Anomalous Persistence of Evaporating Dense Sprays

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This proposal aims at initiating new research for understanding the Anomalous Persistence of Evaporating Dense Sprays which are, in nature and artifacts, the rule rather than exceptions. The question of the lifetime in air of aerosols droplets following, for example, an exhalation is not obvious. These droplets are usually formed in a swarm, with broadly distributed sizes and nearby spacing so that the academic picture of the unique droplet evaporating on its own in a dry environment is an inadequate paradigm. These sprays can be impressively more persistent than expected, a fact which applies to, but prevails beyond the context of disease transmission by coughing or sneezing, or pollutant transport by agricultural spreading. We explain why new research, guided by old but seemingly forgotten findings, is necessary to progress on this issue.

I. MOTIVATIONS

The ongoing Covid-19 pandemic has led to devastating losses in many respects worldwide. The impact of the virus has been linked to a number of factors among which, in particular, its long lifetime on solid surfaces and airborne contagion by postillon from speech, couching and sneezing. To quote the WHO, the virus "spreads primarily through droplets of saliva or discharge from the nose when an infected person coughs or sneezes", which highlights the prominent role played by human exhalations on disease transmission.

It is known that viruses are sensitive to their environment and, while this question is not firmly settled yet, that they are more persistent in an aqueous environment. The question of the lifetime in air of aerosols droplets following an exhalation is thus crucial. This is not an obvious question since these droplets are usually formed in a swarm, with broadly distributed sizes so that the academic picture of the unique droplet evaporating on its own in a dry environment is an inadequate paradigm. This fact prevails beyond the context of disease transmission, and we give a number of examples below in related areas [1]:

1. *Liquid propulsion, combustion, drying:* Fragmentation is a mandatory step in various industrial processes like in furnaces, liquid propulsion engines, or drying facilities, contexts where it is usually called *atomization* (i.e. literally, down to the atom size). Although produced in a swarm with other droplets densely packed in space at the atomization nozzle, it is nevertheless often the fate of an individual liquid droplet which is of practical interest: the length of a liquid-propulsion combustion chamber, or the height of a drying tower depend on the distance from the injection nozzle for the last, biggest droplet of fuel, or solvent, to evaporate, burn [2], or solidify [3]. Conversely, fine droplets burn too soon after their formation, and may damage the injectors. A better control of the fuel droplet size distribution at injection is one of the ways to improve car engines consumption [4].

2. *Agricultural spraying, snow lances, painting and printing industry, dust control:* Spray drift is a major concern in agriculture. Standard flat fan atomizers used to spray fields with fertilizers and pesticides produce broad drops sizes distributions, with a notable fraction with diameter below 100μm (called 'fines') likely to be swept by the wind, reaching the farmer's neighbor field who may not like it, or the river next to it [5, 6]. Strategies to reduce their relative number are the subject of active research [7, 8]. The biggest droplets however soon fall by their own weight, are too heavy to hook on plants leaves, or rebound on them, splash like raindrops do, favoring plant-to-plant contamination [9]. Snow lances, whose popularity is indexed on the progress of global warming, suffer from the same flaw: light snowflakes from tiny droplets wander aloft, missing the targeted ski slope, while big droplets fall on the ground before freezing, finally producing undesired ice. For similar reasons, the rotary atomizers used in the automotive painting industry produce many droplets that fail reaching the car bodies they are supposed to coat [10]. Dust particles are routinely removed from air by sprays with a capturing efficiency depending critically on the droplets sizes [11].

3. *Geophysics, planetary sciences, precipitations:* The Earth was built by high-energy impacts of planetesimals with metallic cores of their own. The composition of the Earth mantle depends critically on the time offered to metal–silicate chemical equilibration as the impactor material settles towards the Earth core. It fragments very much like raindrops form as they fall from clouds in the atmosphere [12], producing broad size distributions [13]. Efficient equilibration is achieved with smaller fragments allowing fast metal–silicate mass transfer, while the fate of bigger ones is to accumulate in the –therefore iron-rich– core.

4. *Sea spray:* The spray produced by wave breaking in the surf zone, or white caps at the ocean surface is a superposition of different mechanisms which results in broadly distributed droplets sizes (nanometers to millimeters, see e.g. [14, 15]). If they all contribute to the global air-sea exchanges, the fate of each droplet in this distribution is not identical: The smallest aerosols are long lived in the atmosphere, carry salt and diverse chemical/biological substances [16, 17] over large distances inland while the biggest spume droplets carry momentum, heat and produce moisture by evaporation, feeding hurricanes for example, before settling by gravity.

5. *Medicine, forensic science, inhaled drugs, scents:* Some therapies rely on inhaled aerosols carrying drugs which should be embedded in particles whose size is critical to escape from the lung's natural clearance mechanisms. Controlling particles sizes, and density is vital in this context [18]. Experts in the forensic technique of Blood Pattern Analysis routinely contemplate blood splats to decipher the circumstances of a homicide. These splats consist of myriads of stains on the floor which are meaningful only when the fragmentation process creating them has been understood [19]. Electronic cigarettes (e-cigs) are efficient, cancer agent free, tobacco smoking alternatives. However, the nicotine-rich aerosol produced by e-cigs has a droplet size distribution appreciably more skewed towards small sizes than the tobacco smoke particles, with a fat tail towards 'nano' particles; they are, for this reason, considered as suspect [20]. There is a, yet unexplored, relationship between the way a fragrance spray has been atomized, and the persistence of its scent, admittedly a fascinating question.

We certainly do not claim that only fluid mechanics aspects are involved in the present pandemic, nor in disease transmission in general. But we are convinced that if the evaporation dynamics of sprays may not be the crucial step in the overall process in the end, it is a necessary step that is worth exploring anyways, and that there is, as the examples above demonstrate, a whole research field there.

II. STATE OF THE ART AND OUTSTANDING QUESTIONS

The fate of a single droplet evaporating in a quiescent environment is well understood from the celebrated *d-squared* law [21–24] which describes how, because the vapor gradient at the droplet surface steepens as its radius decays, the droplet diameter diminishes in a catastrophic way, going to zero in a finite time t_1 given by

$$t_1 \approx \frac{d^2}{8D}\frac{\rho_l}{\rho_s - \rho_\infty} \tag{1}$$

if d is its initial diameter, ρ_s and ρ_∞ are the densities of vapor at the droplet surface and far away from it, both usually much smaller than the density of the ambient gas environment ρ_a. The density of the liquid is ρ_l and the vapor diffuses in the gas with coefficient D. The above law, rooted in the spherical geometry for which the rate of evaporation is inversely proportional to the current droplet radius (or pellet, it was actually discovered with the sublimation of solid iodine crystals [25]), was soon extended to the case when the droplet is in relative motion with its environment, the vapor gradient at its surface being steepened in a boundary layer all the more thin that the motion is fast, thus hastening the process [26, 27].

However, the evaporation of a single droplet embedded in a group, or swarm with other nearby droplet is ruled by a different dynamics. When the swarm is elongated in the form of a strip at a rate γ, the complete evaporation of the liquid in the strip occurs within a finite time t_v given by [28]

$$t_v = \frac{1}{\gamma}\ln(1+\phi^{-1}) \tag{2}$$

$$\text{where} \quad \phi = \frac{\rho_s - \rho_\infty}{\rho}\frac{2}{\sqrt{Pe}}, \quad \text{with} \quad Pe = \frac{\gamma h^2}{D} \tag{3}$$

where ρ is the spray density, ρ_s the vapor density at the lamella border, ρ_∞ the vapor density in the diluting environment, and Pe denotes a Péclet number based on the initial size of the droplets swarm h. The evaporation time now depends on the rate at which the medium is stirred, instead of being solely attached to the diffusional/thermodynamic features.

Our earlier contributions to the topic [28, 29] have shown that the droplets fate in a dense spray is conditioned by the dynamics of the ensemble vapor field, and that understanding the lifetime of a droplet in the swarm amounts to understanding the mixing time of its saturating vapor concentration with the diluting environment. While t_1 is typically of the order of 10^{-3} seconds of a micrometric droplet of water evaporating in dry air, a dense swarm of these same droplets takes of the order of $0.1 - 1$ seconds to disappear when gently stretched in the same environment. This group effect is therefore substancial, and relevant to all the situations alluded to above.

Human exhalations like coughing or sneezing produce a broad spectrum of droplets sizes, possibly carrying pathogens and thus mediate disease transmission [30–33]. This well known fact is currently re-examined in the light of modern methods and ideas [34, 35]. For some diseases, the contamination radius of an infected coughing individual is the distance needed for the last liquid droplet exhaled from his mouth and staying aloft in air to evaporate [36], but it is not clear which are the nastiest most long-lived droplets in the exhaled spectrum, nor what the swarm effect, which is an empirical fact, implies; It has been suggested that the finest the nastiest, through the collective evaporation delay mechanism recalled above [29]. The new claim is thus that, contrary to the naive view in the field [36, 37], there is no point documenting the droplets size distribution in a cough, or sneeze, if the question is to know how long (far) the exhalation cloud will last (travel). Its disappearance in air is *not* limited by single droplet evaporation, but by mixing with fresh air (plus, possibly, other delaying mechanisms to be discovered), making individual droplets much more persistent than if they were considered in isolation, whatever their size.

In fact, the situation is even worse: Old, and therefore overlooked, but extremely clever experiments, notably those of Duguid [33, 38], and before from the German-Scottisch school [31, 39, 40], and at MIT [32] at the turn of the 20th century, were carried in the 40's–50's precisely to investigate the persistence of miasma in air [41].

They suggest that the persistence sneezes products (dust, residues) aloft can last for *hours* or more in opened air for reasons that neither the standard *d-squared* law, nor the group delay mechanism above can explain alone convincingly. New research is therefore needed.

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