Journal of Cosmology, 2010, Vol 5, 818-827.
Cosmology, January 25, 2010

The Search for Life on Other Planets: Sulfur-Based, Silicon-Based, Ammonia-Based Life

Pabulo Henrique Rampelotto
Exobiology and Biosphere Laboratory - Southern Regional Space Research Center / National Institute for Space Research, P.O.Box 5021, 97105-900, Santa Maria, RS – Brazil.
Department of Biology, Federal University of Santa Maria P.O.Box 5096, 97105-900, Santa Maria, RS - Brazil

Abstract

The search for extraterrestrial life is one of the most challenging and interesting scientific themes of the 21st century. This search has been guided by our understanding of the life's nature. Up to now, we only know life on Earth, which uses water as a solvent and the building blocks of which are based on carbon and oxygen. Hence, the search for extraterrestrial life has been the search for life as we know it as based on life which lives on Earth. However, living systems that may have originated elsewhere, even within our own solar system, could be unrecognizable compared with life here and thus not be detectable by telescopes and spacecraft landers designed to detect terrestrial biomolecules or their products.Therefore, we need to expand the boundaries of our Earth-centric concept of life and be open-minded and aware of the most general features of living systems. Life forms based on silicon, ammonia, and sulfur are among those who may have evolved on other worlds, and these possibilities are discussed.

Keywords: Astrobiology, Extraterrestrial Life, Definition of Life, Anthropocentric Concept, Sulfur-Based Life, Silicon-Based Life, Ammonia-Based Life, Panspermia

1. The Search for Extraterrestrial Life

The ancient Greeks were among the first to explain astronomical phenomena in physical terms. It is known, for example, that Aristarco from Samos (320–250 BC) taught that the Earth was just one planet which, as others, moves around the sun and that stars were at great distances. Epicurus (341–270 BC) suggested that the universe is filled with other worlds where extraterrestrial life is possible. Since then, the idea of a universe consisting of many worlds, just like Earth and our solar system, has been raised many times in the course of human history (Crowe 1986).

In 1584, Giordano Bruno, a priest of the Dominican Order, published "Dell Infinito, universo e mondi" ("Of Infinity, the Universe, and the World"). Bruno wrote that the stars were just like our sun, that planets must orbit these suns and that sentient beings, just like the humans of Earth, lived on these planets: "There are innumerable suns and an infinite number of planets which circle around their suns as our seven planets circle around our Sun." However, according to Bruno, we are unable to see these planets and suns "because of their great distance or small mass."

Charles Darwin (1809–1882) also accepted pluralism of life in the cosmos, and in fact this cosmic perspective may have facilitated his attempt to explain by naturalistic means the origin of various terrestrial forms of life.

In 1908 Arrhenius (2009) proposed that the seeds of life flow throughout the cosmos. Arrhenius (2009) developed a cosmic model, known as panspermia, in which life may travel from world to world, seedings the stars with life. However, at that time, it was thought the Milky Way galaxy was the universe, and it was still unknown if planets circled any of the stars.

Until the middle 20th century, the possibility of habitable worlds other than our own remained merely speculative. It is only with recent advances in space exploration and discoveries in the fields of cosmology and astrobiology, and the identification of over 400 planets circling other stars, including super-Earths orbiting in habitable zones (Lal 2010), that the possibility of life on other planets has been given serious scientific consideration (Forgan 2010; Goertzel and Combs 2010; Istock 2010). These include recent discoveries in our own solar system, which has led to numerous scientists to raise the possibility of extant life on Mars (Houtkooper and Schulze-Makuch 2010; Leuko et al., 2010; Levin 2010), Europa (Chela-Flores 2010), Io (Schulze-Makuch 2010), Titan (Naganuma and Sekine 2010) and Encedalus (Chela-Flores 2010).

Moreover, research and discoveries related to planet formation in this and other solar systems has led many scientists to again embrace theories of panspermia (Burchell 2010; Joseph 2000, 2009a; Rampelotto 2009). A number of scientists now believe life began on other planets or other extraterrestrial environments billions of years before Earth was formed (Jose et al., 2010; Joseph 2010a,b; Naitoh 2010; Poccia et al., 2010; Sharov 2010).

In the coming decades there will be increased attention and scientific effort devoted to the search of extraterrestrial life not only in this solar system, but on extrasolar planets (Forgan 2010). These include the missions DARWIN by ESA and TPF (Terrestrial Planet Finder) by NASA, and direct imaging methods (Bounama et al 2007; Cockell et al 2009) to detect extrasolar Earth-like planets and find hints of life on them by examining the composition of their atmospheres. Undoubtedly, the search for extraterrestrial life is one of the most challenging and interesting scientific endeavors of the 21st century.

The design of life-detection experiments to be performed by telescopes and spacecraft landers depends on assumptions about what life is and what observations will be taken into account as evidence for its detection (Forgan 2010; Goertzel and Combs 2010).

Up to now, we only know life on Earth. Therefore, the search for extraterrestrial life has been the search for life as we know it, based on the nature of life on Earth. Certainly, it is highly likely that life forms just like those of Earth, dwell on other planets. Some extraterrestrial life forms may also share a common genetic origins as those of Earth (Jose et al., 2010; Joseph 2000, 2009b, 2010b; Sharov 2010); and those with common origins and which dwell on Earth-like planets may have even evolved in a similar manner resulting in species similar or even more advanced than humans (Joseph 2000, 2010a,b).

Exosolar planets that might sustain life are believed to orbit within a ‘habitable zone’, the region around a star in which water can remain liquid, and where atmospheres might contain carbon dioxide, water, and nitrogen (Lal 2010; Rekola 2009). Consequently, scientists have been looking for biomarkers produced by extraterrestrial life with metabolisms resembling the terrestrial ones, where water is used as a solvent and the building blocks of life are based on carbon and oxygen (Forgan 2010; Istock 2010; Lal 2010).

However, life-sustaining worlds need not orbit in a habitable zone. Nor do they need to closely resemble Earth (Chela-Flores 2010; Goertzel and Combs 2010; Istock 2010). We now know that microbes can thrive in almost every conceivable environment. Therefore, planets which are blazing hot, frigid, or whose atmospheres may contain high levels of sulphur, or which are radioactive and toxic, may be home to a variety of extremeophiles who thrive under these *poisonous* conditions (Houtkooper and Schulze-Makuch 2010; Leuko et al., 2010; Naganuma and Sekine 2010; Schulze-Makuch 2010), just as they do on Earth.

To search for life on planets other than the Earth we must be prepared to recognize life as we do not know it. We cannot rule out other planets just because they are not like our world. An infinite number of life forms may have been fashioned in alien environments with characteristics fundamentally different from those found on Earth. In this context, to recognize alien life, we must learn how to escape from our anthropocentric, Earth-centered way of thinking and abandon the pre-Copernican belief that our planet is the center of the biological universe and all life forms are just like us.

2. Understanding What Is Life

For millennia, philosophers, scientists, and theologians, have attempted define life (Popa 2004). And yet, there is no general accepted definition of life.

Nowadays scientists are content to define life using the "chemical Darwinian definition" that involves "self-sustaining chemical systems that undergo evolution at the molecular level" (Joyce et al 1994). It is a limited definition considering that life on Earth may have originated on other planets (Joseph 2009a; Rampelotto 2009). There are in fact a number of genetic-studies which purport to demonstrate that the common ancestors for Earthly life forms may have first began to form billions of year before the Earth was fashioned (Jose et al., 2010; Poccia et al., 2010; Sharov 2010). It has been speculated the first steps toward actual life may have begun with self-replicating riboorganisms (Jose et al., 2010) whose descendants fell to Earth and other planets through mechanisms of panspermia (Joseph 2009a) thereby triggering the RNA world and then life as we know it (Jose et al., 2010). However, this model of life is still based on life as we know it. In fact, the concept of a self-sustaining chemical process can be applied with some justification to other catalytic, self-sustaining physicochemical process, such as forest fires.

Life on some planets may be like life on Earth (Crater 2010). Life on other worlds may have a completely different chemistry, and may not even possess a genetic code. It would be extremely unfortunate to expend considerable resources in the search for alien life and not recognize it when we find it--or it finds us.

Life that may have been originated elsewhere, even within our own solar system, could be unrecognizable compared with life here and thus could not be detectable by telescopes and spacecraft landers designed to detect terrestrial biomolecules or their products. Life might be based on molecular structures substantially different from those we know.

Therefore, it may be a mistake to try to define life based on a single example – life on Earth. As pointed out by Cleland and Chyba (2002) definitions just tell us about the meanings of words in our language, as opposed to telling us about the nature of the world.

What we really need is a general theory of living systems, analogous to the theory of molecules that permits one to give an unambiguous answer to the question “what is water?” (Chyba and Hand 2005). Prior to molecular theory, the best a scientist could do in characterizing water would be to define it in terms of its sensible properties, such as being wet, transparent, odorless and tasteless. Once we had an understanding of the molecular nature of matter we could identify water in such a way that all ambiguity disappears: water is H_2O. Thus, a precise answer to the question “what is water?” was possible only when situated within an appropriate scientific theory.

Again, however, this may trap us into an Earth-centered perspective. Life in the universe may not be like life as we know it. Therefore, the key to formulate a general theory of living systems is to explore alternative possibilities for life. In this context, first of all, we need to understand the fundamental features of life not just based on examples from Earth, but based on how life may form and then evolve on planets completely unlike Earth. By taking a broad view this will greatly improve the possibility of recognizing life if we come upon it elsewhere in the Universe.

3. Fundamental Features of Life

The search so far has focused on Earth-like life because that is all we know. Hence, most of the planning missions are focused on locations where liquid water is possible, emphasizing searches for structures that resemble cells of terran organisms, small molecules that might be the products of carbonyl metabolism and amino acids and nucleotides similar to those found in terrestrial proteins and DNA.

However, life that may have been originated elsewhere, even within our own solar system, could be unrecognizable compared with life here and thus could not be detectable by telescopes and spacecraft landers designed to detect terrestrial biomolecules or their products. We must recognize that our knowledge of the essential requirements for life and therefore our concept on it, is based on our understanding of the biosphere during the later stages of Earth history (Pilcher 2003). Since we only know one example of biomolecular structures for life and considering the difficulty of human mind to create different ideas from what it already knows, it is difficult for us to imagine how life might look in environments very different from what we find on Earth. In the last decades, however, experiments in the laboratory and theoretical works are suggesting that life might be based on molecular structures substantially different from those we know.

One of the fundamental features of life is its chemical complexity, which is based on polymeric molecules joined by covalent bonds. Carbon appears to be the only element capable of forming polymers that readily undergo chemical alterations under the physical conditions prevailing on Earth.

Organic molecules are now known to be common throughout the universe (Thaddeus 2006). Life, then, is assumed to be carbon-based.

However, our present knowledge of physics and chemistry suggests that an organism could have an entire non-carbon-based metabolism (Baross et al 2007). Silicon is a frequent mentioned option (Bains 2004). Like carbon, silicon can form four bonds. Silicon forms stable covalent bonds with itself and other elements. It can form stable tetra-, penta-, and hexa-coordinate compounds with N, C, and O bonds (Brook 2000).

Indeed, there is an immense diversity of structures that have been assembled from such chemistry (Bains 2004). Furthermore, the greater reactivity of silicon compared with carbon may be an advantage in cold environments. Thus, its chemical and structural flexibility in non-aqueous environments can provide analogues to most of the functions of terrestrial biochemistry.

Sulfur, nitrogen and phosphorus could also potentially form biochemical molecules (Schulze-Makuch and Irwin 2008). Sulfur is capably of forming long-chain molecules like carbon. Some terrestrial bacteria have already been discovered to survive on sulfur rather than oxygen, by reducing sulfur to hydrogen sulfide.

Phosphorus is similar to carbon in its ability to form form long chain molecules on its own, which would conceivably allow for formation of complex macromolecules. When combined with nitrogen, it can create quite a wide range of molecules, including rings.

Though a great variety of prebiotic molecules have been observed in the universe (Thaddeus 2006), they present different characteristics in comparison with specific classes of biomolecules. The same may be said when we analyze organic molecules in meteorites: they present structural diversity, a predominance of branched-chain isomers and its abundance decline with increasing chain length within homologous series (Pizzarello 2006).

The building blocks of life are based on polymers of various types (e.g. proteins, nucleic acids, and polysaccharides). Such polymers consist of a limited number of monomer units arranged in a linear array with some variation in the composition of the side chains. These various types of macromolecules to be functional in living systems are uniform with respect to chirality, i.e. they are homochiral polymers (Avetisov 2007; Tamura 2010). Though chiral enhancement can occur through abiotic processes (Pizzarello 2007), the presence of only one enantiomer, or at least a pronounced chiral excess, could be a sign of life.

To the chemical reactions required to support living processes occur, a liquid solvent is presumably necessary. This is because macromolecules need to be physically stable, yet capable of structural flexibility and chemical reactivity (Schulze-Makuch and Irwin 2008). On Earth, the only accessible common liquid is water and it is compatible with an enormous diversity of organic chemistry. Recent evidence indicates that other locations in the solar system may harbor liquid water (Chela-Flores 2010; Lewis 2004, Naganuma and Sekine 2010). Thus, water, as well as carbon, is assumed to be essential for life. Consequently, much of the astrobiological effort in recent years has been based on a ‘‘follow the water’’ principle.

However, novel studies have demonstrated that a variety of solvents may sustain life (Baross et al 2007). Among them, ammonia is the most cited. Ammonia, like water, dissolves many organic compounds. Many preparative organic reactions are done with this solvent in the laboratory. Although it is liquid at lower temperatures than water, the temperature range over which ammonia is liquid for relevant planetary surface pressures is greater than for water (Schulze-Makuch and Irwin 2006). The increased strength of the dominant base as well as the corresponding enhanced aggressivity of ammonia as a nucleophile imply that the biochemistry based on this solvent would have to be different in comparison with terrestrial life (Benner et al 2004). Considering that liquid ammonia may be abundant in the universe (Lewis 2004), ammonia may have also been employed in the development of alien life.

Ammonia is not the only polar solvent that might serve as an alternative to water. Sulfuric acid and formamide are reasonably good solvents that support chemical reactivity (Benner et al. 2004). Furthermore, there is no need to focus on polar solvents, like water, when considering possible habitats for life. Non-polar hydrocarbons such as methane and ethane are better than water for managing complex organic chemical reactivity since they do not destroy hydrolytically unstable organic species, as water does (Schulze-Makuch and Irwin 2006).

Many of the most important potential solvents found in the solar system exist only in their gaseous form on Earth. They become liquids at very low temperatures. Hence, they are known as cryosolvents. Low temperatures are, however, prominent throughout the cosmos, as are species that are liquid there. Therefore, cryosolvents cannot be dismissed as potential biosolvents (Baross et al 2007).

These studies suggest that if life originated independently in other worlds, which present different geochemical environment, it would likely have selected different solvents and biopolymers for metabolism. Thus, instead of searching for specific biosignatures that appeared later in the Earth's history, future missions should focus to search for the general characteristics of life, which means search for life’s material-independent signatures.

4. Searching for Life As We Don’t Know It

When we discuss about the search for extraterrestrial life, one of the most enticing questions that emerge in our mind is “how such exotic forms of life might look?” or “how similar or different from us will they be?”

Life is likely a result of physical and chemical contingencies presented in the world where it arises. Most of the geochemical and environmental processes of any world remain unclear. Even the conditions that were present in early Earth are not clearly understood, which makes the origin of terrestrial life a mystery far to be resolved (Rampelotto 2009). Furthermore, the history of life on Earth shows us that the evolutionary trajectory of a living system cannot be predicted. The diverse and unimaginable forms of life which arose during the Cambrian period are a good example of the variety of forms life may take. Therefore, the details of form and function that a different history of life elsewhere would take, cannot be known until we find it. However, despite the possibility of so much diversity, at the molecular level underlying mechanisms guide the development of any unimaginable living system. Thus, based on biochemical principles, it is possible to make predictions about the nature of exotic forms of life which may be found in our solar system.

5. Silicon-Based Life

Silicon can form long chains as silanes, silicones, and silicates. Among them, silanes have been considered the most proper compounds to sustain life because they present the closest analog to hydrocarbons, which are so important to terrestrial life processes. However, such silicon-based life would have to be different from life as we know on Earth.

Silanes burn spontaneously when in contact with oxygen to form silicate and molecular hydrogen. Hence, a biochemistry based on such compounds requires an ambient free of oxygen. The affinity of silicon to oxygen is so strong that whether silicon is placed in water, it will form a silica shell, stripping the oxygen from the water (LeGrand 1998). Thus, water is not a compatible solvent for silicon compounds. Methane, ethane or any compounds that contain methyl groups are more compatible solvents for a silicon-based system.

The strong Si-O bond can be avoided and the carbon scenario reproduced if oxygen is replaced by sulfur. Then the resulting ratio of bonding energies of Si-Si to Si-S is comparable to the ratio of the C-C to C-O bonding energies (Firsoff 1963). Also, silicon polymers have been obtained with nitrogen instead of oxygen, where nitrogen acts as an electron donor. In hydrogen poor environments, hydrogen is often replaced by a halogen such as chloride, and long linear chains of silicon and chloride are formed (Firsoff 1963). Large molecules based on Si-NH-Si backbone, with halogens as side-groups, could provide a basis for complex chemical systems. Silanes can form flexible, macromolecular assemblies in the form of sheets, strings, tubes, and other shapes, similar to those formed by lipid bilayers in carbon biochemistry (Unno et al 2000). Furthermore, oligosilanes having up to 26 consecutive Si–Si bonds can be chiral, support a variety of functionalized and non-functionalized side chains, have alkyl side chains that are generally soluble in nonpolar solvents and self-aggregate into amphiphilic structures in water, creating vesicles and micelles (Benner et al 2004).

Although the stability of silanes decreases with increasing chain length, if hydrogen is replaced by organic groups, stable compounds are obtained. For example, polysilanes with molecular weights of above 106 have been synthesized (Sharma et al 2002). Although polysilanes are not stable at the temperature and pressure conditions of Earth's surface they are adequately stable at low temperatures, especially at higher pressures. These studies altogether suggest that whether silicon-based life exist, it may be restricted to an environment with minor amounts of oxygen, scarcity of water, a compatible solvent such as methane and low temperatures (at least below 0°C). Titan provides the best target in our solar system for investigating this possibility. It meets all the described criteria (Fulchignoni et al 2005; Naganuma and Sekine 2010). Although has been considered that the abundance of carbon compounds on Titan may compete with silicon as the building block of life, silicon may have advantage in such extreme cold environment due to its higher reactivity.

6. Ammonia-Based Life

Ammonia, as revealed by its physical properties, may be a good solvent for life. In fact, macromolecules such as proteins, amino acids, and nucleic acids contain both OH and NH2 functional groups in various combinations and proportions with which ammonia could easily interact. However, biochemistry based on this solvent would have to be different in comparison with terrestrial life. Since oxygen would oxidize and break down ammonia, ammonia-based life needs an environment without the presence of oxygen. In such environments, anaerobic metabolism is the alternative. Analogs of terrestrial biomolecules in which oxygen atoms are replaced by NH groups might yield an equally viable biochemistry (Raulin et al 1995). Synthesis reactions like the synthesis of proteins from amino acids through a peptide bond shows similarities in waterbased, ammonia-based and water-ammonia mixtures (Firsoff 1963).

Several lines of evidence suggest that the internal ocean of Titan contain NH_3, mixed with water, in the form of a liquid layer below a rigid water-ice crust (Tobie 2005). Furthermore, its environment free of oxygen provides an excellent opportunity to find living systems which uses ammonia as a solvent. The presences of NH_3 in the internal ocean of Enceladus (Waite et al 2009) also drew considerable attention to the presence of ammonia-based life on this satellite.

7. Sulfur-Based Life

Sulphuric acid has the reputation to be a strong corrosive agent. However, what is not realized is that the process, called hydrolysis, actually requires water. It is the water molecules that split proteins into small pieces; acid merely catalyses the process. Thus, due to its capacity to support chemical reactivity, sulphuric acid may be a reasonable solvent capable to sustain metabolism in non aqueous environments (Benner et al. 2004).

The Venusians atmosphere is the most proper ambient in the solar system where this exotic form of life may flourish. The clouds of Venus are composed mostly of aerosols of sulfuric acid and water is scarce (Markiewicz et al 2007). The layer of clouds 50 kilometers above the surface could provide a friendly environment, at similar pressures to those on Earth, and temperatures of 20 to 80°C (Svedhem et al 2007).

Life could have possibly originated in an early ocean on Venus when the planet's surface was younger and cooler; then retreated into the clouds when the planet heated. To protect them from the high amount of UV radiation received, such hypothetical living systems may use the compound cyclic-octa-sulfur (S_8), which does not react with sulfuric acid. An analogous process is observed on Earth, where some purple sulfur bacteria, green sulfur bacteria and some cyanobacterial species deposit elemental sulfur granules outside of the cell (Tortora et al 2001). Such Venusians life forms may be phototrophic, using hydrogen sulfide, which is oxidized to produce granules of elemental sulfur (Schulze-Makuch et al 2004). Terrestrial purple sulfur bacteria use such anoxygenic process as source of energy (Herbert et al 2008).

8. Final Considerations

The discovery of exo-planets around stars other than the Sun continues to stimulate public and media interest. Undoubtedly, this attention has been driven by the prospects of finding evidence of alien life. At the moment, life on Earth is the only known life in the Universe, but there are compelling arguments to suggest we are not alone. As Carl Sagan said, the absence of evidence is not evidence of absence. This thought is well known in other fields of research. Astrophysicists, for example, spent decades studying and searching for black holes before accumulating today's compelling evidence that they exist (Melia and Falcke 2001). The same can be said for the search for room-temperature superconductors, proton decay, violations of special relativity, or for that matter the Higgs boson. Indeed, much of the most important and exciting research in astronomy and physics is concerned exactly with the study of objects or phenomena whose existence has not been demonstrated.

With regards to our anthropocentric way of thinking, history tells us that it is prudent to be guided by the notion that terrestrial life is not special. This is generally known as the Copernican principle, which has altered our view of the Universe. Based on this principle, we have recognized that Earth is not in the center of the solar system, the solar system is not in the center of the Milky Way galaxy and the Milky Way galaxy is not in the center of the Universe.

Despite the considerable efforts on the search for extraterrestrial life, a manifest tendency exists today to judge alien life through a terracentric vision. However, the search for life should not and cannot be limited to the search for Earth-like features. This cosmic view of the diverse nature of extraterrestrial life, is a revolutionary perspective which has the potential to make a great impact on our way of thinking as profound as the Copernican revolution.

References

Arrhenius, S. (2009). The Spreading of Life Throughout the Universe. Journal of Cosmology, 2009, 1, 91-99.

Avetisov, V. (2007). Question 4: Short remarks about the origin of homochirality. Origins of Life and Evolution of the Biosphere, 37, 367–370.

Bains, W. (2004). Many chemistries could be used to build living systems. Astrobiology, 4, 137–167.

Baross, J. A., Benner, S. A., Cody, G. D., Copley, S. D., Pace, N. R., Scott, J. H., Shapiro, R., Sogin, M. L., Stein, J. L., Summons, R., Szostak, J. W. (2007). The limits of organic life in planetary systems. National Academic Press, Washington.

Benner, S. A., Ricardo, A., Carrigan, M. A. (2004). Is there a common chemical model for life in the universe? Current Opinion in Chemical Biology, 8, 672–689.

Burchell, M.J. 2010. Why Do Some People Reject Panspermia? Journal of Cosmology, 5, 828-832.

Bounama, C., Von Bloh, W., Frank, S. (2007). How rare is complex life in the Milky Way? Astrobiology, 7, 745–755.

Brook, M. A. (2000). Silicon in organic, organometallic and polymer chemistry. John Wiley, Toronto.

Chela-Flores, J. (2010). From the Moon to the Moons: Encedalus and Europa. The Search for Life and Reliable Biomarkers. Journal of Cosmology, 5, 971-981.

Chyba, C. F., Hand, K. P. (2005). Astrobiology: The study of the living universe. Annual Review of Astronomy and Astrophysics, 43, 1–44.

Cleland, C. E., Chyba C. F. (2002). Defining Life. Origins of Life and Evolution of the Biosphere, 32, 387–393.

Cockell, C. S., and 38 colleagues. (2009). Darwin - A mission to detect and search for life on extrasolar planets. Astrobiology, 9, 1-22.

Crater, H. W. (2009). The Search For Life On Other Planets: Geometry of Intelligence, Journal of Cosmology, 2009, 1, 66-70.

Crowe, M. J. (1986). The extraterrestrial life debate 1750–1900, the idea of a plurality of worlds from Kant to Lowell. Cambridge University Press, Cambridge.

Forgan, D. (2010). Numerical Astrophysics, Numerical Astrobiology and the Search for ExtraTerrestrial Life. Journal of Cosmology, 5, 811-817.

Firsoff, V. A. (1963). Life beyond the Earth: A study in exobiology. Basic Books, New York.

Fulchignoni, M. and 41 colleagues (2005). In situ measurements of the physical characteristics of Titan's environment, Nature, 438, 785–791.

Goertzel, B. and Combs, A. (2010). Water Worlds, Naive Physics, Intelligent Life, and Alien Minds. Journal of Cosmology, 5, 897-904.

Herbert, R. A., Gall, A., Maoka, T., Cogdell, R. J., Robert, B., Takaichi, S., Schwabe, S. (2008). Phototrophic purple sulfur bacteria as heat engines in the South Andros Black Hole. Photosynthesis Research, 2008, 95, 261–268.

Houtkooper, J. M., and Schulze-Makuch, D. (2010). The Role of Perchlorates in Martian Life. Journal of Cosmology, 5. 930-939.

Istock, C. (2010). Life On Earth And Other Planets. Science And Speculation. Journal of Cosmology, 5. 890-896.

José, M. V. et al., (2010). How Universal is the Universal Genetic Code? A Question of ExtraTerrestrial Origins. Journal of Cosmology, 5, 854-874.

Joseph, R. (2000). Astrobiology, the origin of life, and the Death of Darwinism. University Press, California.

Joseph, R. (2009a). Life on Earth Came From Other Planets, Journal of Cosmology, 1, 1-56.

Joseph, R. (2009b). The evolution of life from other planets. Journal of Cosmology, 1, 100-200.

Joseph R. (2010a). The Infinite Universe: Black Holes, Dark Matter, Gravity, Life, and the Micro-Macro Cosmos. Journal of Cosmology, 6. In Press.

Joseph R. (2010b). Biological Cosmology and the Origins and Evolution of Life in the Universe. Journal of Cosmology, 5. 1040-1090.

Joyce, G. F. (1994). Introduction. In: Deamer, D. W., Fleischaker, G. R. (Eds.). Origins of life: The central concepts. Jones and Bartlett, Boston.

Lal, A. K. (2010). Searching for life on Habitable Planets and Moons. Journal of Cosmology, 5, 801-810.

LeGrand, A.P. (1998). The surface properties of silicas. John Wiley and Sons, New York.

Lewis, J. S. (2004). Physics and chemistry of the solar system. 2nd edition. Elsevier, London.

Leuko, S., et al., (2010). Halophilic Archaea and the Search for Extinct and Extant Life on Mars. Journal of Cosmology, 5, 940-950.

Levin, G. V. (2010). Extant Life on Mars: Resolving the Issues. Journal of Cosmology, 5, 920-929.

Markiewicz, W. J., Titov, D. V., Limaye, S. S., Keller, H. U., Ignatiev, N., Jaumann, R., Thomas, N., Michalik, H., Moissl, R., Russo1, P. (2007). Morphology and dynamics of the upper cloud layer of Venus. Nature, 450, 633-636.

Melia, F., Falcke, H. (2001). The supermassive black hole at the galactic center. Annual Review of Astronomy and Astrophysics, 39, 309–52.

Naganuma, T., Sekine, Y. (2010). Hydrocarbon lakes and watery matrices/habitats for life on Titan. Journal of Cosmology, 5, in press.

Naitoh, K. (2010). Onto-biology: A Design Diagram of Life, Rather Than Its Birthplace in the Cosmos. Journal of Cosmology, 5, 999-1007.

Pilcher, C. B. (2003). Biosignatures of early Earths. Astrobiology, 3, 471-486.

Pizzarello, S. (2006). The chemistry of life's origin: A carbonaceous meteorite perspective. Accounts of Chemical Research, 39, 231-237.

Pizzarello, S. (2007). The chemistry that preceded life's origin: A study guide from meteorites. Chemistry and Biodiversity, 4, 680-93.

Popa, R. (2004). Between necessity and probability: Searching for the definition and origin of life. Springer, Berlin.

Poccia, N., et al., (2010). The Emergence of Life in the Universe at the Epoch of Dark Energy Domination. Journal of Cosmology, 5. 875-882. Raulin, F., Bruston, P., Paillous, P., Sternberg, R. (1995). The low temperature organic chemistry of Titan's geofluid. Advances in Space Research, 15, 321–333.

Rampelotto, P. H. (2009). Are We Descendants of Extraterrestrials? Journal of Cosmology, 1, 86-88.

Rekola, R. T. F. (2009). Life and habitable zones in the universe. Planetary and Space Science, 57, 430–433.

Sharov, A. A. (2010). Genetic Gradualism and the ExtraTerrestrial Origin of Life. Journal of Cosmology, 5, 833-842.P> Schulze-Makuch, D.(2010). Io: Is Life Possible Between Fire and Ice? Journal of Cosmology, 5, 912-919.

Schulze-Makuch, D., Grinspoon, D. H., Abbas, O., Irwin, L. N., Bullock, M.A. (2004). A sulfur-based survival strategy for putative phototrophic life in the Venusian atmosphere. Astrobiology, 4, 11–18.

Schulze-Makuch, D., Irwin, L. N. (2006). The prospect of alien life in exotic forms on other worlds. Naturwissenschaften, 93, 155–172.

Schulze-Makuch, D., Irwin, L. N. (2008). Life in the universe: Expectations and constraints. 2nd edition. Springer, Berlin.

Sharma, H. K., Haiduc, I., Pannell, K.H. (2002). Transition metal complexes of germanium, tin and lead. In: Rappoport, Z. (Eds.). The chemistry of organic germanium, tin and lead compounds. vol. 2. John Wiley and Sons, New York.

Svedhem, H., Titov, D. V., Taylor, F. W., Witasse, O. (2007). Venus as a more Earth-like planet. Nature, 450, 629–632.

Tamura, K. (2010). Amino Acid Homochirality and the RNA World: Necessities for Life on Earth. Journal of Cosmology, 5.

Thaddeus, P. (2006). The prebiotic molecules observed in the interstellar gas. Philosophical Transactions of the Royal Society B, 361, 1681–1687.

Tobie, G., Grasset, O., Lunine, J. I., Mocquet, J., Sotin, C. (2005). Titan's orbit provides evidence for a subsurface NH3-water ocean. Icarus, 175, 496–502.

Tortora, G., Funke, B., Case, C. (2001). Microbiology: an introduction. 7th ed. Addison Wesley Longman, San Francisco.

Unno, M., Takasa, K., Matsumoto, H. (2000). Formation of supermolecule by assembling of two different silanols. Chemistry Letter, 3, 242–243.

Following. Silicon Based Life / Other. Go To. Ã—.Â The X-Files episode featured ammonia-based alien brain worms that rode to Earth on an asteroid in prehistoric times and were hiding out at the North Pole. How they were able to take over the bodies of the human scientists that were trying to study them, despite the fact that not only is their biochemistry obviously incompatible, but being inside a human body for any length of time should have melted the little bastards is never adequately explained. Doctor Who. The Krotons are tellurium-based.Â GURPS: Space has suggestions for hydrogen- and sulfur-based lifeforms as well as silicon-based ones. Is Silicon-Based Life Possible? As we look for biosignatures on other planets, we should guard against being too Earth-centric. By Dirk Schulze-Makuch. airspacemag.com October 24, 2013. Many of the space missions we send to Mars and other planets search for evidence of life. Or rather, they search for life as we know it â€" life thatâ€™s made of carbon, requires liquid water, and uses light or chemical energy as its main energy source. Sara Seager and her colleagues from MIT, William Bains and Renyu Hu, want to expand this â€œearth-centricâ€ approach. They suggest looking for any gas that is out of e Life on Earth is based on carbon, likely because each carbon atom can form bonds with up to four other atoms simultaneously. This quality makes carbon well-suited to form the long chains of molecules that serve as the basis for life as we know it, such as proteins and DNA. Related: The Search for Life on Mars in Pictures. Still, researchers have long speculated that alien life could have a completely different chemical basis than life on Earth. For example, instead of relying on water as the solvent in which biological molecules operate, perhaps aliens might depend on ammonia or methane. And i