Sustainability **2009**, *1*, 827-837; doi:10.3390/su1040827

OPEN ACCESS

sustainability

ISSN 2071-1050

www.mdpi.com/journal/sustainability

Review

An Astrobiological View on Sustainable Life

Takeshi Naganuma

Graduate School of Biosphere Science, Hiroshima University, Higashi-Hiroshima, 739-8528, Japan; E-Mail: takn@hiroshima-u.ac.jp

Received: 7 September 2009 / Accepted: 16 October 2009 / Published: 19 October 2009

Abstract: Life on a global biosphere basis is substantiated in the form of organics and organisms, and defined as the intermediate forms (briefly expressed as CH_2O) hovering between the reduced (CH_4, methane) and (CO_2, carbon dioxide) ends, different from the classical definition of life as a complex organization maintaining ordered structure and information. Both definitions consider sustenance of life meant as protection of life against chaos through an input of external energy. The CH_2O-life connection is maintained as long as the supply of H and O lasts, which is in turn are provided by the splitting of the water molecule H_2O. Water is split by electricity, as well-known from school-level experiments, and by solar radiation and geothermal heat on a global scale. In other words, the Sun's radiation and the Earth's heat as well as radioactivity split water to supply H and O for continued existence of life on the Earth. These photochemical, radiochemical and geothermal processes have influences on the evolution and current composition of the Earth's atmosphere, compared with those of Venus and Mars, and influences on the planetary climatology. This view of life may be applicable to the "search-for-life in space" and to sustainability assessment of astrobiological habitats.

Keywords: split of water; photochemical; radiochemical; geothermal; reduction-oxidation; entropy

1. Introduction

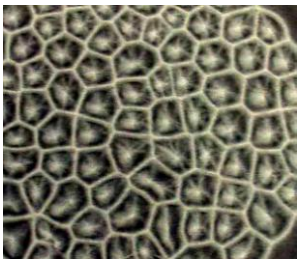
What is life? Erwin Schrödinger, 1933 Nobel Laureate in Physics, tackled this long-standing question and defined life as the organization that maintains complex structure and heritable information in expense of "negentropy" [1]. Negentropy is a useful conceptual tool to understand the physical basis underlying sustenance of biological machinery, and is the counter concept of entropy defined by the

second principle of thermodynamics, i.e., the time arrow theory. According to the principle, the total amount of available energy, or exergy, decreases irreversibly with time, and entropy is a measure of the ever-increasing unavailability, partly as heat. Local entropy within a system may decrease in the expense of potential energy, i.e., negentropy, and such situation is substantiated in living organisms that expend chemical potential energy to maintain their structure and information. Heat, the energy-in-transit, does not directly support life by itself, but it may generate chemical potential energy via thermochemical reactions.

The question *what is life* is thus transformed as *what supports life*, and an answer for a living organism is the chemical potential energy that lowers local entropy, despite an increase of overall entropy. Then, the question is extended to a larger system where living organisms live, and revised as *what supports the biosphere*. The Earth's biosphere receives heat *sens general* from both external and internal sources, i.e., the Sun and Earth's interior, respectively. Heat from the Sun derives ultimately from gravitational and nuclear potential energy of the hydrogen gas disk in the Hadean (Pregeologic) Eon, while heat from the Earth's interior originates from gravitational and nuclear potential energy of the silicate gas disk/microplanets and radioactive ^{40}K, respectively. Contraction of gas disks and accumulation of microplanets liberated gravitational potential energy to yield heat. Heat of the ancient Sun ignited nuclear fusion to burn as a star, irradiating the Earth at the Solar constant of 1.4 kW m^{-2}. The profound underlying problem is how heat potentiates the Earth to host life.

Heat as energy-in-transit may form locally ordered structures in an open non-equilibrated system, as advocated by Ilya Prigogine, 1977 Nobel Laureate in Chemistry [2]. A visual example of the locally organized structure formed by heat is Prigogine's hexagon, or Rayleigh-Benard convection [3] (Figure 1).

Figure 1. Rayleigh-Benard convection. Convection cells in a fluid are formed and maintained when heated from below. The upper surface of the heated fluid is unconstrained and is free to move and deform. This situation is sustained as long as heat energy is given to the fluid system and gives rise to the Prigogine's hexagons, or Rayleigh-Benard convection cells. Photo: Hideo Suzuki, Tokyo Metropolitan College of Technology.



The heat used in the experiments to form convection cells derives from the chemical or electrical potential energy, and therefore chemical potential energy indirectly (via heat) forms convection cells. The minimum unit of living organisms is coincidentally called "cell", and the biological cells are maintained by chemical potential energy contained in foods, or organic compounds. Animals eat organic compounds produced by others, while plants produce organics for themselves and others via photosynthesis. These organic-eaters and organic-producers are collectively called heterotrophs and

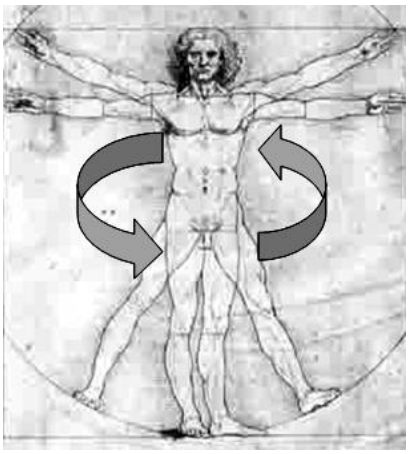
autotrophs, respectively. The non-photosynthetic mode of autotrophy is called chemolithoautotrophy, by which organics are produced in the expense of chemical energy liberated from the oxidation of inorganic compounds such as hydrogen and hydrogen sulfide. This mode of chemolithoautotrophic life is known to thrive in the deep-sea and deep sub-seafloor. This chapter tries to apply Schrödinger's negentropy concept to biosphere, and evaluates the sources of chemical potential energy for chemolithoautotrophic lives in deep-sea and deep sub-seafloor [4,5] from a planetary point of view.

2. Vortex of Life

Prigogine's hexagons, or Rayleigh-Benard convection cells, are generated by continuous flow of heat. Continuous flow of chemical potential energy maintains life. Similarly, continuous flow of water forms vortices, and therefore vortex serves as a key idea to understand life.

Flow of water sometimes form vortices. A vortex is only a temporal pattern of water movement, composed of different water molecules coming-in and going-out moment-by-moment. Kamo-no-Chomei, a Japanese medieval essayist, expressed in *Hojoki* (1212) his view of transitory life as "The flowing river never stops and yet the water never stays the same. Foam floats upon the pools, scattering, re-forming, never lingering long. So it is with man and all his dwelling places here on earth" (translated by Moriguchi and Jenkins [6]). Chomei's transitory bubbles are parallel to vortices in my view of life. Although atoms and molecules of my body have been replaced since my birth, I have never doubted my continuity and identity. That is, my identity is based more on a pattern like a vortex than materials, and I represent a tiny vortex of life (Figure 2).

Figure 2. Leonardo Da Vinci's Vitruvian Man, showing his identity as a pattern like a vortex.

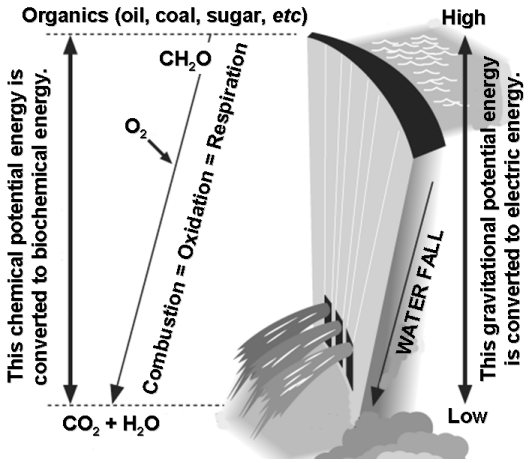


Vortices consist of water molecules flowing in and out every second, and are kept alive by a constant current caused by a water height gradient. Water flows from highs to lows, and manifests gravitational potential energy as kinetic/mechanical energy and even electric energy at hydraulic power plants (Figure 3), as well as vortices. Vortices are formed and maintained by the slopes between high and low water tables. If water tables become flat, there will be no flows and no vortices.

By what water is transported to high places? Water cycling, i.e., evaporation and precipitation, is mainly driven by solar heat energy. Therefore, hydraulic power plants are said to convert solar heat

energy to electric energy via gravitational potential energy of water. Hydraulic high means the water on high spots that contains high gravitational potential energy. Then, what corresponds to the chemical "high" for chemical potential energy? Taking examples of organic compounds (generalized as CH_2O), they manifest chemical potential energy through combustion (parallel to water falling), or oxidation, to yield the most oxidized form of carbon (CO_2) on the lowest. Hence, chemical high and low correspond to more oxidizable (more reduced) and less oxidizable (less reduced) states, respectively (Figure 3).

Figure 3. Manifestation of gravitational and chemical potential energy as electric and biochemical energy via water fall and oxidation, respectively.



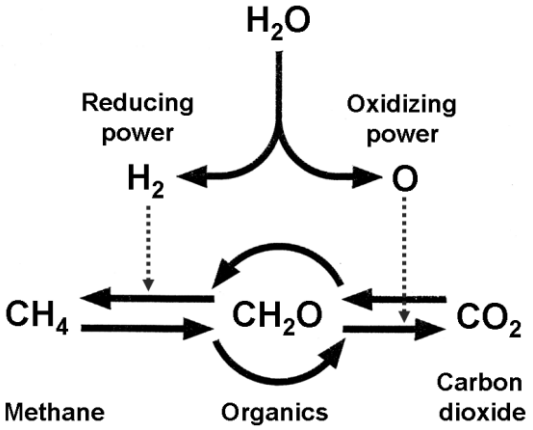
The Sun transports water to high places via evaporation, adding gravitational potential energy. Similarly, the Sun splits water into hydrogen (source of reducing power) and oxygen (source of oxidizing power). Split of water yields chemical highs and lows, or reducing and oxidizing ends, and thus forms chemical vortex of life. Water may split also by geothermal heat, including radioactivity of rock-borne ^{40}K, as described later.

3. Life Vortex as Intermediate between CH_4 and CO_2

Since the life on the Earth is based on carbon, the reduced and oxidized ends of carbon, methane (CH_4) and carbon dioxide (CO_2), respectively, are mainly discussed. Organics and organisms are simply and collectively expressed here as CH_2O, instead of commonly used R for an organic functional group, because it is easily understandable that organics and organisms are substantially intermediates of CH_4 and CO_2. The merit of the use of "CH_2O" to represent organics/organisms would overcome potential confusion arising from use of the exact chemical formula of formaldehyde.

Erwin Schrödinger defined life manifested by biological cells or individuals that maintain structure and information by eating negentropy [1]. In contrast, I view life as "transitory intermediates on the balance of hydrogen and oxygen supplies", considering the Earth's biosphere. In this sense, organisms are only ephemeral and hovering between life and death. This view is depicted in Figure 4.

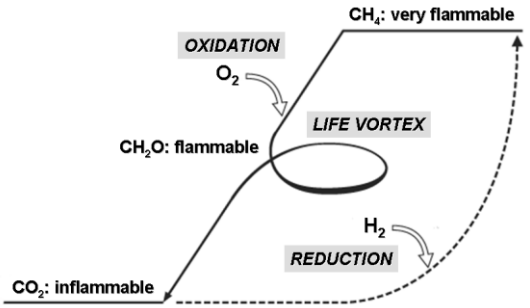
Figure 4. Transitory view of C-based life hovering between the reduced (CH_4) and oxidized (CO_2) ends. The reducing and oxidizing powers are derived from the split of water by heat or geothermal heat.



Methane is produced inorganically by the reaction [$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$], as proposed by Paul Sabatier, 1912 Noble Laureate in Chemistry [7]. Methane is also produced by methanogenic microorganisms mediating the biological counterpart of the Sabatier reaction in deep-sea hydrothermal vents and deep subsurface [4,5].

Organic compounds and organisms, generally expressed here as CH_2O or $[CH_2O]_n$, are intermediates of CH_4 and CO_2, and various organic forms are found in nature. Methane has the maximum number of hydrogen, i.e., four hydrogen atoms per carbon, and the greatest chemical potential energy (890 kJ mol^{-1}) among carbon compounds is manifested via full oxidation to yield carbon dioxide. Methane-oxidizing microorganisms, namely methanotrophs, utilize this chemical energy for metabolism for growth and reproduction, and are often found in deep-sea hydrothermal vents and deep subsurface [8]. That is, life vortex as realized by methanotrophs is manifested on the slope from CH_4 to CO_2 (Figure 5).

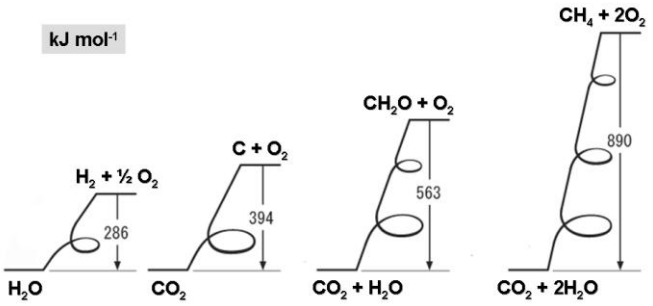
Figure 5. Life vortex in carbon cycling between CH_4 and CO_2. Chemical potential energy is manifested during the oxidation of CH_4 to generate life vortices as intermediates before full oxidation to CO_2, which is in turn re-potentiated via reduction by $H + e^-$ from the split of water.



All the organics and organisms are partially oxidized forms of CH_4, and are to be further oxidized to CO_2. Oil (petroleum) is the mixture of relatively less oxidized hydrocarbon chains (with more hydrogen per carbon on average), while formaldehyde (truly CH_2O) and acetaldehyde (CH_3CHO) are more

oxidized forms and close to the CO_2-end. Life vortices may vary in numbers, sizes, features, etc., according to the amounts of manifested chemical potential energy (Figure 6).

Figure 6. Different numbers and sizes of life vortices on the slope of oxidation of various carbon compounds. The vortices may have different characteristics according to the features of slopes.



4. Splitting of Water

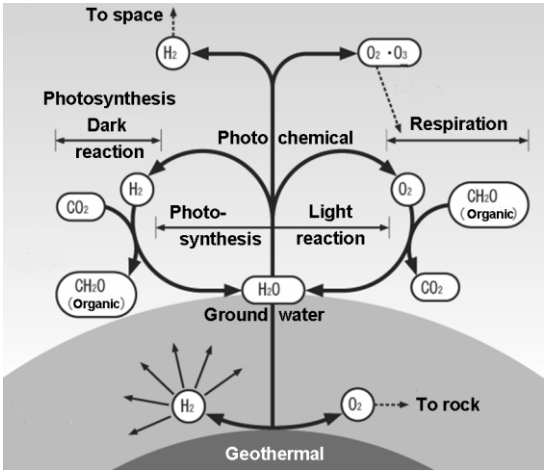
Water, H_2O, may be the most common but also the most miraculous molecule in the Universe. The most abundant element in the Universe is hydrogen, followed by helium, oxygen, carbon, nitrogen, and so on. As helium is chemically inert, hydrogen reacts with oxygen to form water, with carbon to form methane, and with nitrogen to form ammonia. Among these hydrogen compounds, water displays a number of peculiarities that are not seen by other hydrogen compounds as follows:

(1) Water molecules are held together by sharing electrons among two hydrogen and one oxygen atoms via two covalent bonds;
(2) Water is a polar molecule. Although the net electrical charge on the molecule is zero, its structure causes the molecule to become polarized;
(3) Electrostatic bonds (hydrogen bonds) form between the negatively charged oxygen side of one water molecule and the positively charged hydrogen of another molecule;
(4) The existence of these hydrogen bonds explains many of the unique properties of water;
(5) Ice has an orderly, open structure of water molecules held together by hydrogen bonding;
(6) Water ice's crystal structure results in lower density (0.92 g cm^{-3}) than that of liquid water, 1.0 g cm^{-3};
(7) Liquid water structure is intermediate between that of ice and water vapor, and consists of two types of aggregates of water molecules;
(8) Structured water is composed of clusters of hydrogen-bonded water molecules that form and reform very quickly but slow enough to influence the physical behavior of water;
(9) Unstructured water is composed of closely packed free water molecules, denser than structured water;
(10) If hydrogen bonding did not exist, water would only occur as a gas at the Earth's surface;
(11) Water is the only naturally occurring substance on the Earth to exist at the surface in all three states: liquid, solid and gas;
(12) Water dissolves more substances in greater quantity than any other common liquid;

(13) Water has the highest surface tension of all liquids;
(14) Water has the highest heat capacity of all common solids and liquids, which prevents extreme range in aquatic temperature;
(15) Boiling and melting points of water are higher than those of other hydrogen compounds of similar size or oxygen-group ($_{8}O$, $_{16}S$, $_{34}Se$, $_{52}Te$ and so on). For example, CH_4, NH_3, H_2S, H_2Se and H_2Te occur as gases at room temperature; and
(16) Water has the highest heat conductivity of any common liquid.

A metaphysical consequence of the above-listed peculiarities of the water molecule is that hydrogen and oxygen atoms, i.e., H and O, attract each other. The most and third abundant elements in the universe bind by strong covalent bonding to contain chemical potential energy, and they may split by the input of external dissociation energy. The sources of external dissociation energy are the Sun (solar radiation) and the Earth (geothermal heat including ^{40}K radioactivity); and water molecules split via the light reaction of photosynthesis, photochemical reactions (photolysis), ^{40}K β-radiation (radiolysis) and the high-temperature water-rock interaction (thermolysis) (Figure 7).

Figure 7. Split of the water molecule by solar radiation and geothermal heat (including radioactive decay) via the light reaction of photosynthesis and water-rock interaction, respectively.



Organisms are the realization of life, namely biological potential energy, and substantiated with organic compounds, CH_2O. The split products of water (H and O) bind again but intermediated by carbon (C) to form organics and organisms (CH_2O). Only continuous supplies of H and O maintain the ephemeral presence of CH_2O, otherwise CH_2O would shift to the reduced end (CH_4) or oxidized end (CO_2). The idea of the splitting of water is a modern revision of Schrödinger's negentropy for individual organisms, and may be extended to possible biospheres on other planetary bodies.

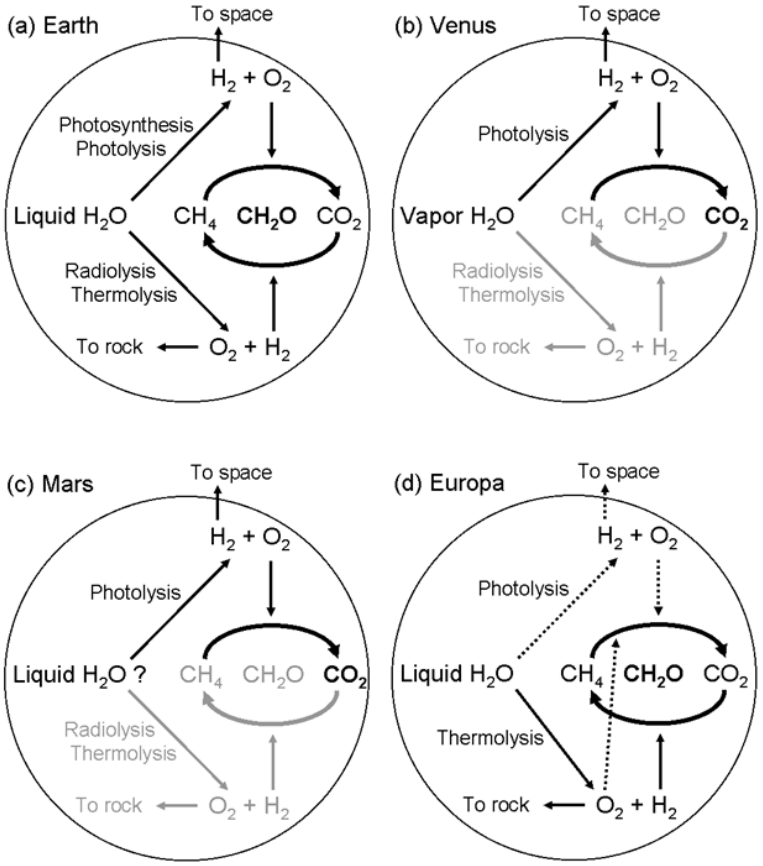
5. Testing Planetary Biospheres

The Earth's biosphere is sustained by solar and geothermal heat via the splitting of water. Even if the Sun radiation ceased, some part of the Earth's life in the deep continue continue as long as the Earth stayed alive with liquid water and active plate/plume tectonics, or volcanism (Figure 8a). Splitting of

water would maintain the existence of organics and organisms (CH_2O), and the levels of CH_4 and CO_2 are kept below 0.04%.

No liquid water but water vapor exists on Venus due to the high surface temperature of about 500 °C. Water vapor may split photochemically. The resultant hydrogen escapes to the extra-Venus milieu, and the leftover oxygen accumulates in Venus' atmosphere, with a CO_2 content of 98%. This biased split of water is unlikely to support life (Figure 8b).

Figure 8. Possibility of carbon-based life (expressed as CH_2O) viewed from solar split of water (via photosynthesis and photolysis) and geothermal split of water (via radiolysis and thermolysis) in **(a)** Earth, **(b)** Venus, **(c)** Mars, and **(d)** Jovian satellite Europa. Black solid lines indicate existing and probable processes; black broken lines show possible pathways; and, gray lines suggest unlikely or negligible reactions. Recent finding of methane in Mars atmosphere [16] may suggest occurrences of split-of-water and thus any form of life.



Hydrothermal activity may have existed or exist on ancient Mars [8], although the existence of liquid water on ancient and recent Mars is still controversial [9]. Regardless of liquid water, no plate tectonic activity is expected on modern Mars, due to short longevity of the planet, which is as light as 1/10 of the Earth's mass. Therefore, only photochemical split, or photolysis, of water is presumed for Martian environment [10], and accumulation of oxygen in the Martian atmosphere as presumed for the Venus' atmosphere results in a CO_2 content of 95%. Ancient Mars may have hosted geothermal splitting of water, and remnants of ancient Martian life have been suggested in the Martian meteorite

ALH84001 [11]; however, the nanofossils are still controversially discussed in the scientific community [12,13]. In contrast, modern Mars is unlikely to be capable of hosting a biosphere (Figure 8c). The latest finding of ground ice of temporal melt-water [14] suggests an icy/watery subterranean Mars. However, just occurrence-of-water on Mars, echoing with another latest evidence for water on the Moon surface [15], does not imply life on modern Mars; splitting-of-water has more realistic relevance to life. In contrast, occurrence-of-methane has more implications for splitting-of-water, according to my scheme (Figure 8c). It is interesting that methane (CH_4) is present in the Martian atmosphere [16,17], and that volcanic activity as recent as four million years ago is suggested [18]. This being so, a modern biosphere may be sustained in the Martian subsurface that could store liquid water and remnant geothermal heat [19]. Another possibility is hydrogen (H_2) production via hydration of one of the most ancient volcanic rock of the Earth, komatiites, whose occurrence on Mars is also suggested [20]. This is the splitting-of-water catalyzed by komatiites, and a recent experiment confirmed that the komatiite-catalyzed H_2 production is robust enough to support H_2-based methanogenesis [21]. Splitting-of-water catalyzed by komiites is likely to be a source of sustaining life forms on ancient Earth and Mars, and the possibility may extends to modern Mars.

Both liquid water and volcanism are postulated to occur under the ice crust of Europa, Jupiter's J2 satellite [22]. That is, geothermal split of water is likely to occur in Europa, as well as photochemical splitting of water in Europa's thin atmosphere [23]. The resultant atmospheric oxygen may be incorporated into melt-and-refrozen surface ice and transported to the interior ocean via the tectonic ice convection of Europa [24,25]. This planetary (or satellitary) setting may facilitate the formation of an extra-terrestrial biosphere (Figure 8d), and thus provides a biospheric basis for a search for life [26].

6. Astrobiological Conclusion

Life on Earth is carbon-based, and is substantiated as intermediate forms (expressed as CH_2O) hovering between the reduced end (CH_4) and the oxidized end (CO_2). The intermediate forms, organics and organisms, are ephemeral and eventually subject to full reduction or oxidation when the supplies of O or H cease, respectively. In other words, life is maintained only with the continuous supplies of H and O, which are in turn provided by the splitting of water. Solar radiation and geothermal heat would split water, and therefore it may not be too extreme to conclude that the Earth's lives are mainly sustained by either the Sun or the Earth, depending on the types of ultimate sources of nutrition, i.e., photosynthesis or chemolithoautotrophy.

In the Japanese language, the Sun is *hi*, and heat (fire) is also *hi* (originally *ho* or *fo*); water is *mi* or *mizu*; and, life is *i-no-chi* meaning energy of breath. The coincidence of two *hi* has impressed me, and I might say that split of *mi* by *hi* nourishes *chi*, at least, on the Earth. Both *hi*, that is the Sun's radiation and the Earth's interior heat, contribute to life. The degrees of contributions vary according to major modes of autotrophy, i.e., photosynthesis or chemolithoautotrophy. Examples of chemolithoautotrophic communities that depend primarily on geothermal *hi* are found in deep-sea hydrothermal vents and deep subsurface, respectively [4,5]. The idea that non-solar splitting of water nourishes life thus derives from the studies of deep-sea and deep subsurface biospheres, and is extended to possible extra-terrestrial biospheres. The concept of planetary biospheres should accommodate a more universal notion of life

than traditional ones. The "non-solar splitting of water" idea is applicable to possible astrobiological biospheres.

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