Fall 2017

A Chemical Quest: What is Life and Where Might We Find It?

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Honors: Astrobiology HONR 480
Fall 2017

Abstract:

What is life? While a simple question, the answer is incredibly complex. Historical views on life and modern popular understanding heavily influence our definition of life, but as extraterrestrial exploration expands our knowledge, it is clear that a new view on life is needed. To effectively define life, it is necessary to examine the nature of life on the chemical level, and to look to research to guide our search for life in extraterrestrial environments. This work examines the historical views of life, the modern chemical elements of life, the research that investigates life in the extraterrestrial setting, and some locations where extraterrestrial life might be found.

A Chemical Quest: What is Life and Where Might We Find It?

If presented with two animals, one living and one dead, the vast majority of people would be able to identify the living one. Similarly, most people would also be able to correctly determine whether a plant is living or dead. In fact, most people would probably be able to describe what characteristics or behaviors make the animal or plant living. But if asked to simply describe life, they might have trouble. The question is deceivingly simple. Most people would revert to the answer they were taught in middle school biology. They might say that life involves organization, metabolism, homeostasis, growth, reproduction, response, and evolution. But in reality, these words only describe the observable traits of a thing that is said to possess life. To illustrate this more clearly, consider the analogous example of influenza. If asked to describe the flu, someone might choose to list some of the symptoms a person with the flu experiences: chills, fever, muscle aches, coughing, etc. While these symptoms do reveal information about the flu, they do not tell the whole story. They simply describe the state of a person who has the flu, but do not get at the root cause of the sickness. Similarly, organization, metabolism, homeostasis, etc also reveal information about life, but they do not tell the whole story. They only describe the state of a thing that has life. In an age where the human capability to explore extraterrestrial environments is ever expanding, there is a need for a more elemental understanding of life. It is not enough to simply think of life as the traits of a thing that possesses it.

So, how might one describe *life*? How would this definition influence the way we think about our lives and the world around us? Furthermore, how would a definition of life influence the search for life on other planets throughout the universe? The answer is not so simple and has been debated by scientists, philosophers, and theologians for centuries. Additionally, despite the astounding advances in space exploration made in the last 100 years, it seems as though we are still incredibly far from finding life outside of the Earth's atmosphere. Some have thought that to elucidate the true nature of life, it is necessary to go to the molecular level of organization. Numerous research studies have delved into this topic, and the results are of great intrigue. To rigorously examine the nature of life, it is necessary to examine the historical views on life, see how these views have influenced our modern understanding of life, particularly in the chemical sense, and see how these views may drive future search for life across the universe.

A Historical Backdrop

How have scientists in the past defined life? Early Greek thinkers collectively created the theory of spontaneous generation. This theory, first cohesively stated by Aristotle (Wilkins, 2004), was based on the belief that life is a necessary outgrowth of matter. When the conditions were right, and when luck favored a chance event, matter would spontaneously lead to life. How else would maggots appear in a discarded piece of meat? This idea, accepted for centuries, and subscribed to by famous intellectuals such as Newton and Descartes, was challenged by a number of experiments in the 17th and 18th centuries (Wilkins, 2004). These challenges were famously confirmed by Louis Pasteur when he developed a strict sterilization protocol, the basis of modern "Pasteurization". Following the fall of spontaneous generation, numerous other advances in the study of life cropped up in the 19th and 20th century, such as Darwin and his then radical proposal of the concept of “descent with modification”. Later, discovery of the structure of DNA and its role as a genetic “code” revolutionized the way we look understand life.

As this understanding of life progressed, it became convenient for people to see life through the lens of “living vs nonliving”. Instead of clearly outlining what makes *life*, the characteristics of something that is *living* were described and systematized into a way of thinking that has found its way into common culture. Most people would be able to recognize the “seven requirements for life” that are commonly presented in a middle and high school education: organization, metabolism, homeostasis, growth, reproduction, response, and evolution. This definition of life has unofficially been adopted in the minds of many people, and in some sense, it guides the way we think about life. However, it is clear that such a definition of life is insufficient. Much like it is easier to eliminate wrong answers on a multiple choice test than it is to fill in a blank with the correct answer, it is much easier to see what is living and nonliving than to clearly define the identity of life itself. With this mindset, it is easy to see how one might even say that a rabbit is an not example of “life”. The rabbit may be living and it may display all the characteristics of a living thing, but a single rabbit is not capable of creating more rabbits that would live on once it had died (Bains, 2004). Further, science has revealed that organisms on Earth stretch our laundry list of living characteristics to seemingly wild extremes. Tardigrades, micrometazoan animals, have been known to show cryptobiosis, an ametabolic state of life, when exposed to anhydrous conditions (Welnicz, 2011). In other words, tardigrades do not exhibit the “characteristics of life” when in an anhydrous environment, but when re-exposed to water, can resume lifelike activities. Clearly, it is not enough to simply list characteristics of life if we are to search for life in extraterrestrial environments.

A Chemical Lens

In an effort to more plainly describe life, it is helpful to turn to the molecular level of organismal organization. This understanding of life will not only help define life, but will aid in the extraterrestrial search for life as well. If we are to look for life in extraterrestrial environments, it is unlikely that we will encounter fully formed or recognizable animals and plants like those on Earth. As science has progressed, scientists have increasingly sought to understand life from the chemical perspective, and in 1994, a NASA panel concluded life to be a "chemical system capable of Darwinian evolution" (Joyce, 1994). This definition has guided a great amount of research, and it is the definition that will be the primary focus of this paper. It is a working definition, and even though it does not fully answer the question "What is life?" it provides us with a somewhat clearer idea of what separates the living from the nonliving. Moreover, a chemical understanding of life is nearly a necessity when exploring outer space for signs of life.

The Carbon Conundrum

As science has developed more advanced technologies and begun to look to the universe outside the confines of the Earth, the quest for life has become even more complex. If someone is to look for evidence of life in far-away planets and solar systems, what must he or she look for? We have already established the need for a chemical definition of life, but what might that look like outside the boundaries of the Earth? For much of the 20th century, it was almost implicitly assumed that any life encountered outside the Earth would be much like life seen on the Earth. After all, the only model of life ever known to humankind is that on Earth. The famous Lawrence Henderson, a scientist immortalized by his work researching acid-base relationships in the human body, wrote in 1913 that life necessarily must be based on the element carbon and its interactions with water (Henderson, 1913). This view, based on observations made about life on Earth, seems like a rather reasonable outlook, given that the only life humans have ever encountered is the life of Earth. Further, the life of Earth is entirely dependent on the properties of carbon. This carbon-centric thinking has, in many ways, prevailed as the leading theory for the chemical basis of life. Some modern scientists have concurred with Henderson, positing that the biochemistry of the Earth is unique in the universe and that extraterrestrial life most likely is an evolving system of specifically organic chemistry (Pace, 2001). Others have stated that the search for life should focus on "life as we know it" (Chyba and Philips 2001), and that we should "follow the water" to see where life might exist in the universe.

However, it is not enough to simply say that extraterrestrial chemical life is carbon or water-based. In fact, it may even be incorrect to say that all life must strictly be carbon or water-based. Carl Sagan, writing about Henderson, stated " I personally find this conclusion suspect, if only because Lawrence Henderson was made of carbon and water and metabolized free oxygen. Henderson had a vested interest" (Sagan, 1973 (Bains 2004)). Sagan also coined the term "carbon chauvinism" and thought that the insistence on a universal carbon-based life was rather presumptuous. Other scientists have voiced similar thoughts, and even Arthur Clarke, famed co-writer of *2001: A Space Odyssey*, believed a system of life limited to the chemistries of carbon, hydrogen, oxygen and nitrogen to be too narrow in scope (Clarke, 1972). Research on extraterrestrial chemical life includes a vast number of topics. The aim of this paper is to present the ideas that have shaped the chemical definition of life, provide some proposed alternative forms of biochemistry and their accompanying research studies, and examine a few possible locations where such chemistry might be found.

Essential Chemical Characteristics

Thermodynamic Considerations

To begin, it is advantageous to look at how scientists have gone about fleshing out the definition of chemical life as well as how this definition may be look in extraterrestrial environments. Many scientists begin with the baseline necessity of thermodynamic equilibrium. Benner, Ricardo and Carrigan (2004) note that thermodynamic disequilibrium is a necessity for almost any conception of life. On Earth, a variety of disequilibria result from biological activity, including atmospheric oxygen and water levels, as well as topographical erosion gradients (Kleidon, 2012). Some scientists have concocted studies to evaluate the usefulness of thermodynamic disequilibrium as a metric for life. Making use of the Galileo Probe's passage over the Earth, it was noted that the thermodynamic disequilibrium of the Earth's atmospheric methane is a key indication of life (Sagan, 1993). It is important to note that this disequilibrium is not expected to take the same form throughout the universe. For instance, the high energy, reduced molecules of Earth are valuable in many cases because of the systems in place that allow for harvest of electrons or energy. However, the energetically favorable reactions these species undergo are largely dependent on the nature of their surroundings. For instance, ATP, the “energy currency” of terrestrial life, is a source of energy due to its phosphate bonds. Yet, breaking of such bonds is facilitated best by a polar solution such as water. On planets where the primary liquid solution is a mixture of alkanes, ATP may have less use.

Bonding Considerations

Some scientists have also noted that the nature of bonding might be important when defining chemical life. Strong, covalent C-C bonds often come to mind, as this carbon-carbon bond is necessary for all organic compounds and is the basis for all living structures on Earth. Weaker bonds, such as hydrogen bonds, are of significant importance as well, as hydrogen bonds give water its characteristic properties and drive its interaction with other molecules. However, the nature of bonding is also dependent on the environment surrounding the bond, and given that the majority of the universe experiences temperature and pressure ranges very different from that of Earth’s, it is possible that the importance and relative strength of certain bonds is wildly different on foreign planets and moons. It has been hypothesized that “the bonding that supports information transfer needed for Darwinian evolution might universally require bonding sufficiently strong at the ambient temperature to be stable for some appropriate time” (Benner, et al., 2004). This implies that the conditions on Earth just so happen to make the covalent and hydrogen bonds important for Earthly life, and that in a particularly cold environment, for instance, the covalent bond may play a different role in sustaining life.

Structural Considerations

Another important chemical requirement for life is the need for carbon-like scaffolding. Carbon has earned its reputation as the element of life. Its ability to form a myriad of stable structures has lead to it being the primary element in complex life forms. Its aptitude to form a variety of bonds with both itself and heteroatoms places carbon at the center of life. At the core of this is the element’s ability to form structures that lend themselves well to life. At the Earthly temperatures of -88 to 58 C^{o}, carbon is an excellent choice for large structure stability. On the other hand, much of the universe experiences temperatures far outside this range. In light of this, significant work has gone into investigating the molecules formed from silicon. Located just below carbon on the periodic table, one might expect silicon to behave similarly to carbon. In fact, it does in many ways. In spite of the fact that the Si-Si bond has a lower dissociation energy than that of the C-C bond (Walsh, 1981), chemists have successfully synthesized a variety of organosilicon compounds. These molecules have ranged from long-chain polysilanes (Maxka et al., 1991) to cyclic polysilanes (Gollner, 2003) to organosilanes with a variety of functional groups, including carboxylic acid, cyanide, phenol, and hydroxyl groups (Hayase, 1989, 1995). It is clear that chemical diversity amongst silicon-based molecules is entirely possible, but it is important to recognize that silicon is significantly more reactive than carbon. Its d atomic orbital allows for bonding before the expulsion of a leaving group, making it more vulnerable to nucleophilic attack than carbon. Some have hypothesized that the wide range of organosilanes and the increased reactivity of silicon make it suitable for life at colder temperatures (Bains, 2004).

Solvent Considerations

A suitable solvent is also hypothesized to be a chemical need for life. While reactions can take place in entirely solid or gaseous phases of matter, liquid is more conducive to stable diffusion of reactants within a relatively short time span. On Earth, the solvent is water, but it is possible that on other planets, the solvent could have entirely different properties that lead to alternative forms of chemical life. Ammonia has been proposed as a possible alternative solvent for life. The National Academy of Sciences notes that ammonia shares a number of characteristics with water, including its ability to dissolve an array of organic compounds, the large temperature and pressure range over which it is liquid, and its abundance in the universe. Ammonia's usefulness as a solvent for life presents a number of challenges. Ammonia is significantly more basic and nucleophilic than water, so common terrestrial functional groups like the C=O carbonyl are susceptible to attack in liquid ammonia. Perhaps an alternative chemistry that utilized C=N instead of C=O would be possible in an ammonia based system of life.

A Suitable Locale

Given the proposed chemical requirements for life to exist, and considering the possible extraterrestrial conditions and chemical systems that might satisfy those requirements, the logical next question is to ask where these chemical systems might be found. A number of different places have been hypothesized as locations for life to form.

One such place is Enceladus. A moon of Saturn, this place is a cold body with mean surface temperatures of -198 ^{O}C and a thick layer of ice covering its surface. Information gathered by NASA's Cassini have led some scientists to think that life may be possible there. In particular, they note that Enceladus has a deep ocean of water underneath the surface of its icy layer, and that there is enough tidal heat to keep this ocean liquid for long periods of time. The Cassini probe also found that plumes of water vapor rising from the surface of the moon contain compounds such as water, CO_2, CH_4, and NH_3. Some hypothesize that hydrothermal sites on the the ocean floor may be sites of chemically life-like reactions (Deamer, 2017). Certain types of "weird life" on Earth is similarly found near volcanic vents in the ocean, and these organisms are known for using alternative electron transport chains and utilizing unique molecules as energy sources. Analogously, organisms on Enceladus might live deep in the ocean and harvest energy from alternative sources.

A case can also be made for Titan, Saturn's largest moon. Titan, the only moon known to have a dense atmosphere, is a rocky place with lots of water ice and a surface temperature of about -253 ^{O}C. Information gathered by Cassini has found that Titan is also the home of large lakes of liquid hydrocarbons, in addition to a large variety of surface features such as mountains, rivers and dunes. Modeling has predicted that the lakes of Titan are roughly 65% ethane and 30% methane (Raulin, 2012). Additionally, computational methods have been used to model a potential cell membrane that might be possible in lakes of ethane and methane. These membranes, termed "azotosomes" would function much like the lipid bilayer common to terrestrial life. Composed of nitrogen-containing short chain molecules, these azotosome are theoretically capable of forming a bilayer that is conducive to life at cryogenic conditions (Stevenson, 2015).

Extensive work has been done to investigate the organic chemistry in the atmosphere of Titan. Interestingly, even though Titan has a higher atmospheric pressure than Earth and a more extended atmosphere due to lower gravity, the stratification of the atmosphere is remarkably similar to Earth's (Cable, 2012). Modern researchers, in a fashion similar to the famous Miller-Urey experiment, are attempting to model the atmosphere of Titan in the lab by exploring the chemistry in simulated environments. They use a variety of techniques to stimulate production of organic matter, including cold and hot plasma discharge, ultraviolet irradiation, and γ-radiation. Such experiments have successfully produced organic materials. These materials, termed "thiolins", vary in composition. The first thiolins produced were sticky, brown, and reddish residues (Sagan and Khare 1979). As atmospheric modeling studies of Titan have progressed, thiolins now include a wide variety of compounds. Thiolins can take the form of amorphous "sticky" balls of material, smooth round aggregations of nitrogenous species, or thin films on the surface of reaction containers. The chemical functional groups found in thiolins also span a range of possibilities. It has been found that generally, thiolins are some form of an unsymmetrical polycyclic aromatic nitrogenated hydrocarbon. However, non-nitrogenous groups have formed as well, including alcohols, diols, aldehydes, and ketones. In fact, the identity of thiolins is in large part dependent on the method used to make them and the conditions that researchers use as the simulated Titan atmosphere. Intriguingly, some experimenters have reported thiolins that include pyridine, pyrrole, carbon dioxide, ammonia, alanine, and glycine. Such molecules are hallmarks of terrestrial biochemistry, and while such studies are still in very preliminary stages, they invite deeper investigation of the chemistry on Titan.

It has also been shown that some of the photochemically produced compounds in the atmosphere of Titan could react with hydrogen gas and serve as a chemical energy source for life (Schulze-Makuch 2013). In particular, the use of acetylene as a potential biofuel has been highlighted (McKay 2016). Challenges to this model include the fact that given Titan's location in the Saturn system, it receives a fraction of the sunlight that is seen in places like Earth.

Closing Remarks

The human understanding of life has come a long way. Originally thought to arise from nothing, we now are able to identify and understand life on Earth in ways scientists of even 50 years ago could not have imagined. As we stretch our exploratory nature into the extraterrestrial universe, the characterization and search for life is taking a new form. Extraterrestrial exploration demands a different definition. It is no longer adequate to think of life as the collective traits that describe the things we have previously found to be living. As the search for life becomes more complex, the understanding of life must become more elemental. The chemical view of life is simply the next step in our scientific understanding. While the hypothetical biochemistries and life systems mentioned here may prove to be nothing more than scientific wishful thinking, it is important to realize that we are on the unexplored frontiers of human knowledge.

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