Feature

Water: The Molecule of Life
An Interview with Philip Ball

wet earths

One of NASA's guiding policies in the search for alien life is to "follow the water." Water is fairly common in the universe, found everywhere from vast interstellar dust clouds to the orange-red fields of Mars, but most of this water is in the form of ice. Solid water can't act as a lubricant for the molecular processes of life, so the search is on for liquid water -- a commodity that is far more rare in the universe.

water world

Water (Dihydrogen Oxide, H2O) is a truly remarkable chemical compound and is fundamental to life on Earth.
Credit: NASA

Philip Ball, author of the book, "Life's Matrix: A Biography of Water," says that liquid water is essential for the kind of delicate chemistry that makes life possible. Liquid water is a universal solvent, a mediator of life's chemical reactions, and it has a structure unlike that of any other liquid. In an interview with Astrobiology Magazine, Philip Ball recently discussed his thoughts on the role of liquid water for life on Earth and on other worlds. (An excerpt from his book follows the interview.)

Interview with Philip Ball, consultant editor of the journal "Nature" and Writer in Residence in the Chemistry Department of University College, London:

Q: Do you think liquid water is necessary for life to exist on other worlds? Alternatively, what do you think of suggestions that life elsewhere might evolve without liquid water, and instead make use of liquids like sulfur?

PB: I think that the discussion about this, with its attendant charges of "terra-centricity," generally fails to acknowledge what is really unique about water. The more we understand about biological water, the more we see that its unique ability to form a three-dimensional, hydrogen-bonded network enables it to participate in biochemical processes and not just to act as a passive backdrop.

At a somewhat crude level, life is about molecular processes, such as templating, molecular recognition and replication, which can be duplicated in non-aqueous solvents. But we find that even for the simplest organisms, many of the molecular interactions are facilitated by water in an extremely fine-tuned way. I'm not sure we know of any solvent that can play a comparable role in terms of enabling the kind of highly delicate chemistry that makes life possible.

If we accept that any form of life will require a comparable degree of chemical sophistication, it is hard to see what other solvent would make this possible. In other words, I'd put it like this:

1. Life most probably needs a solvent.
2. That solvent needs to perform an active, diverse, and flexible role.
3. Water is so far the only common liquid we know that is capable of this.

So I think that Lawrence Henderson may have been right when he argued in 1913 that water is biophilic -- though he didn't use that word, and his interpretation of that fact was rather different!

Q: You note in your book that in some ways, water is more like a crystal than a liquid. This brought to mind some theories that suggest crystals might have played a role in the origin of life, especially in regard to the chirality problem. Could water have played the role in life's origin that others have attributed to crystals?

Marianas trench

Click here for larger image. A sketch showing the Marianas Trench.
Image Credit: Economic Service Council, Inc.

PB: I say that water has attracted the attentions of people who have tended to be more interested in the crystalline rather than the liquid state, like Bernal and Pauling. But I'd say that water is literally like a crystal in just one respect: it has an unusually high degree of LOCAL ordering. But of course this is just on average -- there is nothing like a persistent ordered structure even on a local level. So I don't see that water could have played any kind of templating role like that proposed for some mineral crystals in the origin of life.

Q: You also mentioned in your book some experiments that used different pressures and temperatures to study the (sometimes strange) effects on water. Do you think on planets with pressures and temperatures significantly different from Earth's, that water would still play a fundamental role in life?

PB: The pressure at the bottom of the Marianas Trench in the Pacific is around 1,000 atmospheres, under which conditions liquid water has a significantly different structure -- more like that of high-density amorphous ice. Yet life persists there. So it seems entirely possible that high pressures on other worlds are no impediment to life in water.

It is surely possible for life to persist in super-cooled water below its normal freezing point too -- but this would be a very precarious existence, as the danger of freezing would be ever present.

As for high temperatures -- I believe that the conditions around some hydrothermal vents are above water's critical point. I doubt whether carbon-based life can exist in such an environment, however, not just because many organics fall apart above a few hundred degrees, but because the solvent properties of supercritical water are quite different -- hydrophobic species become more soluble, for instance.

Q: What is your preferred theory for the origin of life on Earth -- hydrothermal vent, sunlit shallow pool, panspermia, or other?

PB: I think the vent theory has the most going for it, not least because it posits a relatively stable environment in the face of a pretty changeable and often rather nasty situation at the surface of the land or sea.

Panspermia always feels unsatisfying because it merely displaces rather than addresses the problem. But that is not, of course, to say that it is ruled out for that reason!

Q: What do you think are some of the most interesting or exciting recent findings about the properties of water?

PB: Right now, I think some of the biggest questions hinge around the nature of water in the cell. There is still a lot of controversy about this: is cell water more or less like bulk water? Biochemists usually treat it this way. Or is it so modified by the presence of so many macromolecules and surfaces that it has a quite different structure?

hydrothermal vent

"I believe that the conditions around some hydrothermal vents are above water's critical point."
Credit: University of Delaware

Some people think that cell water is more like a gel. Others believe that it is strongly inhomogeneous, sometimes having an enhanced density -- encouraged by the presence of certain dissolved ions -- and sometimes a reduced density, making it a poorer solvent and more ice-like.

Very recently there have been several reports that water very near hydrophobic surfaces is vapor-like: that such surfaces are relatively "dry." This would have important implications for things like the hydrophobic attraction, as well as for the nucleation of gas bubbles at surfaces, which has been proposed as an explanation for the mysteriously long-ranged attraction between hydrophobic surfaces.

We also have more and more examples of water bound to proteins playing an important functional role -- for example, chains of water molecules inside protein pore-like channels acting as "proton wires." All of this makes it clear that water plays a subtle and dynamic role in molecular biology, and is itself a biomolecule.

Water: The Real Elixir

Yesterday it rained, and now the garden will go crazy. It is early summer, and for weeks the ground has been parched. I have feared for the roses, tended them with an irresponsible hose. But yesterday the skies growled, the lightning flashed, and the heavens opened. In my garden, precious lives are no longer at stake; water has returned.

Like any gardener, I overdramatize the situation. Life here in northern Europe is amply watered; only my arbitrary floral preferences are at risk. Life is tenacious enough that it will make do with absurdly limited, sporadic supplies of water if that is all there is to be had. In parlous circumstances -- in the deserts and the dry, rocky lands of the planet -- living organisms become mechanisms for sequestering water, little enclaves of the fluid stuff in a parched world. For whether you are a scorpion or a cucumber, a salmonella bacterium or a bull elephant, water is literally your lifeblood, give or take a few additives.

You don't have to be a biochemist or a science-fiction enthusiast to be familiar with the notion that all life on Earth is based on carbon -- that the "biomolecules" that make up living organisms are constructed largely around a backbone of carbon atoms. This idea is actually a bit of a myth, as atoms of other elements -- particularly nitrogen, oxygen, and phosphorus -- are essential parts of those molecular frameworks too. But the point one tries to convey with talk of "carbon-based life forms" is that carbon has some very special chemical properties, such as its ability to form strong, stable bonds with itself and to link up into the long chains that feature the molecules of life.

water molecule

A water molecule, showing two hydrogen atoms and one oxygen atom.
Credit: Martin Chaplin

Carbon is indeed a very remarkable element; but I don't think I shall detract too much from its glamour if I suggest that it is not exactly the ur-substance of life that it is sometimes jacked up to be. If life (one has to say "as we know it" and live with the cliché) is ever going to get started on any planet, carbon is surely needed -- but even before that, life needs flowing water.

Water is life's true and unique medium. Without water, life simply cannot be sustained. It is the fluid that lubricates the workings of the cell, transporting the materials and molecular machinery from one place to another and facilitating the chemical reactions that keep us going. Water is sustenance and cleansing fluid, bearing nutrients to where they are needed and taking away wastes. It is even a structural agent in plants -- it enables flowers to hold up their heads to the Sun. No wonder we would quickly die without it, for we need to consume at least two pints a day for long-term health. Some cells can avoid death if their water is extracted, but then they shut down utterly until rehydrated.

And we tend to forget, landlubbers that we are, that until comparatively recently, an aquatic environment was the sole milieu for life on Earth. The planet has apparently hosted living organisms for an astonishing 3.8 billion years of its 4.6-billion-year history, and yet colonization of the land began only around 450 million years ago.

Inner Space -- Water in the Cell

We're two-thirds water, but where is it all? Why do we not slosh and wobble like a bulging wineskin? Some of this fluid gurgles in our guts, surges in our veins, lubricates our palate and our eyelids and joints. But much is bound up in individual parcels smaller than the droplets of a fine mist. Have you seen what a sad, shriveled brown thing a banana becomes when it is dried? That's what our flesh would look like if drained of the fluid that fills its cells.

Apart from water's extraordinary capacity to dissolve a wide range of substances, you might imagine that any old liquid could fulfill the role of solvent and transportation agent for the body's cellular machinery. Maybe this just happens to be water because there is a lot of water about. But when the biologist and Nobel laureate Albert von Szent-Györgyi described water as the "matrix of life," he had in mind something more profound than a backdrop on which life's tapestry is embroidered.

Phillip Ball

Philip graduated in Chemistry from the University of Oxford, and holds a PhD in Physics from the University of Bristol.
Credit: Nature

The fluid medium inside all living cells, called cytoplasm, is mostly water. But what a cocktail! -- spiced with proteins and DNA, sugars, salts, fatty acids, seething with hormones. It is all too tempting to regard the relationship of this fluid to the biomolecules it contains like that of the paper of a page to the words printed on it: as a carrier, a bland background on which the important business is displayed. But this won't do. Water plays an active role in the life of the cell, to the extent that we can consider water itself to be a kind of biomolecule.

Without it, other biomolecules would not only be left stranded and immobile, like beached whales -- they might no longer truly be biomolecules, unraveling or seizing up and losing their biological function in the process. In scanning through the literature of modern molecular biology, you could be forgiven for concluding that the subject is all about proteins and genes, embodied in the nucleic acid DNA. But this is only a form of shorthand; for biology is really all about the interactions of such molecules in and with water.

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