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# Chemistry, Life, and the Search for Aliens

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## ABSTRACT

While "life" may universally be a self-sustaining chemical system capable of Darwinian evolution, alien life may be quite different in its chemistry from the terran life that we know here on Earth. In this case, it will be difficult to recognize, especially if it has not advanced beyond the single cell life forms that have dominated much of the terran biosphere. This review summarizes what we might infer from general physical and chemical law about how such "weird" life might be structured, what solvents other than water it might inhabit, what genetic molecules it might contain, and what metabolism it might exploit.

**Keywords.** Alien life, weird life, extraterrestrial life, water, planetary exploration

## 1. INTRODUCTION

Most exploration for life does not take us very far from the life that we know. This fact, together with years of experience with science fiction has taught us, raises some far-reaching questions. Are more exotic forms of life possible? If so, what would they look like? How might we recognize them as "life"?

Some questions are best answered by a simple: "We don't know". We have direct knowledge only terran life forms, and these all are related by common ancestry. We have no way to decide whether the similarities that they share reflect common ancestry or the needs of life universally. But if we retreat to a position of defensible agnosticism, we have no fun. Accordingly, we might choose "constrained speculation" as a method to consider these questions.

The modifier "constrained" is what allows speculation to be given the title "scientific". Fiction writers can propose whatever they want. Scientific speculation, however, must be constrained by what we know. We are not allowed to say that water is H<sub>2</sub>O. The challenge in constrained speculation is not to be *too* constrained. We want to stray as far as possible from the known.

Can life use sources of energy that are not used by terran organisms? Why not life in acidic or alkaline water? Can we change the elements that dominate terran biology? Replace carbon by silicon? Replace phosphorus by arsenic? Can we move further along the scale of weirdness, perhaps replacing the solvent water by something else? Can life exist at greatly different temperatures if it is not constrained by the freezing and boiling points of water? Can life exist in solids or gases? Can we change the fundamental structure of genetic systems, making them two dimensional? Can we dispense with genetic systems entirely, or even with Darwinian evolution?

We now enter the Wonderland of weird life. Again, problems with scientific method emerge. The farther away we move from what we know, the more difficult experiments become. One we leave the general structures of standard terran DNA or protein, or standard terran metabolism, we are confronted with too many differences and too many problems to work through. We hardly know where to begin. Hence, little work has been done to address the most extreme types of "counterfactual" molecular biology.

## 2. WHAT CHEMISTRY SAYS

The NASA definition-theory for life as a "self-sustaining chemical system capable of Darwinian

evolution" offers a useful place to start, as it allows us to consider what might *not* be possible. These considerations generate the constraints that we need to make our speculations scientific. They come from chemical principles, which (we think) we understand well and which should be truly universal. Chemical principles generate a hierarchy of constraints for life given our definition-theory. These constraints can be embedded within speculation concerning the weirdest life for life as a universal, at least the life that falls within that definition-theory. Let us consider some of these as we try to constrain life as a universal from theory down.

### 2.1 Life needs free energy

To the extent that life actually does anything, it requires an environment that is not at *thermodynamic equilibrium*. This constraint is often stated as a requirement for life to have a source of free energy, or for "high-energy compounds".

The requirement for free energy almost certainly applies for all life, including artificial life, silicon life (weird, but still within our definition-theory), and non-Darwinian life (if it exists). How can we be so sure?

As broad-minded scientists, we cannot dismiss the possibility out of hand. Rather, we must ask: What must be false among what we believe to be true, for life to *not* require thermodynamic disequilibrium? Lots, as it turns out. In particular, if life does not need a source of free energy to evolve, then it should be possible to make a perpetual motion machine from it. Many have tried and failed to make perpetual motion machines. This does not mean they cannot be made, of course. But this failure, and its interconnection to millions of other observations, some quite distantly related, are together enough for us to move on.

Under other well-supported laws of physics, life must conserve mass, conserve momentum, and conserve energy. Unfortunately, such constraints rule out some of the most cherished story lines among science fiction writers, such as travel back in time. Again, perhaps time travel is possible. But if it is, then it violates these conservation laws.

Why? Conservation laws state (as physicists like to say) "time invariance". In other words, the amounts of mass, momentum, and energy must be the same at all times.

Thus, these conservation laws mean that the amounts of mass, momentum, and energy today must be the same as these amounts tomorrow. If we move mass (let us say, in the form of James T. Kirk and Mr. Spock, as in *The Voyage Home*) from the 23<sup>rd</sup> century to 19<sup>th</sup> century San Francisco, more mass would exist as they walk the streets looking for humpback whales than in the future that they left in the 23<sup>rd</sup> century. Of course, after they moved the massive whales forward in time, the amount of mass in the 23<sup>rd</sup> century will become greater than the amount of mass in the 19<sup>th</sup> century that they left. Time travel violates the conservation of mass.

### 2.2 Thermodynamic disequilibrium is not a strong constraint on where we might find weird life

Unfortunately, thermodynamic disequilibrium is easy to find in the cosmos. Almost any environment in the vicinity of a nuclear fusion reaction, such as that in our Sun, will not be at equilibrium. Indeed, unshielded exposure to the energy of the Sun can easily present the opposite problem, too much energy. Those with sunburn appreciate this problem.

Until recently, a star was regarded as the only way to obtain free energy, directly or indirectly. For example, in *Have Spacesuit Will Travel* (1958), Robert Heinlein suggested that the ultimate punishment that a miscreant planet can receive from an intergalactic court was to deprive it of its sun, which would presumably cause its life to expire. In this view, life universally must be based on a food chain that begins with photons.

But planets have other ways to generate disequilibria. For example, atoms in a rocky planet like Earth are

remnants of supernovas. Some of these atoms are radioactive, and their decay is a powerful source of not-at-equilibrium environments. On Earth, the energy from radioactive decay drives volcanism and the movement of tectonic plates. As heat rises to the surface in hydrothermal vents, free energy becomes available at the place where the heat below meets the cold ocean above.

These considerations suggest certain kinds of energetically weird forms of life. One such life form might get its energy by converting mass directly into energy under Einstein's famous equation,  $e=mc^2$ . Conversely, how about a form of life that converts the energy in photons into the elements that it uses?

Actually, life of this kind already exists on Earth, if we stretch things a bit. The energy from radioactive decay drives chemical reactions that generate chemical disequilibria at the place where the heat below comes up from below and vents at spots on the ocean floor, some several miles down. These vents are called "black smokers". The chemical disequilibrium around them supports entire communities of life without sunlight. These life forms all live on the energy arising from the atomic nuclei that are the remnants of supernovas, all delivered to the Earth in its formation.

Of course, this multistep process that converts the mass of the atoms into heat, from there into chemistry, and from there into life, is very inefficient. A better way for life to use the energy in mass would be for it to evolve a catalyst that converts mass *directly* into the energy. *That* kind of life is not known today.

### 2.3 Weird life could be cruising the universe

Recognizing that geothermal energy arising from radioactive nuclei could stand at the foundation of a food chain, David Stevenson at the California Institute of Technology generated yet another idea. He noted that as solar systems form, *many* small, Earth-like planets might form. Many of these would not be in stable orbits, especially in solar systems that also had large gas giant planets, like our own Jupiter. Thus, many of these small rocky planets should be ejected via gravitational interaction with bigger planets.

After ejection, such rocky planets would travel the galaxy, free of any star. Those planets could carry life surviving on the decay of radioactive nuclei left over from past supernova explosions. Indeed, depending on the frequency of these formations-followed-by-ejections, such planets might hold the vast majority of life in our galaxy, cruising free of any star. How might we find it? That is a tough question. The Universe is very big.

### 2.4 Covalent chemical bonding as a universal for life?

A weaker constraint on life requires that it be assembled from molecules whose constituent atoms are held together by covalent bonds. This offers a stronger constraint on the forms that weird life can take than the laws mentioned above. In particular, most covalent bonds between carbon atoms are not stable at temperatures much above those where water is liquid. Thus, this constraint places a general upper limit on the temperature where life might be found.

Unfortunately, the distinction between covalent and non-covalent bonds is anthropocentric. The distinction reflects the fact that *we* ourselves live at 310 K, and that we live for a few dozen years. At this temperature, carbon-carbon covalent bonds can survive for our lifetime. In contrast, the non-covalent hydrogen bonds, break and form rapidly at that temperature, on a time scale measured in just thousandths of a second. If we ourselves lived on the millisecond time scale, or if we lived at lower temperatures, then we might not make the same distinction. We might not be so fixated on covalent bonds as the basis for life.

In fact, bonds in chemistry come in a wide range of strengths. The strongest survive for a time even at temperatures as high as 1000 K. The weakest exist only near absolute zero. On Titan, for example, the temperature is ca. 112 K, and that is *cold*, and even hydrogen bonds are stable for long period of time. If we lived on Titan, we might view hydrogen bonds in the same way as we view covalent bonds in our

kitchen today. Hydrogen bonds in life on Titan would serve the same role in Titan life as covalent bonds in terran life.

These thoughts expand our view of where in our solar system life might exist. Most of the universe does *not* lie at temperatures where water is liquid, between 273 and 373. The chemistry of life at low temperatures may well be dominated by non-covalent bonds. Possibly universal, however, is a requirement that the bonds used to support information transfer in a Darwinian system must be sufficiently strong at the ambient temperature to stay put for an appropriate time. In water between 273 and 373 K, the combination of covalent bonding, hydrogen bonding, and the hydrophobic effect is sufficient to meet this requirement. In different solvents, or at different temperatures, different types of bonding may be better suited.

## 2.5 Assuming that a liquid is necessary for life, what other bioliquids are possible?

If we wish to move away from the temperature range where water is a liquid, and if we assume that a liquid is necessary for life, we must find another solvent. There are many to choose from, and we can start with liquids that have certain properties like water, but are not water.

One of these is ammonia ( $\text{NH}_3$ ), which is abundant in the solar system. From a chemical perspective, water and ammonia are analogous. Ammonia is a relatively polar liquid, like water. Like water, ammonia is held together as a liquid by hydrogen bonds between different solvent molecules. Ammonia, however, has three hydrogen bond donors and one hydrogen-bonding acceptor, while water has two of each. Therefore, water is held together better.

This means that ammonia is a liquid at a lower temperature than water at any given pressure. For example, at one atmosphere of pressure, ammonia is liquid from 195 to 240 K. The liquid range is even broader at higher pressure. For example, at 60 atmospheres of pressure, ammonia is liquid from 196 to 371 K. Ammonia is therefore expected to be found in liquid form in the outer Solar System. For example, liquid ammonia exists in liquid form in aerosols in the clouds in Jupiter's atmosphere.

Ammonia, like water, dissolves many organic compounds. Further, many synthetic organic reactions can be done in ammonia in the laboratory. Ammonia would not support *exactly* the types of metabolic chemistries that are found in terran life, of course. Terran life is based on compounds containing the C=O carbonyl unit. In ammonia, the C=O unit is converted into the corresponding C=N imine unit, which we saw existing only transiently in water (for example, in the synthetic proteins that catalyze the decarboxylation of oxaloacetate). Nevertheless, hypothetical reactions that exploit a C=N unit in ammonia can be proposed in analogy to the metabolic biochemistry that exploits the C=O unit in terran metabolism in water. Given this adjustment, a metabolism in liquid ammonia is easily conceivable.

The adjustment also needs to reflect the greater alkalinity of a liquid ammonia environment. The acid in water is  $\text{H}_3\text{O}^+$ , while the base is  $\text{HO}^-$  (hydroxide). In ammonia, the acid is  $\text{NH}_4^+$  and the base is  $\text{NH}_2^-$ .  $\text{H}_3\text{O}^+$  is 100 billion times stronger as an acid than  $\text{NH}_4^+$ . Likewise,  $\text{NH}_2^-$  is about a quadrillion times stronger as a base than  $\text{HO}^-$ . As you know if you cleaned your glass windows with ammonia, the alkalinity of ammonia stings your eyes. But remember, *you* evolved to live in water. A life that evolved to live in ammonia would not find ammonia unpleasant; it may find water unpleasant.

The same considerations apply when we consider liquids that are water-like, but more acidic. For example, sulfuric acid ( $\text{H}_2\text{SO}_4$ ) is a reasonably good solvent, and supports chemical reactivity well. Sulfuric acid is known in the solar system, particularly in aerosols in the clouds 40-70 kilometers (24-42 miles) above the surface of Venus. The temperature in these clouds are consistent with stable covalent bonding between carbon compounds (ca. 310 K) at an altitude of ca. 50 km at an pressure 1.5 times that at sea level on Earth. Given these facts, Carl Sagan and Harold Morowitz speculated that the Venusian atmosphere may hold organisms that float above the hot surface using hydrogen balloons ("float bladders"), analogous to

bladders found in terran aquatic organisms (where the flotation gas is air). Dirk Schulze-Makuch has argued for a sample return from the atmosphere of Venus to address the possibility of life in this environment.

Metabolic hypotheses are not in short supply for the hypothetical life in Venusian atmospheric aerosols. In strong acid, the C=C bond is sufficiently reactive to support a metabolism as an analog of the C=O unit in terran metabolism. Nor are sources of energy in short supply in the Venusian atmosphere. For example, Dirk Schulze-Makuch suggests that a metabolism might exploit the relatively high flux of ultraviolet radiation in the Venusian clouds.

Formamide (Figure 1) is a third solvent that is polar, like water, but is not water. Formamide has a huge liquid range at standard atmospheric pressure (272 to 492 K). Further, formamide would be a great solvent to get life started. In formamide, many species are stable (including RNA) that are thermodynamically unstable in water with respect to hydrolysis. Formamide dissolves most things that water dissolves. Unfortunately, although formamide is formed by the reaction of hydrogen cyanide with water, it does not appear to be abundant anywhere in today's Solar System.

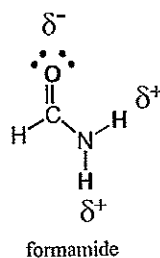


Figure 1. Formamide

## 2.6 Hydrocarbons: Non-polar solvents for biology?

Less polar liquids are also available in the Solar System. These include hydrocarbons, ranging from the smallest (methane, CH<sub>4</sub>) to higher homologs (ethane C<sub>2</sub>H<sub>6</sub>, propane C<sub>3</sub>H<sub>8</sub>, butane C<sub>4</sub>H<sub>10</sub>, and so on). These constitute, for example, approximately 0.2% of the atmosphere of Jupiter.

The temperature at which a hydrocarbon is liquid depends on its size. Thus, methane, ethane, propane, butane, pentane, and hexane have boiling points of ca. 109, 184, 231, 273, 309, and 349, respectively, at one atmosphere of Earth pressure. In principle, one can match the hydrocarbon to the temperature and pressure of the planetary environment to select one that would be suited as a biosolvent. Generally, higher hydrocarbons that are solids as pure substances at these temperatures can dissolve in the liquid hydrocarbon having a lower melting temperature.

Broad empirical experience shows that organic reactivity in hydrocarbon solvents is no less versatile than in water. Indeed, many terran enzymes are believed to catalyze reactions by having an active site that is not water-like. Further, hydrocarbons with polar groups can be hydrocarbon-phobic; acetonitrile and hexane, for example, form two phases. One can conceive of liquid/liquid phase separation in bulk hydrocarbon that could achieve Darwinian isolation. The reactivity of water means that it destroys hydrolytically unstable organic species.

Titan, the largest moon of Saturn, is an extremely attractive place to go look for weird life that lives in a

hydrocarbon solvent. Titan has methane rain, methane ice, and methane oceans. Thus, a hypothetical form of life living in a hydrocarbon solvent in a Titan ocean would be able to use hydrogen bonding more (Figure 2).

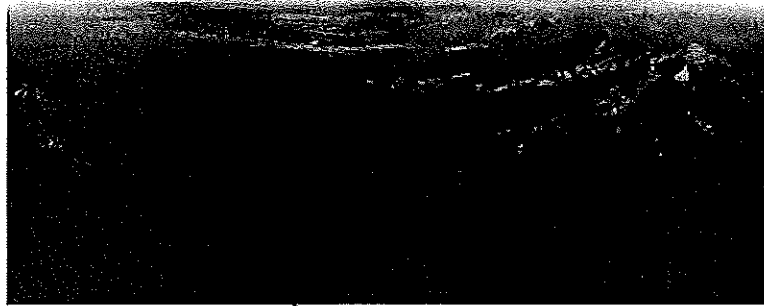


Figure 2. In this image derived from the Cassini Huygens lander as it descended to Titan's surface, Titan's landscape is reminiscent of San Francisco Bay, except that the oceans are of liquid methane, ethane and propane. Credit: NASA/ESA.

Titan holds the possibility of yet another opportunity for weird life. Normally, water freezes at 273 K. Ammonia, however, is an excellent antifreeze. Water-ammonia mixtures will remain liquid as eutectics at temperatures expected for the subsurface of Titan (Figure 3). Further, some images returned by the Cassini-Huygens mission to Titan were interpreted as flows resulting when those water-ammonia mixtures came to the surface. Thus, water-ammonia fluids may also be solvents for weird life, a kind of life that lives in cold temperatures in the same kind of liquid that you use to de-grease your windows.



Figure 3. Images of flow on the surface of Titan suggests the possibility of water-ammonia fluids below the surface, where the antifreeze properties of ammonia keep the mixture liquid at Titan temperatures.

As an environment, Titan meets all of the constraints that we have imposed so far on weird life. Titan is not at thermodynamic equilibrium. It has abundant carbon-containing molecules. It has heteroatoms (although the amount of oxygen appears to be sparse by terran standards). Titan's temperature is low enough to permit a wide range of bonding, covalent and non-covalent. Titan undoubtedly offers other

resources believed to be useful for catalysis necessary for life, including metals and surfaces. And Titan has a choice of liquid solvents.

If life is an intrinsic property of chemical reactivity, we are driven to conclude from that perspective that weird life exists on Titan. Indeed, for life not to exist on Titan, we would have to argue that life is *not* an intrinsic property of the reactivity of carbon-containing molecules. Rather, we would need to believe that either life is scarce in these conditions, or that there is something special, and better, about the environment that Earth presents for life.

## 2.7 Solvents exist that are not like water and not hydrocarbons

We need not stop here as we consider liquids that might be weird biosolvents. The most abundant liquid in the solar system is neither polar (like water, ammonia, or formamide) nor hydrocarbon. Rather, the most abundant compound is molecular hydrogen ( $H_2$ ). Molecular hydrogen is the principal component (86%) of the upper regions of the gas giants, Jupiter, Saturn, Uranus and Neptune. These giant planets make up most of the volume in the solar system, excluding the Sun itself.

But is molecular hydrogen a liquid? The physical properties of a substance are described by a phase diagram that shows the temperatures and pressures at which the compound (if stable) is a solid (of various types), a liquid, or a gas. In general, a line extends across the phase diagram. Above this line, the substance is a gas, while below the line, the substance is a liquid. Typically, however, the line ends at a *critical point*. Above the temperature and pressure represented by the critical point, the liquid becomes supercritical. At this point, the substance is neither liquid nor gas, but is rather a supercritical fluid.

The properties of supercritical fluids are often very different than those of the corresponding regular fluids. For example, supercritical water is relatively non-polar and acidic, and is an excellent solvent. Indeed, many of the gemstones that we know are formed by the crystallization of rock that has been dissolved in supercritical water. Supercritical carbon dioxide is used in industry to dissolve caffeine from our coffee flakes.

Supercritical hydrogen, the fluid that is found in gas giants like Jupiter and Saturn, has been little studied. However, a little bit of data from the 1950s and 1960s show that some organic molecules dissolve in such fluids.

Could life live in the supercritical hydrogen fluid within Jupiter? Indeed, do gas giants have regions where the temperatures are consistent with stable organic molecules and the temperatures and pressures permit supercritical dihydrogen to be a solvent? The answer is "yes", as long as one does not go too far towards the core of those planets.

We can define two radii for each of the gas giants. The first is the radius where dihydrogen becomes supercritical. The second radius is where the temperature rises to a point where organic molecules are no longer stable (let us say 500 K). If the second radius is smaller than the first, then there is a "habitable zone" on the planet where life can survive living in supercritical dihydrogen as a solvent. If the second radius is larger than the first, however, then the planet has no habitable region, that is, no region where both organic molecules are stable and supercritical dihydrogen is available to serve as a solvent.

On Jupiter, temperature and pressure rise rapidly as one descends. At about 200 km down from the point where the molecular hydrogen becomes supercritical, the temperature rises above 500 K, the upper limit where most carbon-carbon bonds are stable. Life, according to our constrained speculation, is not possible further down. Thus, the habitable zone on Jupiter is a thin (relative to the diameter of the planet) shell of the planet.

For Saturn, and then for Uranus and Neptune, the slice is thicker relative to the planetary radius). On Jupiter, where the temperature is 300 K (clearly suitable for organic molecules), the pressure (ca. 8



atmospheres) is still subcritical. On Saturn, however, the temperature is ca. 300 K when hydrogen becomes supercritical. On Uranus and Neptune, the temperature when hydrogen becomes supercritical is only 160 K; clearly organic molecules are stable at this temperature, and the habitable zone is still larger.

Imagine being a weird life form living in the supercritical ocean-atmospheres of one of these planets. Just as the oceans on Earth, these ocean-atmospheres are in turmoil, with fluid moving from the habitable layers down towards death as fluid from the cooker below into the habitable zone. To survive if your metabolism relied on carbon-carbon covalent bonds, you would need to stay by floatation (or quite rapid swimming) in the habitable zone. This is, of course, true for life in any fluid environment, even in terran oceans. Sagan and Salpeter presented a detailed discussion of what might be necessary for a "floaters" to live in the Jovian atmosphere.

### 2.8 Can we exclude forms of weird life by arguing that water is necessary for life?

As much fun as this constrained speculation is, it does not help NASA much as it seeks to go look for life in the Solar System. After all, funds are limited. The most helpful constraint, from a purely practical perspective, is one that identifies a *single* location in the Solar System where life is (almost) certain, and rules out all other places. This would allow NASA to focus its budget. For example, if liquid water is an absolute requirement for life, then NASA could go only to those places that have (or have had) liquid water. Indeed, NASA's missions to Mars "follow the water".

But is this a real constraint? Liquid water certainly appears to be required for terran life. Thus, the bacteria that live above 373 K (100 °C, 212 °F, boiling at sea level) on the ocean floor near black smokers do so only because the high pressure of the ocean above keeps water liquid. Bacteria living in the Antarctic ice pack presumably require melting to grow. In the Atacama desert, where three mountain ranges conspire to keep liquid water from ever arriving, life may not be present at all, despite the abundance of solar energy that makes chemical disequilibrium possible.

This sets up the most fascinating of conundrums. Wherever liquid water is available on Earth, life seems to be present. From deep in mine shafts to deep in oceans, in environments dominated by reductants as strong as hydrogen sulfide and methane to oxidants as strong as dioxygen, in every environment that has been examined, life seems to be there. And not just life, but rather that has evolved from the universal ancestor of all life on Earth. As long as water is available, life finds a way to exploit whatever thermodynamic disequilibria exist.

But again, we do not want to be terracentric. Does terran life need water because our last common ancestor needed water? Or has terran life evolved specifically to become adapted to water, simply because it is the dominant liquid in its environment? Would life exposed to another liquid become equally well adapted to that other solvent? And is the Atacama desert lifeless because it lacks water? Or because it lacks a liquid of any kind?

Books have been written to address this question, many for the layperson. Many argue with some certitude that the properties of water make it optimally, if not uniquely suited for life. Let us construct a "good news-bad news" dialectic for some of these.

For example, some have argued that water is uniquely suited for life because water expands when it freezes. This expansion means that ice floats. This, in turn, means that as water freezes by the loss of heat to whatever lies above, a surface layer of ice forms that insulates the liquid water below, slowing its freezing. At least for a time, that insulated liquid can harbor life. In contrast, both ammonia and methane are denser as solids than as liquids. Therefore, ammonia and methane shrink when they freeze. This exposes the liquid surface to further freezing. It is argued that this is bad for life.

This argument is a bit terracentric. First, ice comes in various forms, as those who read Kurt Vonnegut's

book *Cats Cradle* know. Ice I floats. Ice II, in contrast, sinks. Why do we call Ice I "Ice One"? Because it is the most stable form of frozen water at sea level, on *Earth*. If we lived in water on a more massive planet, we would be calling Ice II "Ice One", and noting the virtues of a biosolvent that sinks when it freezes. After all, the insulating layer of ice provided on *Earth* does not protect you from long term cooling. And a sinking ice would bring heat from below by convection to allow the entire body of water to remain liquid.

Another feature of liquid water is its ability to dissolve hydrophilic compounds, many of which are metabolites in modern terran metabolism. But this too is circular. Is water good because it dissolves our metabolites? Or were our metabolites chosen by Darwinian processes to be suited to dissolve in water?

The same issues apply when we speak of the hydrophobic effect, a shorthand way of saying that water and oil do not mix. When proteins fold, they put their hydrophobic amino acids inside, away from water. Of course, if we lived on Titan in liquid methane (and had proteins), it would be the other way around. Proteins would still fold, but they would put their hydrophobic amino acids *outside* and their *hydrophilic* amino acids inside, away from the methane bath.

For those who still like water, let us point out that water engages in undesired reactions as well. Thus, the cytidine in DNA and RNA loses ammonia to give uridine with a half-life of ca. 70 years in water at 300 K. Adenosine loses ammonia to give inosine. Guanosine loses water to give xanthosine, one of the other extra letters in our synthetic genetic alphabet. As a consequence, terran DNA in water must be continuously repaired.

In other ways as well, water is toxic. The toxicity of water creates special problems for the prebiotic chemistry, as repair mechanisms presumably require a living system. Thus, even if we assume that we can make polymeric RNA in substantial amounts in a prebiotic soup to support the emergence of an RNA-directed RNA polymerase the start of an RNA world, it is not clear (in the absence of evolutionary mechanisms) how to prevent that information from rapidly decomposing due to hydrolysis in water. And so the dialectic is established.

## 2.9 Weirder life might not live in a liquid at all

A liquid phase is widely regarded as being helpful, if not necessary, for life. Liquids certainly help along chemical reactions. As a solvent, a liquid allows metabolites to dissolve, disperse, and encounter other metabolites at reasonable rates.

Chemical reactions can take place in the gas and solid phases, of course. Indeed, life in the gas phase (*The Black Cloud*, Fred Hoyle) or in the solid phase is conceivable. But gaseous and solid habitats both have disadvantages relative to liquid habitats. In the gas phase, chemistry is limited to molecules that are sufficiently volatile to vaporize, and sufficiently stable to survive the higher temperatures where they do vaporize. This is a severe constraint on what molecules can support life. DNA, for example, does not vaporize at a temperature below the temperature at which it decomposes.

Obviously, if time scales are long, even low concentrations of biomolecules might support a biosystem in the gas phase, perhaps in the vacuum of interstellar space. Such weird life must solve the problem of diffusion; it is difficult to hold together the components of such an interstellar life form. Gravity does not work, as gravity would cause diffuse gaseous life to collapse to be no longer gaseous.

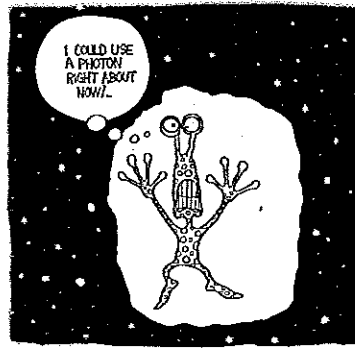


Figure 4. Hypothetical life in the Oort Cloud

On the other hand, interstellar gas-phase life might have some advantages. For example, such life need not be encumbered by the lifetime of a planetary system or its associated star. Indeed, one can imagine life in the gas phase might be associated with a galaxy and its energy flux for nearly the age of the universe.

The solid phase might also be considered as a habitat for weird life. Molecules can diffuse through solids to react with other molecules in the solid. Movement through a solid phase is slow, of course; any weird solid phase life form would live very slowly (Figure 4). Nevertheless, given cosmic lengths of time and the input of energy via high-energy particles, a biochemistry able to support Darwinian evolution can be conceived. For example, a weird form of life might reside within solids in the Oort cloud out past the planet Neptune living in deeply frozen water. Here, it could live from the occasional disequilibrium create by the energy from a photon or a trail of free radicals left behind by ionizing radiation, carrying out only a few metabolic transformations per millennium.

### 2.10 Can other elements support carbon-like scaffolding

But why are we talking about covalent bonds between carbon atoms and solvents and temperatures where they are stable? The stability of covalent bonds between carbon atoms has long made carbon the first choice within the community as an the element to serve as a scaffold for biomolecules. And so, we commonly refer to ourselves as carbon-based life.

This appellation is, in part, inappropriate. Carbon *alone* is not particularly useful to support life unless it is combined with other elements. Hydrogen is needed for many reasons; at the very least, it terminates chains of carbon atoms. Hydrocarbons, organic molecules made from *only* carbon and hydrogen, have very little interesting reactivity. Only when we add *heteroatoms*, defined as atoms that are neither carbon nor hydrogen, do our organic molecules acquire the reactivity needed to support metabolism. In terran life, these heteroatoms are predominantly oxygen, nitrogen, sulfur and phosphorus.

Further, it is incorrect to say that terran life is "carbon scaffolded". In proteins, the sequence of atoms in the backbone is carbon-carbon-nitrogen-carbon-carbon-nitrogen, and so on. In DNA, the sequence of atoms in the backbone is carbon-carbon-carbon-oxygen-phosphorus-oxygen-carbon-carbon-carbon-oxygen-phosphorus-oxygen, and so on. Thus, even in our "carbon-based life", other atoms participate in the backbones of our most important biomolecules.

For those who are prepared to set aside carbon-o-centricity, silicon becomes a favored second choice (see, for example, *Star Trek* Episode 26, *The Devil in the Dark*). Like carbon, silicon can form four bonds. Silicon atoms can join to other silicon atoms to form chains. The silicon-silicon bond is weaker than the carbon-carbon bond, but not excessively so. A typical silicon-silicon covalent bond has 75% of the strength of a typical carbon-carbon covalent bond, and compounds with as many as 26 consecutive silicon-silicon

covalent bonds are known. Further, silicon chains can carry side chains with interesting atomic functionality, just like proteins carry different functionalized and non-functionalized side chains.

Heteroatoms can participate in scaffolds involving silicon as well. For example, the silicon-oxygen-silicon-oxygen sequence also makes scaffolds. *Silicones*, molecules having this sequence are found in (for example) superballs and breast implants. Again, silicon and oxygen alone cannot generate particularly interesting chemistry. To get interesting reactivity, Si-O-Si-O units must have side chains that include carbon, hydrogen, nitrogen, oxygen, and other heteroatoms. The life might nevertheless be called silicon-based, just as we call terran life carbon-based.

One must not stretch the analogy between carbon and silicon too far, however. The reactivities of silicon and carbon differ in some notable ways. First, nucleophilic attack on silicon atoms is generally faster than nucleophilic attack on carbon atoms. Whether this difference in reactivity is an advantage or disadvantage for silicon depends on context. The greater reactivity of silicon compared with carbon from any reactions may in fact be an advantage in cold environments where the kinetic barriers to reaction are too high for carbon. William Bain, for example, has suggested that silicon-based life might be especially appropriate for Triton, the cold moon of Neptune where oceans of liquid nitrogen are found.

### 2.11 Creative use of the Periodic Table

The Periodic Table does not offer any good third choice for covalent scaffolding, although alternative elements might be embedded in a scaffold that contains many carbon or silicon atoms. These atoms include arsenic, phosphorus, sulfur, and selenium. Weirder forms of life might dispense with covalent bonding, relying instead on ionic bonding.

But there is no reason not to consider other elements in weird metabolism. Science fiction writers have thought about this too. For example, in the movie *Evolution*, Ira Keene (played by David Duchovny) encountered an alien as a professor Glen Canyon Community College; the alien had arrived in Arizona via meteorite. This alien grew, with some disregard for the laws of thermodynamics, by converting pure heat into matter.

Following a "logic" illustrated in Figure 5, Keene discovered that the biochemistry of the alien was based on nitrogen instead of carbon. Keene noted that arsenic was poisonous to carbon-based life. Then, in an extreme example of an argument from analogy, he noted that to get from terran carbon-based life to nitrogen, one goes one step to the right across the Periodic Table, "meaning" that to get a toxic element to nitrogen-based life, one must return to the Periodic Table, find arsenic, and take one step to the right. This gets you to selenium, a component of anti-dandruff shampoo. He purchased a bucket of the shampoo and injected it into the alien. End of alien.

Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Uub	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo

Figure 5. Assume a life form based on nitrogen. Note that nitrogen (N, element 7) is one step to the right in the periodic table from carbon (C, element 6). Arsenic (As, element 33) is toxic to carbon-based organisms. So selenium (Se, element 34) should be toxic to the aliens.

## 2.12 High dimensional genetics

We can return to the structural features of genetic molecules and cells to revisit theories central to terran biology (such as the polyelectrolyte theory of the gene or cell theory), to ask: Why? For example, RNA, DNA, and proteins are all linear strings of building blocks. Accordingly, they are fundamentally unidimensional. This is useful as it allows them to be biosynthesized by adding one building block at a time to a growing chain.

It is conceivable, however, that weird life might be supported by genetic systems that are two-dimensional. In this type of weird genetic systems, information is placed into the two dimensional surface by introducing defects. For example, adapting a model from Cairns-Smith, let us have the surface be a flat silicate (like mica). Every now and then, replace a silicon atom by something else (let us use germanium, which is the atom in the periodic table that is in the row right below silicon). Let us store genetic information there.

With this flat genetic system, replication is done using the third dimension, which allows two dimensional surfaces to interaction. The model for the replication of information is as old as the printing press. Here, one flat genetic system containing the information is pressed against another flat genetic system that contains no information. Information is passed from the first to the second just as ink is passed from a printing plate to a sheet of paper.

We can also think of cells having different dimensions. A key element of Darwinian evolution is believed to be isolation. In terran biology, this isolation is achieved by having, effectively, a bag in which one lives. But suppose isolation is achieved in other ways. For example, Louis Lerman speaks of aerosols as isolation environments. Water droplets suspended in oil can serve as cells. Or, more exotically, isolation might be achieved by lying in a region on a two dimensional surface, or within a region of a frozen solid.

## 2.13 What can we do when we cannot observe, even indirectly?

Experimental approaches to asking about the plausibility of such weird life are conceivable. For example, we could set up a set of laboratory experiments to understand better the solubility of organic molecules in some of the more exotic liquids that we might consider as possible biosolvents. Very little is actually known about what dissolves in liquid nitrogen (a liquid on Neptune's moon Triton), supercritical hydrogen or supercritical helium. We can do laboratory experiments that would establish metabolisms that use acetylene, a high energy organic molecule known to exist in the atmosphere of Titan, to drive the synthesis of other molecules as an ATP-equivalent suitable for life in methane oceans. We can explore the reactivity of organic species containing C=O and C=N units in water-ammonia fluids at low temperatures.

At some level, these can only be preludes to exploration, the best way to "jolt" our thinking. For more information, see the book entitled *Life, the Universe and the Scientific Method* ([www.ffmpeg.org](http://www.ffmpeg.org)).