

Is Water the Universal Solvent for Life?

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“Follow the water” is our basic strategy in searching for life in the universe. The universality of water as the solvent for living systems is usually justified by arguing that water supports the rich organic chemistry that seeds life. Nevertheless, it has been recently pointed out that alternative chemistries are possible in other organic solvents (Bains 2004; Benner et al. 2004). Does that mean that our exploration strategy has restricted us to looking for life under the storied lampost? Or, perhaps, there are other criteria for life that have not been sufficiently considered so far? Answers to these questions would satisfy our scientific curiosity and inform us about the origins of life. But those answers are also essential to planning space exploration by helping to select the most promising targets to search for life in the solar system (Shapiro and Schulze-Makuch 2009) and to define observational strategies for identifying habitable exoplanets.

Presence in a given space environment, e.g., a planet, or a moon, is a clear prerequisite for a solvent to support life. In this respect water is privileged as one of the most abundant molecular species in the universe. This point led to the concept of habitable zones (Kasting et al. 1993). Other requisites and desiderata of a medium of life follow. They are based on principles of chemistry and physics, as applied to properties of biological systems that are considered universal.

We emphasize that we should not be restricted to “life as we know it,” although terrestrial life serves as the dominating example. One essential criterion that extends beyond prebiotic organic chemistry and has not received sufficient attention is the ability to promote the self-

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organization of matter into structures that are sufficiently versatile, robust yet flexible to support functions of a living system. This criterion is the focus of the discussion below.

A cell, or even a protocell, is a complex system whose structure and functions are largely modulated by non-covalent interactions. Indeed, non-covalent interactions — interactions that do not involve making or breaking chemical bonds — play a central role in almost all processes essential to terrestrial life. Examples are self-assembly of boundary structures, protein folding and aggregation, ligand-enzyme interactions, transcription and replication of information polymers, ion transport across membranes, regulation of gene expression, and signal transduction. Most of these processes in their general form are universal to life, although possibly mediated by different polymers. To be effective in a living system, these interactions must operate in a moderate energy range, as indeed is the case with non-covalent interactions. They have to be sufficiently strong that inherent thermal noise and natural heterogeneity of the environment do not raise havoc. But they cannot be so strong that regulation, including repair and disposal, could not be accomplished without considerable expenditure of energy and response to global or local environmental signals would be sluggish. Biomolecular interactions would then become irreversible for practical purposes. Furthermore, the system should exhibit sufficient stability that it could function properly over the temperature range of the environment. These additional requirements are imposed by basic physical chemistry rather than synthesis issues of organic chemistry.

In this context, the solvent is then not only a medium with favorable diffusion properties, compared to solid or gas phases, or an environment that assists organic synthesis, but also a mediator of non-covalent interactions. The strengths of these interactions depend critically on the solvent. They can be divided approximately into three components – electrostatic, van der Waals and solvophobic interactions.

Of these three types, electrostatic and solvophobic interactions are widely recognized as exquisitely sensitive to the solvent. Polar liquids, such as water, are typically good solvents for polar or ionic materials. Ionic materials, for example, can dissolve, dissociate into ionic fragments, and thereby offer a wide range of functionality. Such possibilities are limited in nonpolar solvents such as liquid methane. By comparison with the cases of gas phase or nonpolar solvents electrostatic interactions between ions in polar liquids are reduced in strength inversely proportionally to the solvent dielectric constant. This can bring the strength of those ionic interactions into the range of other non-covalent interactions. This is illustrated in Fig. 1 in which the free energy of interaction between Na^+ and Cl^- in water as a function of their separation is compared with the same quantity for two methane molecules. At contact, the stabilizing $\text{Na}^+ \dots \text{Cl}^-$ pairing free energy is larger than that for two methane molecules by only a factor of 2. In the gas phase this difference would be more than two orders of magnitude. This means that the solvent for life should be characterized by a high dielectric constant, ϵ . Otherwise strong, electrostatic interactions would render signaling and regulations quite ineffective. A number of liquids fulfill this criterion. For example, hydrogen cyanide and formamide have the dielectric constant even higher than water. Examples of other liquids with high ϵ are several di- and tri-alcohols and acetonitrile. Hydrocarbons, however, are not among them.

Besides tempering electrostatic interactions, water exhibits a remarkable trait that it also promotes hydrophobic interactions between nonpolar molecules or groups, rich in hydrocarbons (Tanford 1978). This is manifested by the tendency of these groups to minimize their contacts with the solvent and instead interact with each other. This implies low solubility of nonpolar species in water. We know that water and oil do not mix and we exploit hydrophobic effect in everyday life, for example when using soaps and detergents to wash off greasy, oily residues. In biology, the hydrophobic effect is responsible, for example,

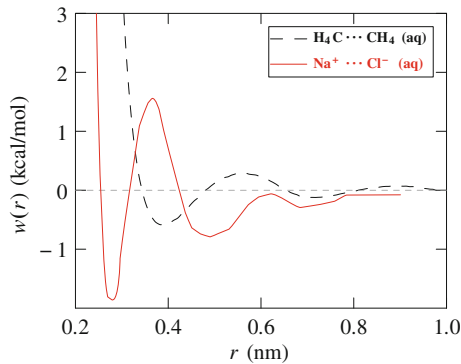


Fig. 1 Potentials of mean force (interaction free energy) between Na^+ and Cl^- in water at $T=300\text{K}$ and Earth normal pressure (red, solid line, data from Fennell CJ, Bizjak A, Vlachy V, Dill KA (2009) *J Phys Chem B* 113: 6782); and between two CH_4 (black, dashed line, data from Chaudhari MI, Pratt LR, Paulaitis MI (2010) *J Chem Phys* 133: 231102) under the same conditions

for self-organization of cell walls, and protein folding and aggregation. A signature of the hydrophobic effect is its unusual temperature dependence: in contrast to electrostatic and van der Waals interactions it often becomes stronger as temperature increases reaching a maximum above 60°C . A particularly intriguing example of the inverse temperature dependence of the hydrophobic effect is the cold denaturation of proteins whereby proteins loose their native structure upon cooling (Privalov 1990).

Hydrophobic effects contribute to almost all self-organizing processes in biology. Electrostatic or van der Waals effects cannot substitute for them. This means that any liquid that is a candidate for supporting life must exhibit some form of solvophobic effect. To identify such candidate liquids it is therefore essential to establish which properties of water are responsible for hydrophobic interactions.

Early theories of hydrophobic effects centered on tetrahedrality as a feature of the local structure of liquid water, and on entropic contributions associated with constraints on this structure that might be imposed by hydrophobic solutes. In this pictorial view single water

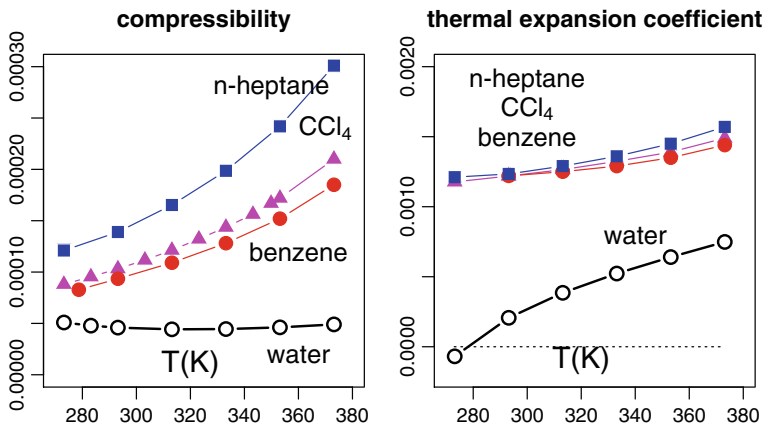


Fig. 2 Distinctive thermodynamic characteristics of liquid water that govern molecular-scale models of hydrophobic effects. Left: isothermal compressibility $-\left(\partial \ln V / \partial p\right)_T$ (bar^{-1}). Water is stiffer than comparative organic liquids. Right: thermal expansion coefficient $\left(\partial \ln V / \partial T\right)_p$ (K^{-1})

molecules can be represented as a tetrahedron with the oxygen atom at the centre and two hydrogen atoms and two electron lone pairs at the vertices forming hydrogen bonds with other water molecules. This concept, however, has not been successful in identifying alternatives to water, as it suggests that other tetrahedral molecules capable of forming hydrogen bonds, such as NH_3 or H_2S , should be similar to water. This is, however, not the case and solvophobic effects appear not to exist in those liquids.

Rationalization of the hydrophobic effect through invoking entropy has been based on the following argument (Kauzmann 1959). Water molecules contacting hydrophobic groups are ordered, and therefore suffer an entropy penalty. When these groups are buried due to phase segregation or folding, contacting water molecules are released to the bulk, regaining the penalized entropy. For this reason, the demixed or folded state has higher entropy and is the stable outcome at higher temperatures. Viewed in the opposite temperature direction, this suggests that cold denaturation works because at lower temperatures water molecules interact more strongly with proteins and by doing so pry open folded protein structures.

This view is a rationalization that gets to the correct result, but as a molecular-scaled mechanism it has never been fully developed and proven. The proven molecular theories of classic hydrophobic effects (Ashbaugh and Pratt 2006) provide a subtler and more general explanation of hydrophobic phenomena that is closely tied to peculiarities of the equation of state of liquid water. This is illustrated in Fig. 2. From the left panel in which compressibilities of liquid water and several other organic solvents are shown it follows that water is qualitatively stiffer. The compressibility of water is only weakly sensitive to temperature along the vapor saturation curve. Similarly the density of water changes unusually slowly along that vapor saturation curve, as is shown in the right panel of Fig. 2. Modern theories (Hummer et al. 2000) link these thermodynamic features to the low and unusual solubilities of inert gases in liquid water. From a survey of 150 liquids (Marcus and Hefter 1997) several other stiff liquids have been identified: glycerol, diethylene glycol, ethylene glycol, formamide, 2-aminoethanol, 1–4 butanediol and 1–5 pentanediol. Among these, formamide stands out because it can be directly formed from molecules H_2O and HCN that are known to be in planetary environments. Others of these molecules could be formed by oxidation of small hydrocarbon molecules that are also known to be present, for example on the surface of Titan. Glycerol (McDaniel et al. 1983), 1,3-propanediol, and formamide (McIntosh et al. 1989) have been successfully substituted for water in laboratory studies of membrane bilayers.

Water is again remarkable in displaying a vast temperature range of stability, some 374 K between critical and triple temperatures. The temperature sensitivity is also reflected in the heat capacity of the liquid, a property that is again remarkably large for liquid water. The water fluid phase equilibrium and the large heat capacities serve to moderate temperature excursions for the terrestrial biosphere. It would be desirable to categorize possible non-aqueous alternative for a matrix of life through investigation of fluid phase equilibria.

In summary, principles of physics and chemistry dictate that a solvent for life should be characterized by a high dielectric constant, support for solvophobic effects and structural invariance over a range of temperatures experienced by living systems in a given environment. These can be considered as minimal requirements for a milieu supporting life. Water fulfills these requirements neatly. In fact, it is the only liquid that does so. However, information about alternatives, including mixed solvents, is not sufficiently complete to exclude other possibilities.

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References

- Ashbaugh HS, Pratt LR (2006) Colloquium: scaled particle theory and the length scales of hydrophobicity. *Rev Mod Phys* 78:159–1978
- Bains W (2004) Many chemistries could be used to build living systems. *Astrobiol* 4(137):167
- Benner SA, Ricardo A, Carrigan MA (2004) Is there a common chemical model for life in the universe? *Curr Opin Chem Biol* 8:672–689
- Hummer G, Garde S, García AE, Pratt LR (2000) New perspectives on hydrophobic effects. *Chem Phys* 258:349–370
- Kasting JF, Whitmire DP, Reynolds RT (1993) Habitable Zones Around Main Sequence Stars. *Icarus* 101:108–128
- Kauzmann W (1959) Some factors in the interpretation of protein denaturation. *Adv Prot Chem* 14:1–63
- Marcus Y, Hefter GT (1997) The compressibility of liquids at ambient temperature and pressure. *J Mol Liq* 73:61–74
- McDaniel RV, McIntosh TJ, Simon SA (1983) Glycerol substitutes for water in lecithin bilayers. *Biophys J* 41:A116
- McIntosh TJ, Magid AD, Simon SA (1989) Range of the solvation pressure between lipid membranes dependence on the packing density of the solvent molecules. *Biochem* 28:7904–7912
- Privalov PL (1990) Cold Denaturation of Proteins. *Crit Rev Bioch Mol Biol* 25:281–306
- Shapiro R, Schulze-Makuch D (2009) The Search for Alien Life in Our Solar System: Strategies and Priorities. *Astrobiol* 9:335–343
- Tanford C (1978) The hydrophobic effect and the organization of living matter. *Science* 200:1012–1018