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Research paper

# Habitable Trinity

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A B S T R A C T

Habitable Trinity is a newly proposed concept of a habitable environment. This concept indicates that the coexistence of an atmosphere (consisting largely of C and N), an ocean (H and O), and a landmass (supplier of nutrients) accompanying continuous material circulation between these three components driven by the Sun is one of the minimum requirements for life to emerge and evolve. The life body consists of C, O, H, N and other various nutrients, and therefore, the presence of water, only, is not a sufficient condition. Habitable Trinity environment must be maintained to supply necessary components for life body. Our Habitable Trinity concept can also be applied to other planets and moons such as Mars, Europa, Titan, and even exoplanets as a useful index in the quest for life-containing planetary bodies.



## 1. Introduction

Habitable planets have largely been defined as having an adequate climate, which includes a sufficient atmosphere (e.g., Strughold, 1953; Huang, 1959, 1960; Dole, 1964; Shklovski and Sagan, 1966), as well as the presence of liquid water on its surface (e.g., Kasting et al., 1993). In addition to the "follow the water" theme (e.g., Kasting and Catling, 2003), there has been a call for the "follow the energy" consideration (Hock et al., 2007; Hoehler et al., 2007) in the search for extraterrestrial life. In addition to these parameters, planetary radius, density, escape velocity of the atmosphere, surface temperature, and bulk composition have formed the basis for developing indexes to search for potential habitable exoplanets; over eight hundred exoplanets have been confirmed to date, and of those nearly ten potential habitable planets have been identified (based from PHL@UPR Arecibo). Recently, icy satellites such as Europa have been the foci to discuss the possibility of the presence of life under ice sheets, and even the possible presence of evolved multi-cellular organisms, such as fish-like life (Greenberg, 2008); a water-enriched planetary body is often assumed to be a habitable planet.

The currently prevailing planetary habitability concept is largely based on the concept of the Circumstellar Habitable Zone (CHZ). The CHZ, a well-known region around a star where a planet with sufficient atmospheric pressure to maintain liquid water on its surface, originated during the 1950s (e.g., Strughold, 1953; Huang, 1959). Since that time, due in part to the success of the Kepler mission, a heightened search for so-called habitable planets in the CHZ is well underway (e.g., Cruz and Coontz, 2013; Kopparapu, 2013).

However, any conditions discussed so far for habitable planets, such as the presence of liquid water and an adequate climate, do not necessarily meet the requirements for the beginning and evolution of life. We point out here a new concept for habitable environment called Habitable Trinity, which will be applicable to the exploration of life in our solar system or exoplanets beyond.

## 2. What is life?

For biologists, the three-fold definition is common: (1) a membrane to separate the life body from the outer world, through which necessary elements for life such as water enter and exit the cell, (2) a metabolism which is a set of chemical reactions occurring in a living organism, such as receiving energy through spending nutrients and sugar, and (3) self-replication which allows life to continue through time (e.g., Luisi, 1998; Cleland and Chyba, 2002). However, these three are not sufficient enough to

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make life a continuous functioning system through time. Organic radical reaction is another important definition for life. To enable life to continue organic radical reaction, it is necessary to supply not only water but also the other components continuously, similar to daily food for us human beings. If no food in addition to water is supplied, we will die. This holds true even for microorganisms. First, we will summarize the necessary materials to allow life to survive.

## 3. Chemical composition of life

The presence of water is undoubtedly the most important factor for life. The amount of water in an adult human body, for example, is known to range from about 55 to 60% in weight (Guyton, 1976, 1991). Table 1 shows the chemical composition of a 70 kg adult human body (Mizutani, 2007), which is mainly composed of water, carbon, and nitrogen, occupying over 96 wt.% of the body. When including nutrients for life to ingest energy to live and function, six elements (C, H, O, N, Ca, and P) mainly compose the human body, being equivalent to 98.5 wt.% of the body.

Importantly, the chemical composition of life is not tightly fixed like that of rocks. This is because living system is always open to its natural surrounding world through a permeable membrane, which is the nature of life. For example, the amount of water in the human body differs not only from one individual to the next, but also within itself through time. Fluctuations in body water of an individual human being increase when water is ingested, or the amount of water decreases when excreted through bodily waste or perspired as a normal bodily function to regulate the temperature of the body. Body water also changes with age, exemplified through a body of a baby which reaches 75 wt.% and an adult human body ranging from 55 to 60 wt.% (Watson et al., 1980; Schoeller, 1989). In this way, the water component in a body constantly traffics among the outer world and the inside of the body as long as it lives. Therefore, the chemical composition of life body fluctuates in a certain range. In this sense, the chemical composition of life is essentially different from minerals which have fixed stoichiometric chemical formulas.

As well as the water component, elements in a living system are also not fixed. Major elements in addition to water such as C, N, and P, which are used by all living organisms, vary in ratio through time. Alfred Redfield focused on the elemental ratio in marine plankton, proposing the so-called Redfield ratios of C:N:P = 106:16:1 (Redfield, 1934, 1958). Actual chemical composition of an individual organism, however, differs from this modeled ratio depending on its environment, including whether it lives: in the water, on the land, below the surface, in a specific climate, and at a certain latitudinal or elevation range (e.g., Elser et al., 2000a,b, 2010; McGroddy et al., 2004; Sardans et al., 2012; Cease and Elser, 2013).

**Table 1**
Elements of a 70 kg human being.

| Element | Weight (kg) | wt.% | Compose of |
|---|---|---|---|
| O | 45.50 | 65.00 | All |
| H | 7.00 | 10.00 | Ocean |
| C | 12.60 | 18.00 | Atmosphere |
| N | 2.10 | 3.00 | Atmosphere |
| Ca | 1.05 | 1.50 | Landmass |
| P | 0.70 | 1.00 | Landmass |
| Minor[a] | 1.05 | 1.50 | Landmass |
| Total | 70.00 | 100.00 | |

Life is composed of elements of water (H and O), primarily supplied from the ocean, but also from the atmosphere (C and N) and landmass (nutrients such as Ca and P).
[a] Minor elements: K, Na, S, Cl, Fe, Cu, Zn, Mo, Cr, Co, Ga, Se, I, Si, F, Cd, Ba, Sn, Hg, Ni, V.

In spite of such fluctuations within living organisms, however, the chemical composition forms the building blocks of life including its distinguishing characteristics. Fig. 1 shows a simple comparison of elemental composition among mammals (animal) and angiosperms (plant) (Takahashi, 1984). This data shows that 99% of living forms are composed of ten elements: C, H, O, N, S, P, Ca, Mg, K, and Na. Remarkable differences include animals using more N, S, Ca, Na, and P and much less O, K, and Mg than plants. A higher concentration of N and S in animals is due to bone, with higher concentrations of protein, Ca, and P (particularly as calcium phosphate), which composes one-third of the body. The lower concentration of O is explained by a lack of cellulosic cell walls characteristic of plants, which indicates a higher concentration of proteinic cytoplasm in the animal body (Takahashi, 1984). From such a simple comparison as shown above, the life body is generally understood to be composed of a variety of elements with concentrations changing through time due to bodily functions.

Most important is that all necessary elements for life, such as C, N, H, and O, and P and other nutrients, are derived from three components: atmosphere ($CO_2$, $N_2$), ocean ($H_2O$), and landmass (supplier of nutrients). The existence of water (ocean) and/or atmosphere has dominated the discussion on the origin and the evolution of life, including the search for life beyond Earth. Here, we emphasize that the landmass, as the primary supplier of nutrients, combined with the ocean and atmosphere to form the Habitable Trinity (Fig. 2), and material circulation among these three components driven by the main engine, the Sun, is paramount to the origin, proliferation, and diversification of life. Phosphorus, for example, which plays an essential role in metabolism, does not originate from the ocean or atmosphere, but rather the landmass.

## 4. Continuous material circulation system on the Earth

All necessary elements for life systems are supplied and spent in the material circulating system on the surface of the Earth. Major elements to form life systems are provided from the atmosphere (C and N), ocean (H and O), and landmass (nutrients; e.g., Ca, Fe, P, Mg, and K) (Maruyama et al., 2013, 2014), all of which play a vital role for living systems to be born, flourish, and self-duplicate (Fig. 1).

| | C | H | O | N | S | P | Ca | Mg | K | Na |
|---|---|---|---|---|---|---|---|---|---|---|
| angiosperms | 45 | 6 | 41 | 3 | 0.5 | 0.2 | 1.8 | 0.3 | 1.4 | 0.1 |
| mammal | 47 | 7 | 18 | 12 | 2 | 4 | 8.5 | 0.1 | 0.7 | 0.7 |
| Plankton | 36 | 7 | 50 | 6 | - | 1 | - | - | - | - |

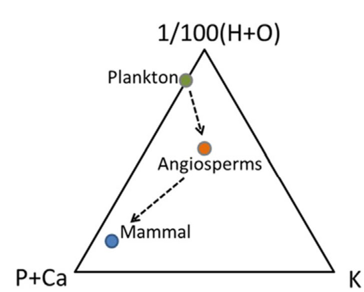


**Figure 1.** Comparison of elemental composition. The table (above) picked up three samples for rough comparison between plant (angiosperms), animal (mammal), and microorganisms (plankton). Figures are weight percentage normalized to individual body (given from dry cells of angiosperms and mammals (Takahashi, 1984); average chemical formula for plankton (Redfield, 1934)).
The triangle diagram (bottom) shows the characteristics of chemical composition of each organism. It clearly shows on land life is dehydrated than aquatic life.