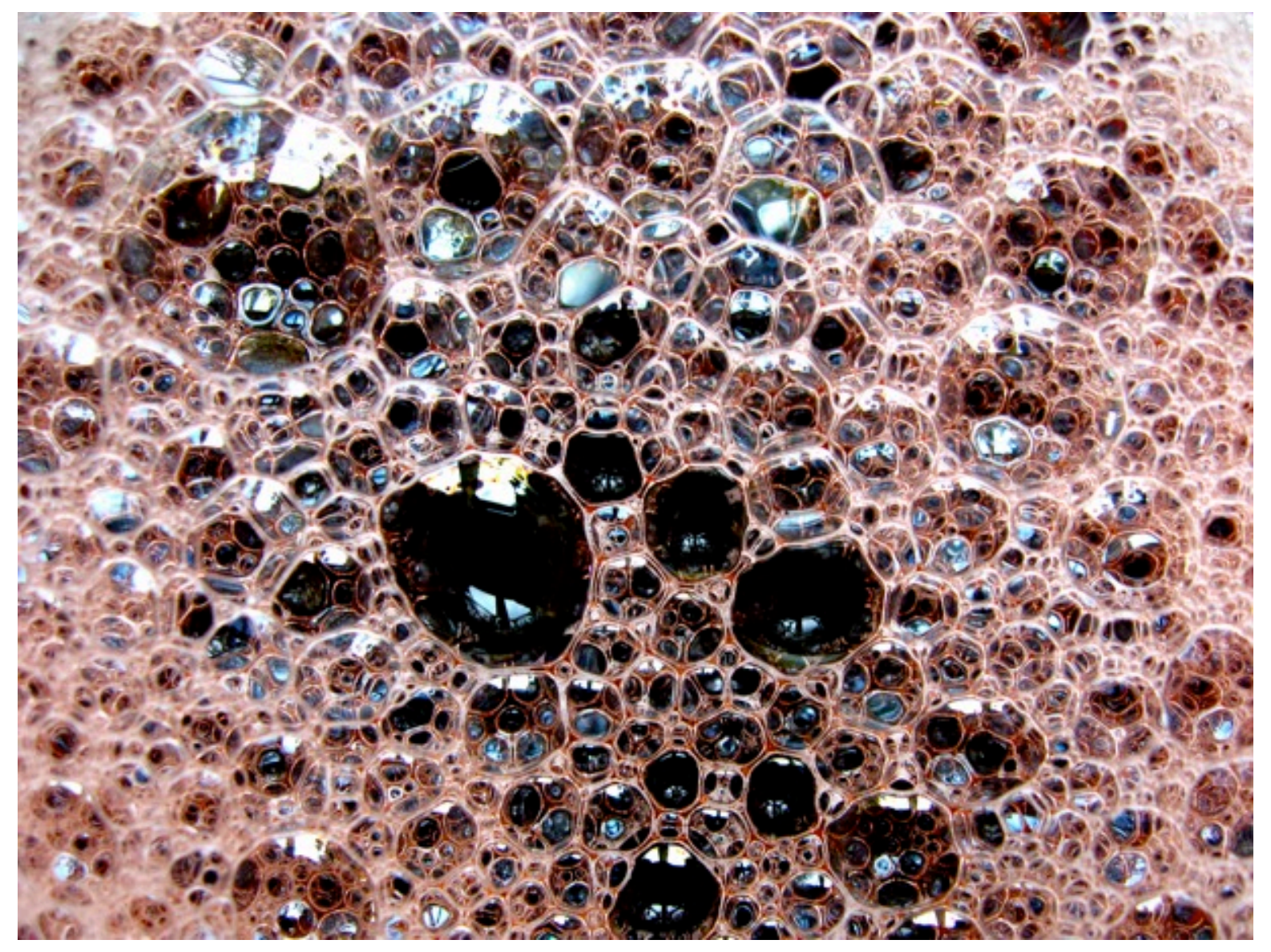
Arthur A Few
Professor Emeritus
Rice University Physics and Astronomy
few@rice.edu
www.ruf.rice.edu/~few
700 Hill Street – Gold Hill; Boulder Colorado 80302–8786

Bubbles

Bubbles are the product of surface tension in fluids, and to the extent that fluids are ubiquitous in our Earth-surface environment, we find bubbles in most liquids. In your morning cup of coffee the bubbles typically form a single layer and then evolve by merging and bursting. When bubbles form in multiple layers we call them foam or froth when dense. The foam photo left is red wine with a drop of dish soap to stabilize the bubbles for photographing. Note that you can see through some of the larger bubbles and see smaller bubbles beneath them; this would qualify as a thin foam. You will note that all of the bubbles are touching other bubbles and very small bubbles fill in the spaces around the larger bubbles.

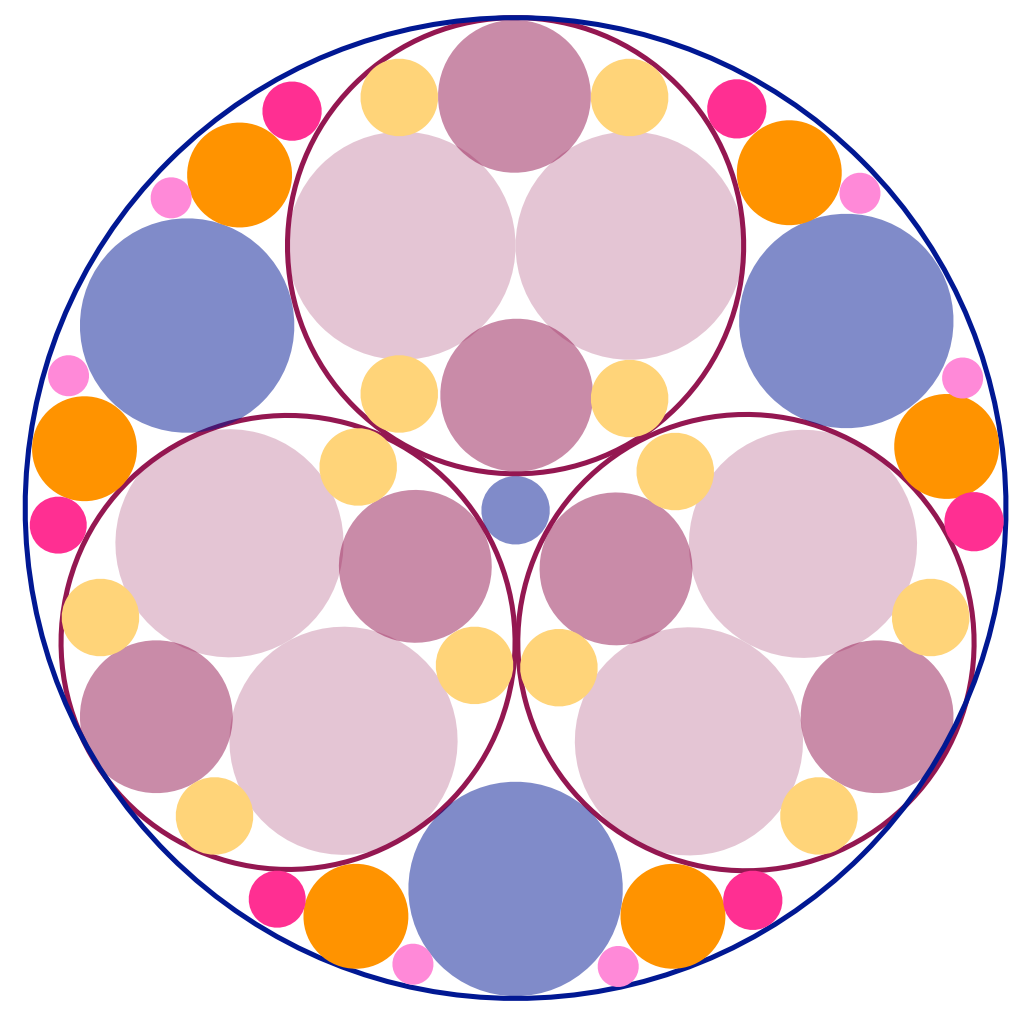


The arrangement of touching circles in two dimensions is called Apollonian Gaskets; there is a mathematical relationship among all of the circles. For any four touching circles with radii “a”, “b”, “c”, and “d” there is a mathematical relationship originally postulated by Rene’ Descartes’:

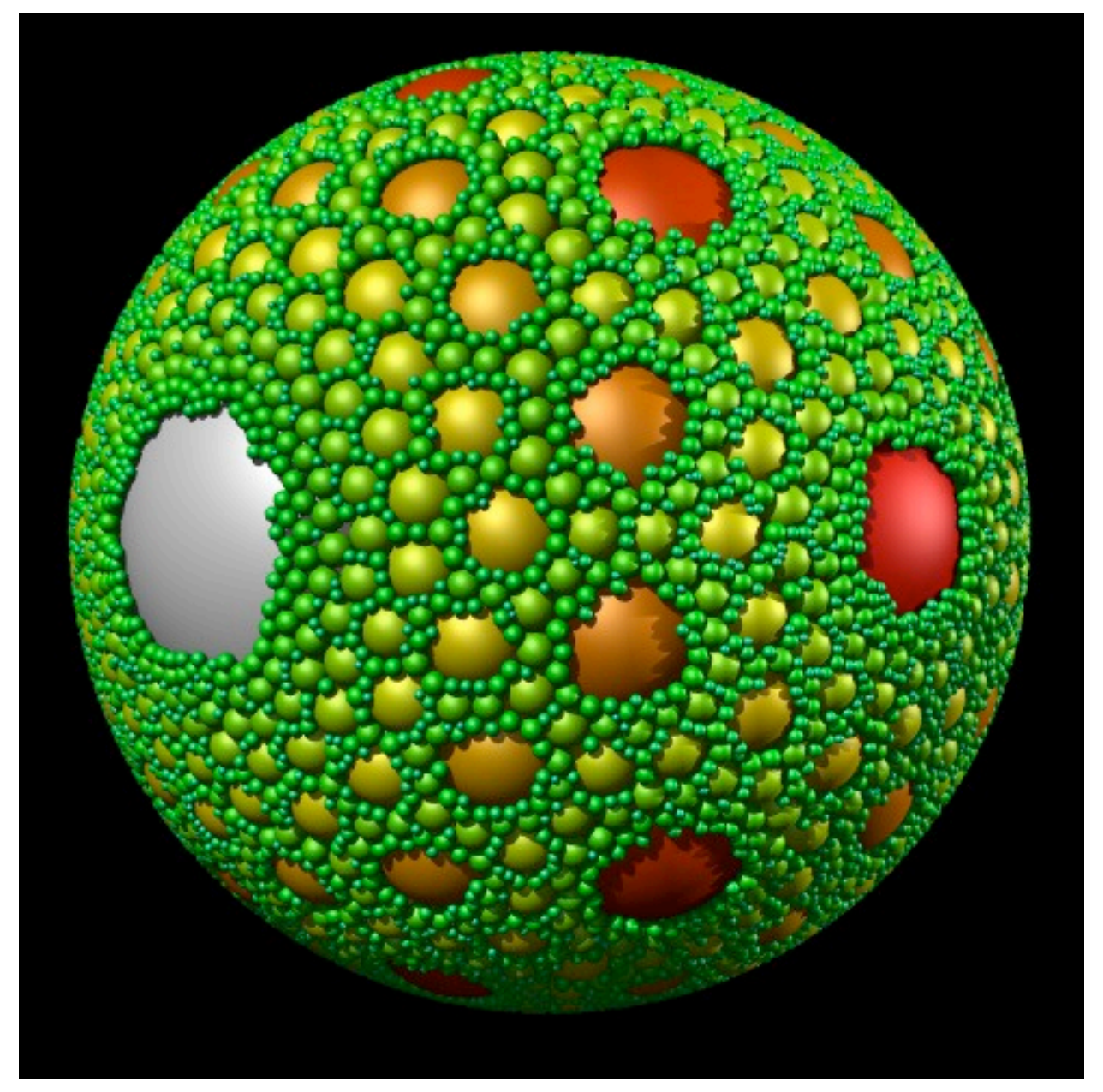
$$(1/a^2 + 1/b^2 + 1/c^2 + 1/d^2) = 1/2(1/a + 1/b + 1/c + 1/d)^2.$$

Using this relationship and starting with three touching circles the forth touching circle can be found. Actually owing to the quadric relationship there are two “forth” touching circles; an inner and an outer.

In the figure to the right there are three large interior touching circles of equal size; one solution to the quadratic equation above is the large circle containing the figure; the other solution is the small blue circle in the center of the figure. In the foam above left you will see a similarity in the behavior of the bubbles; there is a tendency to fill the space with touching bubbles of the appropriate size.

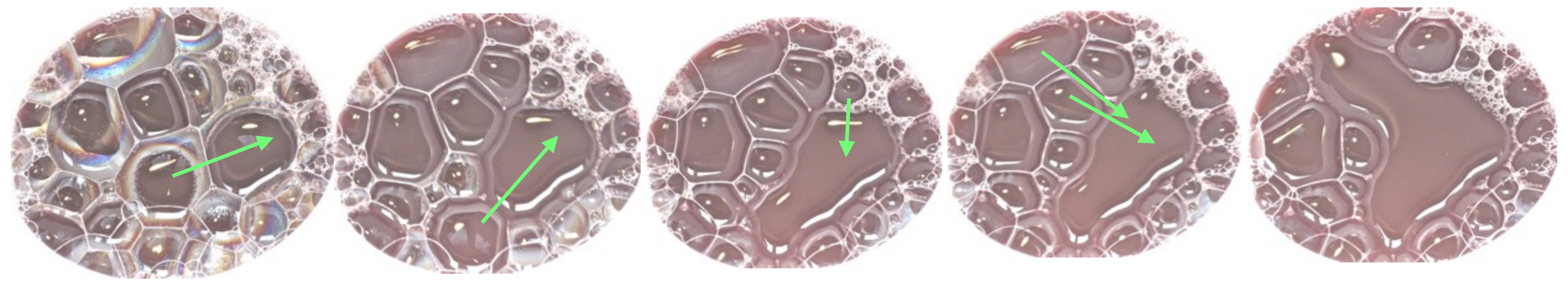


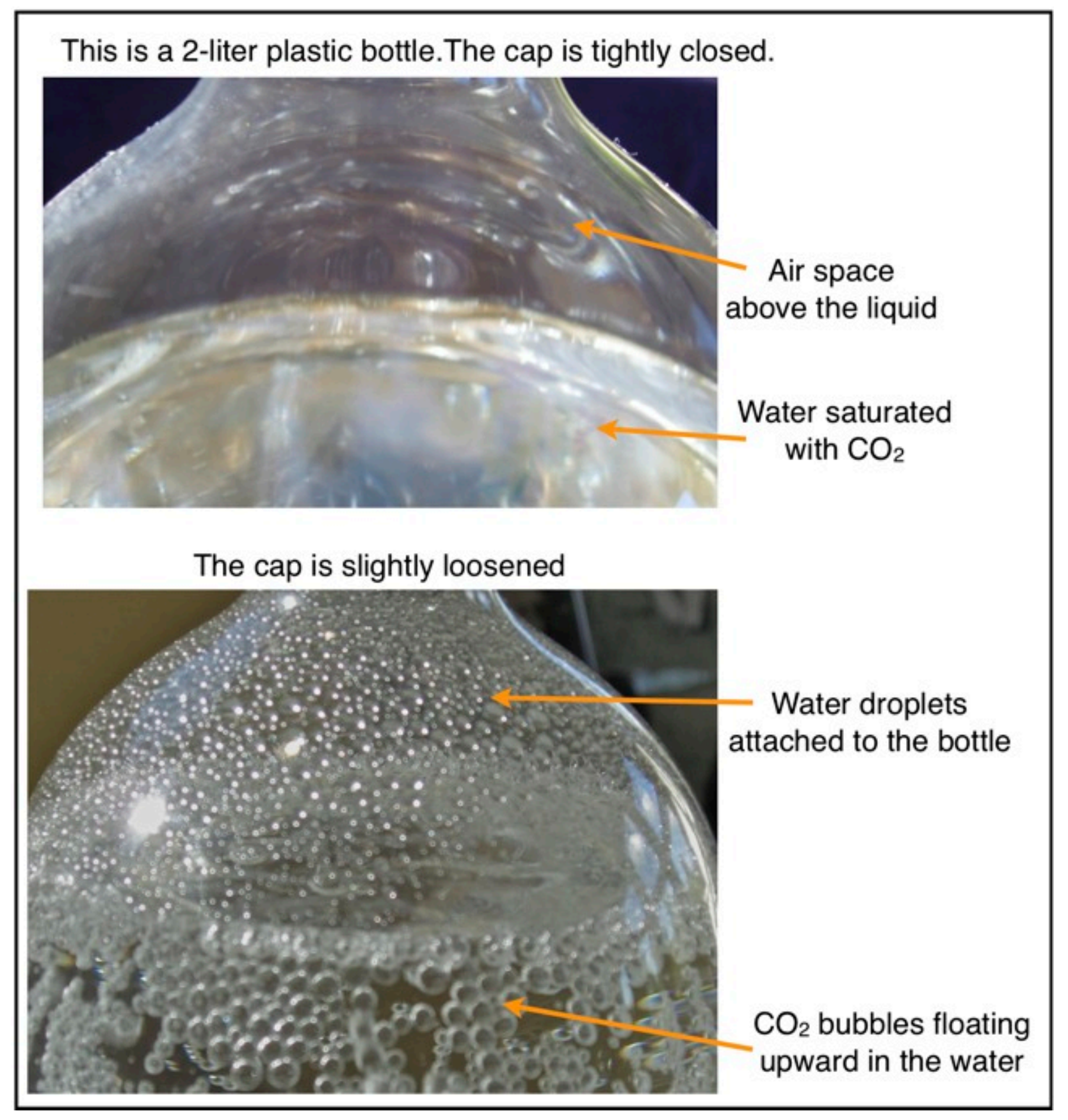
Apollonian sphere packing is the three dimensional equivalent of the Apollonian gasket. The figure below is from Wikipedia; the mathematics for the three dimensional packing is much more complex.



For a single bubble the surface tension compresses the gas inside; the smaller the radius the greater is the surface tension and the greater is the internal pressure. When two bubbles are in contact there is a partial shared surface, which distorts the spherical shapes. Again, it is the smaller bubble with the higher internal pressure that usually penetrates the surface and merges with the larger bubble. This is how bubbles grow, and also how they weaken and become less stable.

In the sequence of bubbles below I have used stabilized red wine and created larger bubbles by blowing in the fluid with a soda straw. This sequence of photos was taken over a period of 3 minutes. The green arrows follow the sequence of bubble mergers from left to right; the mergers are always smaller bubble into larger bubble. The final photograph on the far right is the result of two bubble mergers as shown in the fourth photograph. The bubble nearest the large elongated bubble merges first followed by the bubble on the edge. The final result of these bubble mergers is a large highly distorted bubble. The highly distorted bubbles are a result of the stabilization with the soap; without this the bubbles would remain slightly distorted spheres and would burst. Using stabilized bubbles allows us to observe the sequence of merging.





In the simple experiment shown on the left we can demonstrate a consequence of bursting bubbles. Starting with a 2-liter plastic bottle containing carbonated water with a tightly closed lid, we see in the upper photo the surface of the water and the clear air space above the surface. Then as we slightly loosen the lid bubbles are produced as the CO_2 precipitates out of the water. In the lower photo we see the bubbles floating toward the top of the water while contacting the side of the bottle and other bubbles. Note the close packing of groups of bubbles along the side of the bottle. When floating on the surface, bubbles merge and burst. The bursting disrupts the bubble’s water skin and the internal pressure of the bubble disperses the fragments. In the photo to the left some of the fragments have attached to the upper surface of the bottle. Although there is similarity in their appearance to bubbles they are actually droplets.

When dealing with bubbles in magma the conditions are very different but the consequents are similar. Instead of water bubbles being being dispersed as water drops, we have volcanic ash being dispersed.

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ABSTRACT BODY: The paper [Durant *et al.*, 2008] includes a review of research on ice nucleation in explosive volcanic clouds in addition to reporting their own research on laboratory measurements focused on single-particle ice nucleation. Their research as well as the research they reviewed were concerned with the freezing of supercooled water drops (250 to 260 K) by volcanic ash particles acting as ice freezing nuclei. Among their conclusions are: Fine volcanic ash particles are very efficient ice freezing nuclei. Volcanic clouds likely contain fine ash concentrations 104 to 105 times greater than found in meteorological clouds. This overabundance of ice nuclei will produce a cloud with many small ice crystals that will not grow larger as they do in meteorological clouds because the cloud water content is widely distributed among the numerous small ice crystals. The small ice crystals have a small fall velocity, thus volcanic clouds are very stable. The small ice crystals are easily lofted into the stratosphere transporting water and adsorbed trace gasses.

In this paper we examine the mechanism for the production of the small ice nuclei and develop a simple model for calculating the size of the ice nuclei based upon the distribution of magma around imbedded bubbles. We also have acquired a volcanic bomb that exhibits bubble remnants on its entire surface. The naturally occurring fragments from the volcanic bomb reveal a size distribution consistent with that predicted by the simple model.

Durant, A. J., R. A. Shaw, W. I. Rose, Y. Mi, and G. G. J. Ernst (2008), Ice nucleation and overseeding of ice in volcanic clouds, J. Geophys. Res., 113, D09206, doi:10.1029/2007JD009064.

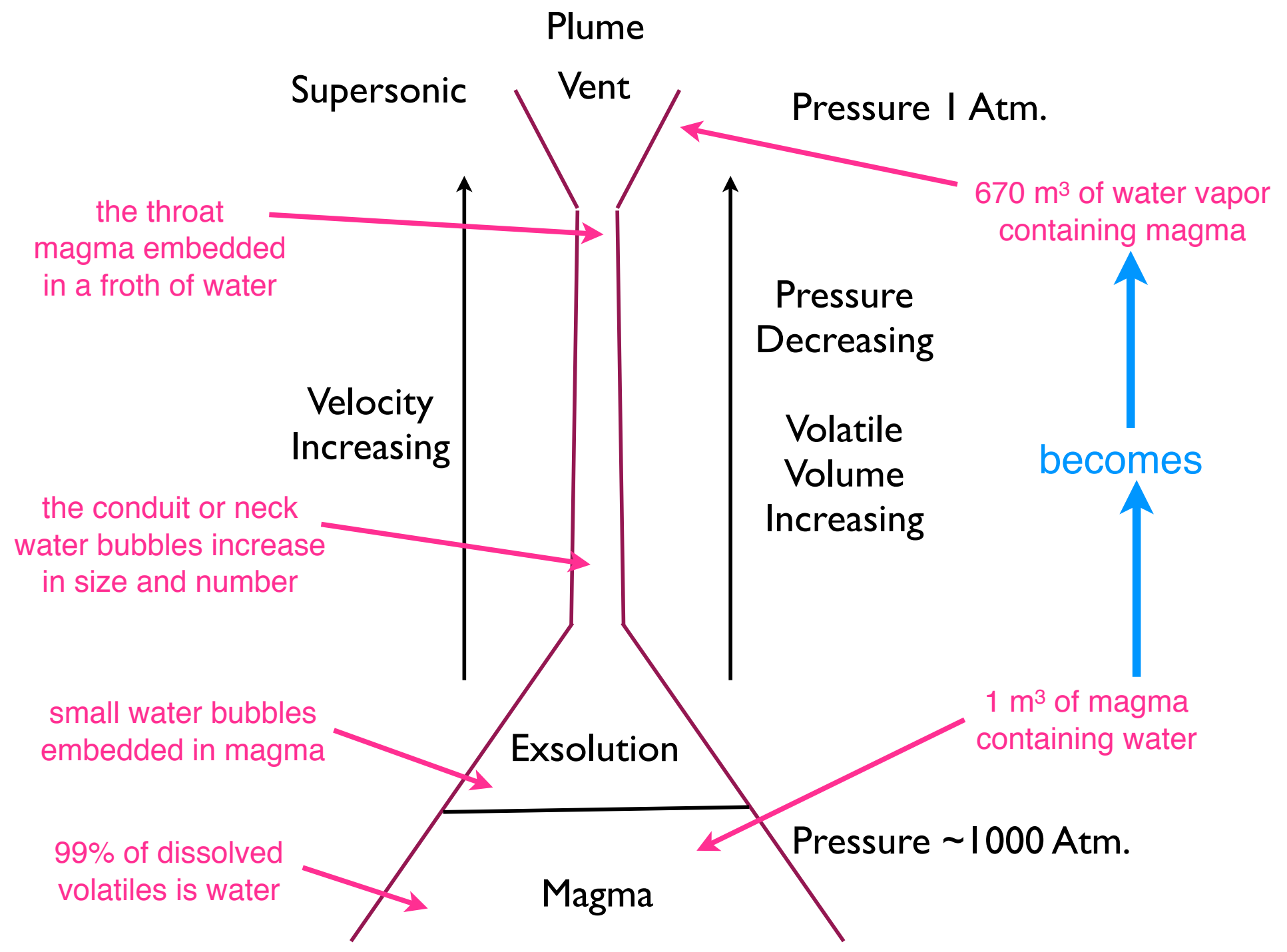

Figure 1

Drawing above is based upon Sparks *et al.*[2]

Explosive Volcanos

The explosive force in explosive volcanos is produced by rapidly expanding water vapor bubbles. See the drawing to the left. In the magma chamber prior to the development of the conduit the magma contains water in solution; up to 7% of the mass. As the magma expands upward the pressure decreases and the water comes out of the magma to form small water vapor bubbles, exsolution. The bubbles increase in number and size as additional exsolution proceeds. The bubbles greatly increase the volume of the magma and produce an upward force by the magma, which leads to the development of the conduit. As the magma with bubbles moves upward in the conduit, the decreasing pressure accelerates bubble production and growth. Near the top of the conduit the bubbles become a froth; instead of bubbles imbedded in magma, we now have magma imbedded in a froth of water vapor bubbles. In the vent the external pressure drops to local atmospheric pressure and many of the bubbles burst ejecting the thin film of magma covering. The fragments of bubble film become volcanic ash and the smaller ones are ice nuclei.

It is possible to estimate the size of the bubble fragments using the information provided by Sparks *et al.*[2] above and shown in Figure 1.

Radius of bubble	Number/m³ of magma	Thickness of skin
0.1 mm	$2 * 10^{14}$	0.05 μ
1 mm	$2 * 10^{11}$	0.5 μ
10 mm	$2 * 10^{8}$	5 μ
100 mm	$2 * 10^{5}$	50 μ

1 m^3 of magma in the magma chamber containing water in solution expands to 670 m^3 of water vapor and magma in the vent. Approximately 670 m^3 are water vapor bubbles and 1 m^3 is the magma film around the bubbles. Assuming an average bubble radius, r, for the bubbles, the volume of the average bubble will be $V = (4 \pi r^3)/4$, and the surface area will be $A = 4\pi r^2$. If all bubbles were average, which they aren’t, the number of bubbles, N, would be $N = 670\ m^3/V$, and the skin thickness would be $T = 1\ m^3/N{*}A$. The table to the left was generated using these simple relationships; the thicknesses calculated are in the range of sizes for small ash and ice nuclei. This size range is consistent with the sizes of the bomb fragments in the photo far right (next column). Durant *et al*[1] identify fine-ash particles in the 1 to 1000 μm range are probable ice freezing nuclei.

Acknowledgments

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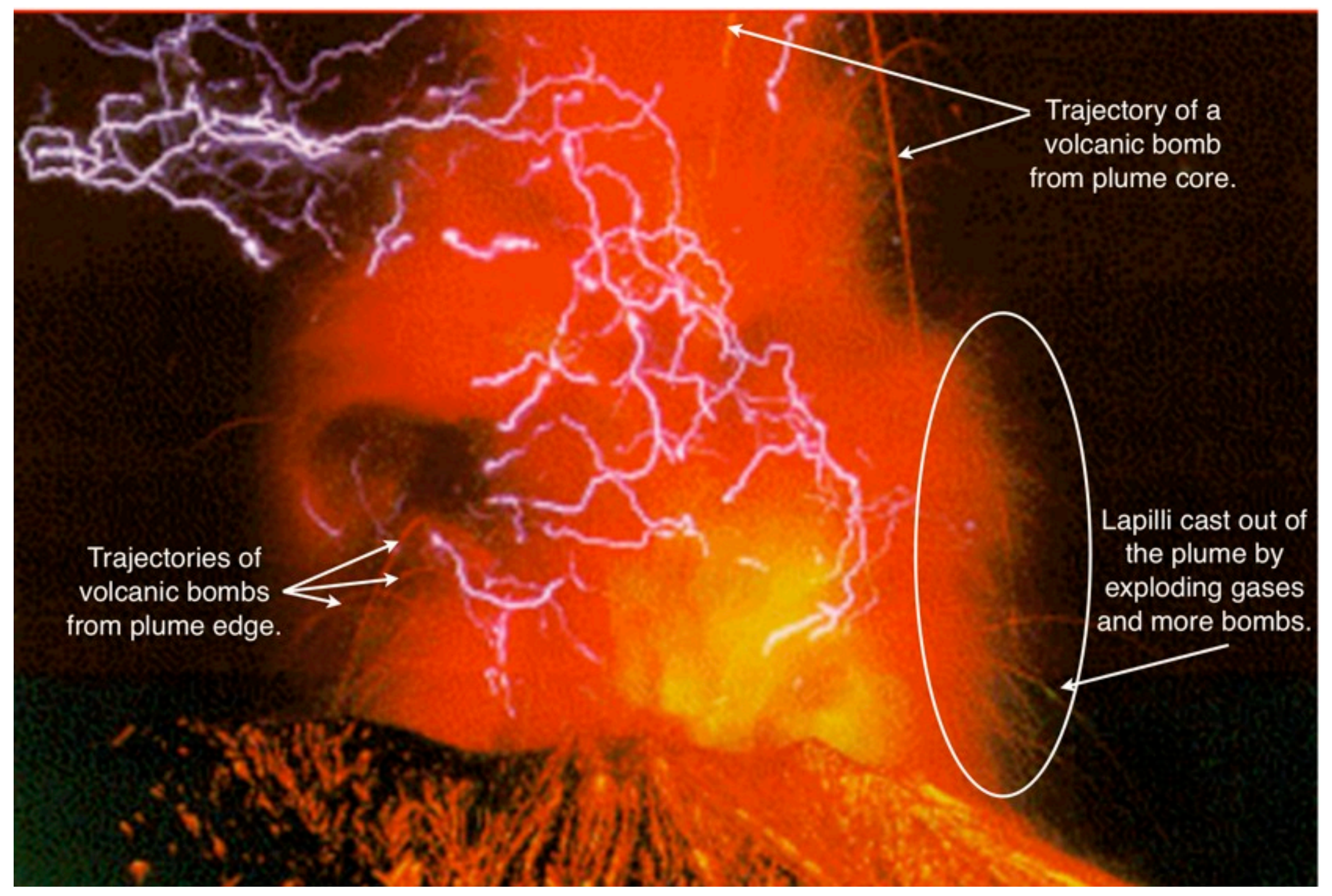
I wish to thank Ulyana Horodyskj and Paul Boni, Earth Sciences University of Colorado, for cutting the bomb.

References

1. Durant,A. J., R. A. Shaw, W. I. Rose, Y.MI, and G. G. J. Ernst (2008), Ice nucleation and overseeding of ice in volcanic clouds, *J. Geophysical. Res.*, **113**. D09206, doi:10.1029/2007JD009064.
2. Sparks, R. S. J., M. I. Bursik, S. N. Carey, J. S. Gilbert, L. S. Glaze, H. Sigurdsson, and A. W. Woods (1997), *Volcanic Plumes*, 574 pp., John Wiley, Chichester, U. K.
3. Mackenzie, Dana, A Tiskit, a Taskit, an Apollonian Gasket(2010), pp. 10 -14. American Scientist, Volume 98 Number 1.

Volcanic Bomb from Eyjafjallajokull (Ay-ya-fyadd-la-Yo-kuddl)



Sakurajima Volcananological Observatory; volcanic lightning, May 18, 1991.

The general term for products of a volcanic plume is tephra; which includes:

ash < 2 mm
2 mm < lapilli > 64 mm
bomb > 64 mm.

In the nocturnal time exposure photo to the left, the prodigious lightning activity is the eye catcher, but there are details of the volcanic plume that deserve close examination. Note the supersonic core of the plume and the interactions of the lower edges with the ambient atmosphere. This photo captures several tracks of glowing volcanic bombs.

The photo right is the Eyjafjallajokull volcano; this photo was taken on June 13, 2012, during an excursion of the AGU Chapman Conference on Vulcanism and the Atmosphere; Selfoss, Iceland, 10-15 June 2012. The Eyjafjallajokull volcano in southern Iceland began erupting on 2010 March 20, with a second eruption on 2010 April 14. The second eruption, broke through the caldera wall allowing lava to flow out onto the glacier. The lava flow and frozen melt water are evident in the center of the photo.

In the foreground is the sandur from the Eyjafjallajokull glacier; among the larger objects are many volcanic bombs; see photos below.

In the upper photo left a volcanic bomb is in place on the sandur; nearby there are smaller bombs. These bombs all show surface pits, which are the remnants of the water vapor bubbles. The tops of these bubbles were blown off and became tephra. In the lower left of the photo is ash.

In the lower left photo I am holding a volcanic bomb for a closeup photo. Note the wide variation in sizes of the bubble remnants. Even the curvature of the bubbles is evident, as are non-spherical pits produced by bubble merging.

I have used the bomb to the left to make further studies of bombs and their debris. When placed on my desk I noticed after several days that it was shedding small black particles. I moved the bomb to a shelf and placed it on white printer paper. Every couple of days I would rotate it so a different side was down, and I collected the fragments seen in the photo below. There is a broad range of fragment sizes. I have placed a human hair in the photograph with a measured diameter equal to 0.04 mm. The smallest fragments are difficult to see; some appear gray rather than black, but there are ample examples of fragments ≤ 40 μ.

I wanted to know what was inside the bomb, so I arranged to have it cut and a thin slice (~ 6 mm) prepared. The photo to the left shows the two sides of the thin slice. Note that the bubble-hole cross sections are not circular but are elongated and the long axes are aligned. It appears that the bomb experienced a sheer force while in a plastic state.