THE PLASMA CONNECTION

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Lightning in a Bottle: Harnessing the Power of Plasma to Restore Our Environment

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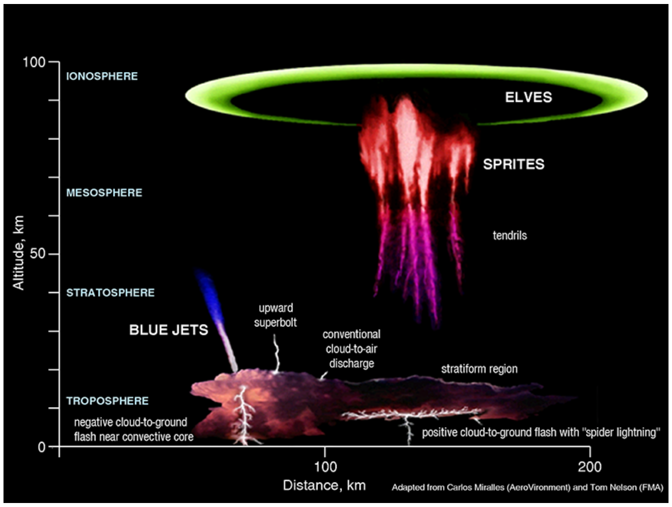
Since the dawn of time, the interaction of plasma—in the form of lightning--with water has been critical to life here on planet Earth. A lightning breaks down molecules into atomic constituents as well as provide energy for chemical reactions important for life. Resulting species, such as nitrogen oxides, NOx, in particular can be uptaken by droplets in the atmosphere and find their way to the surface as rain—depositing essentially as bioavailable liquid fertilizer (nitrification). Additionally, a lightning stroke produces copious amounts of the hydroxyl, OH, radical which plays a critical role in degrading organic pollutants in the atmosphere via oxidation. *While it is now clear of the importance of atmospheric plasma in maintaining life here on Earth, it naturally generates the question, can these processes be created artificially for even greater effect to address climate, agriculture and pollution problems facing society at the moment?* Indeed, in the spirit of Ancient wisdom as stated by Alexander Pope, "Learn hence for nature rules a just esteem to copy Nature is to copy Them," which is a statement of the quest to replicate natural systems to achieve similar ends—exquisitely optimized and in harmony with the environment. Currently, there is a revolution going on in artificially generated "lightning" called cold plasmas, which is made in regular air for technological applications. These are now being explored to address a range of environmental problems such as water treatment, air pollution control and even on-demand nitrification for fertilizer production. And all, of these processes rely on the interaction of the plasma with water.

Making Plasma in Room Air

So how do we put plasma in contact with water at atmospheric pressure to realize these applications?



Adapted from Carlos Miralles (AeroVironment) and Tom Nelson (FMA)

Figure 1. High altitude lightning. (Physics Today)[a] [a]Williams, E., Physics Today 54, 11, 41 (2001); https://doi.org/10.1063/1.1428435

This contrasts with plasmas used for applications such as the manufacture of semiconductor devices, which must be carried out in a vacuum chamber a million times below atmospheric pressure. Well, if one applies a high voltage to closely spaced sharp electrodes the gas is said to break down—rendered conductive—but the discharge rapidly transitions into an arc. Arcs are hot –reaching nearly 10,000 degrees—which would be completely impractical to treat contaminated water as it would immediately evaporate it away. While there are many ways to prevent this transition to the arc, environmental plasma applications rely on cold plasmas where the plasma is near room temperature. How can this be achieved? One way is to use periodic, high voltage fast pulses that accelerate electrons to ionization energy before they collide gas molecules. The pulse ends before appreciably heating can occur, then the next pulse arrives. In this repetitive manner, the energy goes into primarily ionization, thus minimizing the heating to the molecules. The process produces plasma-activated air, where the electrons break bonds and produce reactive species required to carry out functions such as water purification.

Water Crisis and Plasma Solutions

Figure 2. City of Chicago wastewater treatment plant aerial view—processes 700 million to 1.4 billion gallons per day.

Federal agencies have identified a range of industrially-derived chemical contaminants in our drinking water, at varying concentration levels depending on site location. Some of these chemicals are known to cause cancer in laboratory animals and are thus a risk to public health. Conventional treatment plants cannot remove these contaminants. While more advanced technologies such as reverse osmosis can remove these micropollutants, the process is expensive and its application results in the generation of a highly contaminated waste stream that still must be disposed—typically by incineration or dumping into the ocean—both of which are harmful in the long run to the environment. Plasma treatment on the other hand introduces reactive species into the water. These chemical species have high oxidation potential and can via a series of reactions mineralize the contaminant to harmless products such as carbon dioxide, water, and salts. This process is known as advanced oxidation and in itself is considered the future of water treatment. This process has been proposed as a stage in methodologies posed for water reuse, where wastewater is directly treated by advanced methods to make the water potable. Such technologies are needed in drought-stricken regions or those with limited water resources. While advanced oxidation can be achieved without plasma, conventional approaches require onsite consumables such as hydrogen peroxide or pure oxygen. Conventional methods generally drive only one type of advanced oxidation process. Plasma on the other hand when placed in contact with liquid water drives a range of processes that produce not only OH but also other reactive species—such as reactive nitrogen species, electrons, ions, shock waves and UV light—thus greatly enhancing the reactivity, resulting in reduced decomposition time—using only air, an essentially free and readily available consumable. Indeed, plasma at laboratory scale has demonstrated the capacity to decompose most organic contaminants found in freshwater including those that are fluorinated such as PFAS compounds, now found in everything from wrappers and pizza boxes to nonstick skillets and firefighter foam. Such compounds are not as susceptible to advanced oxidation but do degrade when exposed to solvated electrons produced by the plasma.

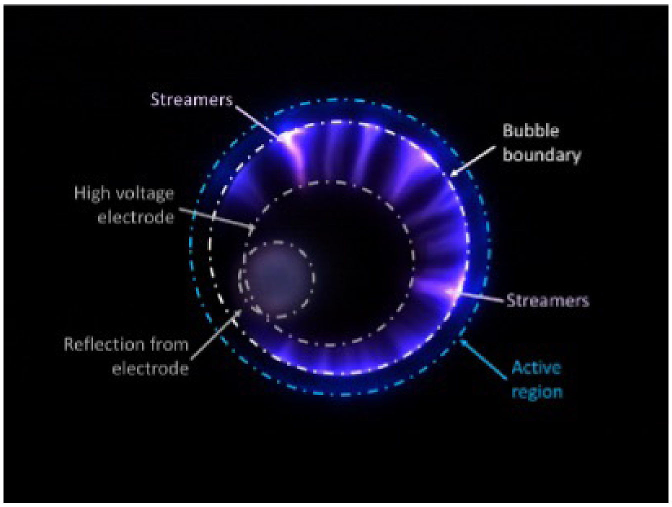


Figure 3. Complex plasma interaction and surface ionization wave formation at plasma liquid interface (in-house, La/Foster, U. Michigan)

How May Plasma be Exploited for These Remarkable Technologies?

Currently, a number of groups worldwide are exploring the efficacy of plasma methods for water treatment. At the beaker scale, many of these tests have shown great promise. At this point, even pilot scale plasma reactors involving the treatment of many gallons per minute are being explored. Key questions however remain to be addressed. These include what is the cost of this technology relative to conventional methods? How much energy will be needed to power a full-scale plasma treatment stage? Is the technology scalable in a practical sense? This final question is critical since typical water treatment facilities deal with water flows in the millions of gallons per day even on the low end. Plasma produced species permeate the water via diffusion, a slow process, which leads to long contact times implying low throughputs which is not acceptable for practical applications. Plasma-induced

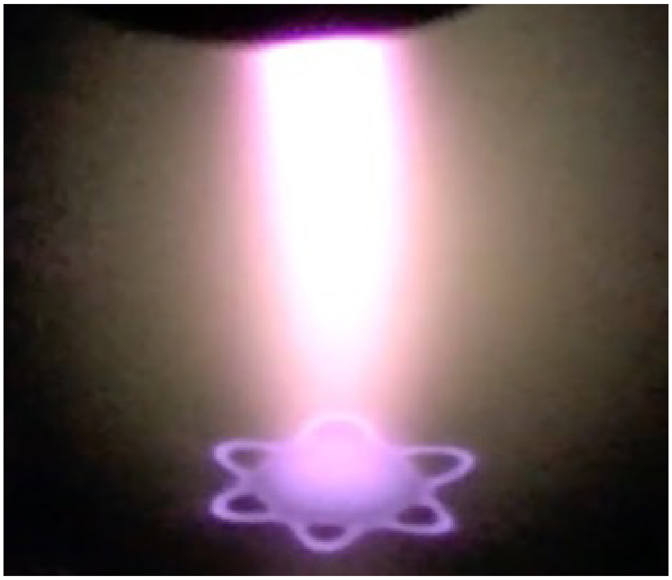


Figure 4. Star-shaped plasma pattern observed on the surface of a liquid water. (Kovach/Foster, U. Michigan)

fluid motion and forced diffusion/convection all increases the mixing of plasma-produced species into the water may be a solution. Plasma interaction with water can also initiate charge deposition that launches plasma waves that can race across the surface depositing oxidants and electrons along the way thus increasing contact area—and thus treatment efficiency. Plasma self-organization on the surface of liquid water, which occurs under certain conditions, can potentially be exploited to increase contact area. Control of these processes in combination with optimizing reactor geometry may provide a pathway for the scale-up challenge to be surmounted.

Progress is indeed being made through the efforts of researchers in this community. The demonstration pilot reactors are only the first step. One day soon, when you fill a cup of water, it may very well be generated courtesy human-made lightning—plasma purified!

Text and images by J. E. Foster; Edited by M. Laroussi

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Suggested Reading

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ABOUT THE AUTHOR

John Foster is a full professor at the University of Michigan—Ann Arbor and head of the Plasma Science and Technology Laboratory, which he founded in 2006. His research focuses plasma science solutions for technological problems here on Earth and in space. This work includes the study of phenomena associated with plasma liquid interactions and the exploration of plasma for water treatment and plastics waste recycling. The group also studies novel plasma source development for materials processing and space propulsion as well.

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