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Genies in Jars, Clouds in Bottles, and a Bucket with a Hole in It

But presently there came forth from the jar a smoke which spired heavenwards into ether . . . and which trailed along earth's surface till presently, having reached its full height, the thick vapor condensed, and became an Ifrit [genie, also spelled jinni].

The passage at the head of this chapter is from "The Fisherman and the Jinni," one of the tales from the *Arabian Nights*. When the fisherman in this tale uncorked the jar, its contents expanded rapidly into the surroundings, and the vapor it contained condensed into a genie. So also does water vapor in expanding air condense into cloud droplets.

A CLOUD IN A BOTTLE

I am unable, alas, to conjure a genie from a jar. But I can make a cloud in a bottle, and so can you. I use a large bottle, half of which is painted black so that the cloud will be more noticeable when illuminated by a bright light. The bottle should have a stopper with a hole in it. Put a little water in the bottle, just enough to cover its bottom, and blow hard into a length of tubing inserted through the hole in the stopper. Seal the end of the tubing with your finger, then release it suddenly. The result is likely to be disappointing (Fig. 2.1) because I have forgotten something: more particles are needed. Since the bottle is an enclosed space, many of the particles in it have either settled out or have diffused to the walls, especially if it has been stoppered for a long time (see the previous

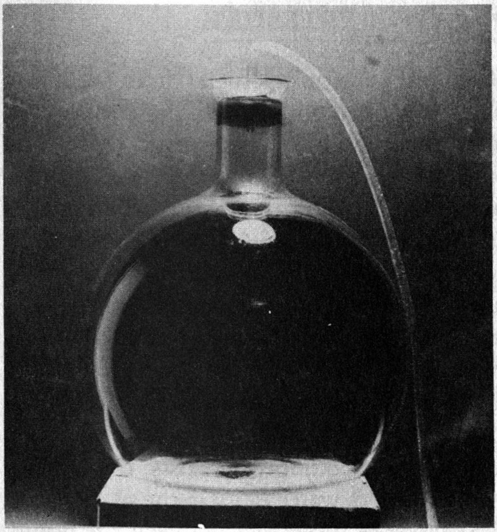

Figure 2.1 An unsuccessful attempt at making a cloud in a bottle. Photograph by Gail Brown.

chapter). Particles are provided readily enough by a smoldering match. First decrease the pressure in the bottle by sucking out some of the air. Wave the match near the end of the tubing; as air rushes back into the bottle, it will carry with it some of the smoke. Now try once again to make a cloud. This time your efforts are more likely to be met with success (Fig. 2.2); if not, try adding more particles. To understand why the cloud forms and what the particles have to do with it, I must first discuss a few concepts and elucidate them with further demonstrations.

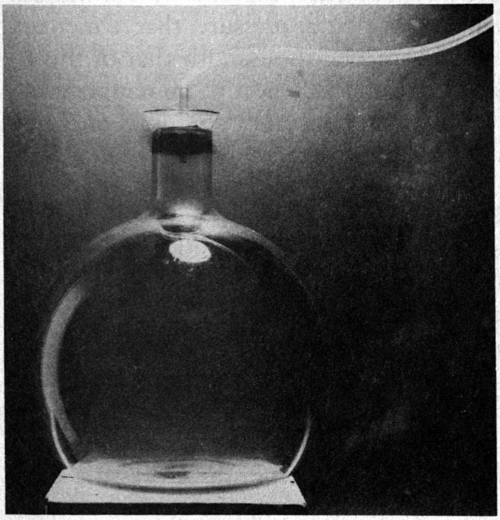

Figure 2.2 A successful attempt at making a cloud in a bottle. Photograph by Gail Brown.

SATURATION VAPOR PRESSURE

Let us consider a hypothetical experiment; we won't actually do it, we'll just imagine it to be done. Take a bottle, partly filled with water, and cork it. But before corking it, remove all the water molecules from the space above the liquid surface. This space will not, however, remain free of water molecules for long. Molecules in the liquid are continually jostling about and colliding with one another. Every now and then a molecule will acquire a bit of extra energy from its neighbors, sufficient to allow it to overcome their attraction, and will escape into the space above the liquid. This will occur again and again at a very rapid rate. As the number of water molecules—water in the gas phase—in this space increases, the rate at which they return to the liquid also increases. Eventually, the rate at which water molecules leave the liquid phase and enter the gas phase—the rate of *evaporation*—is balanced by the rate at which the reverse process—*condensation*—occurs. Thus a dynamic equilibrium exists: the level of the liquid remains constant as does the amount of water vapor in the space above it, although there is a continuous exchange of molecules between the liquid and gas phases. When equilibrium is reached, the *partial* pressure of the water vapor (small compared with the *total* pressure, the sum of partial pressures contributed by each of the constituents of air) is called the *saturation vapor pressure*. But equilibrium vapor pressure would be a better term: "saturation" evokes, incorrectly, the image of a sponge. There is no end of blather about the "holding power of air" and how air can "hold" more water vapor at high temperatures than at low temperatures; this implies that in air there is only so much space—like rooms in a hotel—between air molecules, and when filled with water molecules the air is saturated, just like the pores of a sponge. But air doesn't "hold" water vapor—it coexists with it. Indeed, the presence of air (oxygen, nitrogen, etc.) in the space above the liquid is largely immaterial: the pressure of a vapor in equilibrium with its liquid would be nearly the same with or without air. It is worth noting here that *everything* has a vapor pressure; that of mercury at room temperature, for example, is about one-thousandth that of the atmosphere at sea level. That of most solids, especially near room temperature, is very much lower—but it is not zero. Your skin has a vapor pressure. Fortunately, it is rather low or you wouldn't be here to read this—you would have evaporated away long ago.

If the notion that air "holds" water vapor were correct it would necessarily follow that the saturation vapor pressure would increase if the distance between air molecules were increased by reducing the air density, thereby providing more room for water molecules. But the saturation vapor pressure above a flat surface of pure water depends only on temperature (this will be qualified ever so slightly in Chapter 4), and it increases with increasing temperature. Why this is so is easy to understand. The greater the temperature, the greater the energy of the molecules in the liquid and the easier it is for them to escape. And the greater the rate of evaporation, the greater will be the vapor pressure once equilibrium is reached. A bucket with a hole in it helps to explain why by analogy.

A BUCKET WITH A HOLE IN IT

Make a hole near the base of an empty bucket (a plastic bottle will serve just as well); then pour water into it, from a tap for example, at a constant rate. Any liquid would do, water is just the handiest. Initially there is no water in the bucket so none can leak out. As the water level rises, however, the rate at which water leaks from the hole will increase. Eventually, the water will leak out as fast as it pours in, and the water level will be constant—dynamic equilibrium has been reached. Now increase the rate of inflow—give the tap a twist. The water level will rise to a new, higher equilibrium level. The height of water in the bucket once equilibrium is reached is analogous to the saturation vapor pressure above a liquid (or a solid for that matter); the constant rate of inflow is analogous to the rate of evaporation of the liquid; and the rate at which water leaks out of the hole is analogous to the rate of condensation of vapor. Moreover, the equilibrium height of water in the bucket depends only on the rate of inflow. By analogy, therefore, the saturation vapor pressure depends only on the rate of evaporation, which in turn depends only on the temperature. So the saturation vapor pressure is in one sense merely a measure of the rate of evaporation, and it is often advantageous to look at it this way.

HOW DOES A CLOUD DROPLET FORM?

Two qualifications crept quietly into the previous discussion: I stated in passing that the saturation vapor pressure above a *flat surface of pure water* depends on temperature only. What if the surface is not flat? Or the water not pure?

The rate of evaporation from a water droplet increases with decreasing radius because a water molecule at the surface has fewer neighbors attracting it. So the smaller the droplet the easier it is for a water molecule on its surface to escape. As far as evaporation is concerned, droplets larger than about 1 μm (a millionth of a meter) are flat surfaces. But the rate of evaporation from a droplet of radius 0.001 μm, for example, is more than three times that from a droplet of radius 1 μm, both at the same temperature. Just as every general was once a lieutenant, and every frog once a tadpole, every cloud droplet of radius 10 μm, say, was once much smaller: cloud droplets grow, they aren't hatched fully fledged. This presents us with a puzzle. For a droplet to grow it must be in an environment such that the rate of condensation is greater than the rate of evaporation, which makes rather severe demands on the environment.

Relative humidity is usually defined as the actual vapor pressure of water divided by its saturation vapor pressure above a *flat surface of pure water* at a given temperature. Another definition, one which I much prefer because it incorporates physical processes, is that it is the rate of condensation relative to the rate of evaporation. If a cloud droplet of radius 0.001 μm is not to shrink, the relative humidity of its environment must be greater than 300 percent because the rate of evaporation from such a small droplet is about three times that from a flat surface. Such relative humidities are not observed in the atmosphere. I do not doubt the existence of clouds, they are a matter of everyday experience; yet I have just presented an argument that calls their existence into question. There must be more to the formation of clouds than I have yet revealed.

A DEMONSTRATION WITH SALT GRAINS

Cloud droplets can avoid being very small by beginning their existence as solid particles, or *condensation nuclei* (see the previous chapter). If water vapor condenses on a nucleus of radius 0.1 μm, say, growth is possible in an environment with a modest amount of supersaturation (relative humidity in excess of 100 percent), a few percent or less. And if the condensation nucleus is soluble, so much the better: the saturation vapor pressure above a solution is less than that above pure water, both at the same temperature (the reason for this is discussed in Chapter 4). Thus a salty water droplet will evaporate at a slower rate than a pure water droplet, both of which are the same size and at the same temperature. This may be demonstrated with grains of table salt even though they are enormous compared with particles in the atmosphere.

Sprinkle a few salt grains onto the lid of a tin can elevated above the bottom of a dish (Fig. 2.3); bent paper clips serve nicely as supports for the lid. For classroom demonstrations I put the salt grains on a glass slide in a Petri dish, a transparent glass dish used for growing bacterial cultures, and project their image onto a screen as far from the projector as possible to obtain the greatest magnification. Note in Figure 2.3 that the grains are mostly cubes. Now carefully add some water to the dish, just enough to wet the bottom, and then cover it. If you wait a bit, perhaps twenty minutes or more, the cubes will be transformed into hemispheres (Fig. 2.4). Water evaporates from the liquid and condenses onto the salt grains; in so doing it dissolves them. Of course, water also

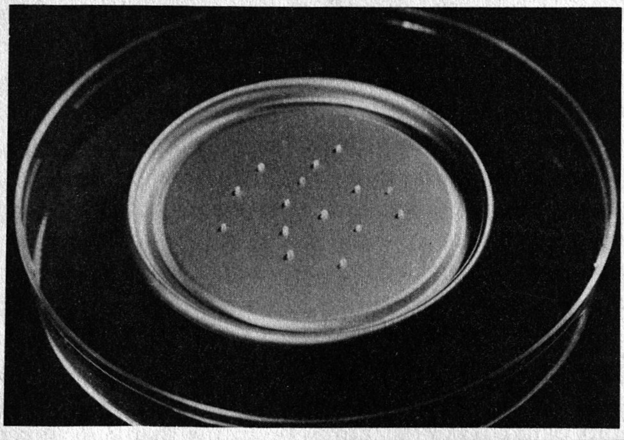

Figure 2.3 Dry salt grains elevated above the bottom of a dish.

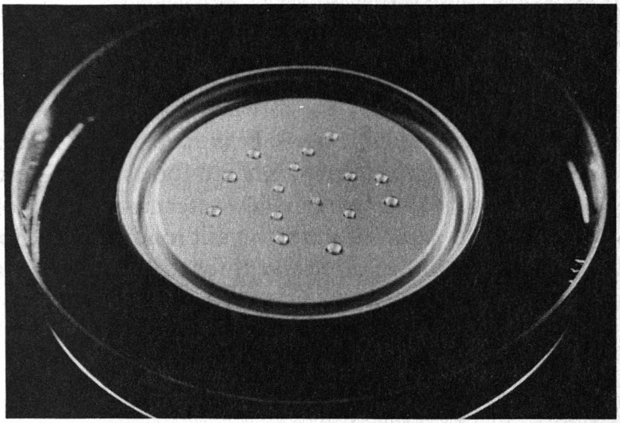

Figure 2.4 The grains of Figure 2.3 are transformed into salty water droplets when a little water is put in the dish and it is covered.

evaporates from the grains, but at a slower rate than from the pure water. Hence there is a net transfer of water from the bottom of the dish to the grains. Given enough time each grain will completely dissolve and in its place will be a droplet of salty water. A very thin film of oil on the surface holding the salt grains results in more pronounced droplets (see Chapter 7). The grains accumulate water only in an environment with a high relative humidity, about 80 percent or higher. Unless you are in a very humid room, therefore, the droplets will evaporate when the disk is uncovered, each leaving in its wake a residue of salt (Fig. 2.5).

Salt particles are just one among many types of condensation nuclei. How does salt get into the atmosphere? When students are asked this question, the

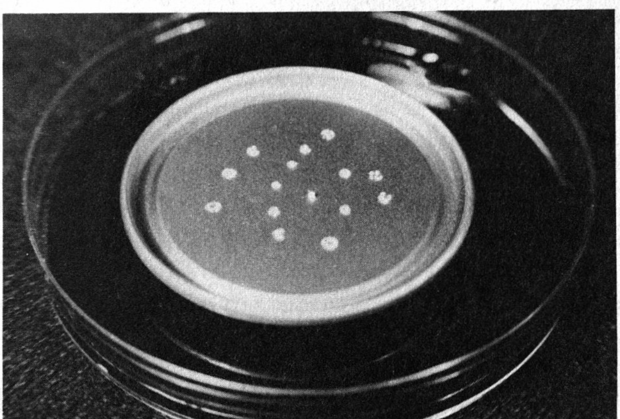

Figure 2.5 The water droplets in Figure 2.4 evaporate when the dish is uncovered leaving behind a residue of salt.

usual response is evaporation of ocean water. Yet, as we have seen, when salty water evaporates, the salt is left behind; it doesn't evaporate into the air. The mechanism by which salt gets into the atmosphere forms one of the more interesting chapters in cloud physics, and a fascinating discussion of it is given in Duncan Blanchard's very readable book *From Raindrops to Volcanoes: Adventures with Sea Surface Meteorology*. In brief, when bubbles of entrained air break through the ocean surface small droplets of salt water are formed; some of these are carried away by updrafts and evaporate; this salt residue, in the form of small particles, can then serve as condensation nuclei for clouds far away in space and time.

BACK TO THE CLOUD BOTTLE

At last we have done enough to explain the first demonstration. After increasing the total pressure in the bottle by blowing into it, and then suddenly releasing the pressure, a visible cloud was formed—if there were enough particles in the bottle. When air rushes out of the bottle, the air left behind cools rapidly. Cooling upon expansion is familiar to anyone who has ever noticed a pressurized spray can cool; sometimes ice even forms on the can. As the air in the bottle cools, the rate of evaporation of water from the particles decreases. The rate of condensation also decreases because water vapor was lost from the bottle (this water vapor would be replenished from the liquid water in the bottle in a minute or more, but the cloud forms in a much shorter time). Evaporation depends so strongly on temperature, however, that the decrease in evaporation exceeds that in condensation. Condensation therefore exceeds evaporation, and the nuclei grow rapidly into droplets large enough to strongly scatter light thereby making their presence visible.

I leave it to your ingenuity to put the proper ingredients—liquids, solids, and particles—into a jar to ensure that a genie condenses out of the gas phase when the jar is uncorked.