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Research paper

Nuclear geyser model of the origin of life: Driving force to promote the synthesis of building blocks of life

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ABSTRACT

We propose the nuclear geyser model to elucidate an optimal site to bear the first life. Our model overcomes the difficulties that previously proposed models have encountered. Nuclear geyser is a geyser driven by a natural nuclear reactor, which was likely common in the Hadean Earth, because of a much higher abundance of ^{235}U as nuclear fuel. The nuclear geyser supplies the following: (1) high-density ionizing radiation to promote chemical chain reactions that even tar can be used for intermediate material to restart chemical reactions, (2) a system to maintain the circulation of material and energy, which includes cyclic environmental conditions (warm/cool, dry/wet, etc.) to enable to produce complex organic compounds, (3) a lower temperature than 100 °C as not to break down macromolecular organic compounds, (4) a locally reductive environment depending on rock types exposed along the geyser wall, and (5) a container to confine and accumulate volatile chemicals. These five factors are the necessary conditions that the birth place of life must satisfy. Only the nuclear geyser can meet all five, in contrast to the previously proposed birth sites, such as tidal flat, submarine hydrothermal vent, and outer space. The nuclear reactor and associated geyser, which maintain the circulations of material and energy with its surrounding environment, are regarded as the nuclear geyser system that enables numerous kinds of chemical reactions to synthesize complex organic compounds, and where the most primitive metabolism could be generated.

1. Introduction

What is life has long been a central topic in biology, at least since the discussion of the origin of life by Oparin (1924). The most accepted definition is three-fold: (1) metabolism, (2) membrane, and (3) self-replication (e.g., Oparin, 1924; Dyson, 1985). Following these criteria, a virus is not a life, because it cannot replicate by itself. Viruses are in an intermediate position between life and the inorganic world, although intensive debates continue. So far, three possible formation sites of life have been proposed: a tidal flat, submarine hydrothermal vents, and outer space (Fig. 1).

Considered as one of the most famous experimentations to discuss the origin of life, Miller (1953) and Miller and Urey (1959) detected amino acids (glycine α-alanine, and β-alanine) from a water condensation in the experiment with electric discharges in a gas mixture of H_2, NH_3, CH_4, H_2O, considered to be possible chemical compositions in the primitive Earth's atmosphere. The electron discharges are used to produce radicals instead of lightening or ultraviolet photons from the Sun to promote reactions for HCN and HCHO and those for further complex organic compounds, such as amino acids, nucleotide, and hydrocarbons. Here, note that key to their success would be the application of electric discharge as a non-thermal energy source with energy density as high as several $\times 10^{-2}$ W cm^{-2} (Table 1).

However, the tidal-flat model has a difficulty in obtaining a sufficient high-density energy source. Chyba and Sagan (1992) estimated global energy dissipation of lightening as 10^{18} J yr^{-1} and that of ultraviolet light ($\lambda < 200$ nm) in the stratosphere from the Sun as 6×10^{20} J yr^{-1}. These correspond to 6×10^{-9} W cm^{-2} and 4×10^{-6} W cm^{-2}, respectively (Table 1). Both of them are by far lower than what Miller and Urey used in their experiments. They also estimated the HCN global production rate (3×10^9 kg yr^{-1}) which corresponds to 20 nmol cm^{-1} yr^{-1}. On the other hand,

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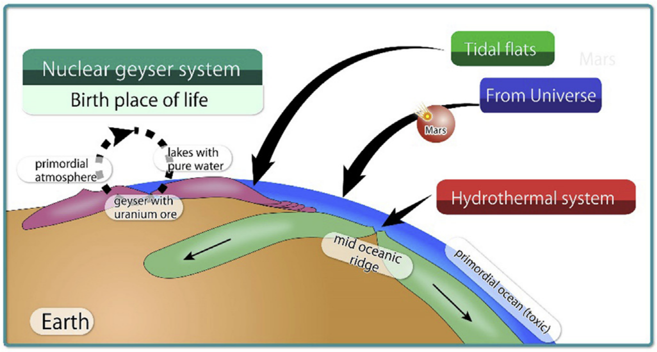

Figure 1. Proposed models for the birth place of life: tidal flats, submarine hydrothermal vents, outer space, and nuclear geyser system (the present work).

Table 1
Energy flux of energy source for the birth of life.

	Energy flux (W cm^{-2})	References
Miller & Uray experiment	$\sim 10^{-2}$	Miller and Urey (1959)
Lightning	6×10^{-9}	Chyba and Sagan (1992)
UV flux from the Sun	4×10^{-6}	Chyba and Sagan (1992)
Natural nuclear reactor		Meshik et al. (2004)
Core	1–10	
Peripheral	10^{-2}–10^{-1}	

Stribing and Miller (1987) estimated the concentration of HCN in the primitive ocean assuming the steady state of hydrolysis and production. At pH 8 and 50 °C, the concentration of HCN, however, was evaluated to be as low as 3×10^{-10} mol/L for the production rate of 100 nmol cm^{-2} yr^{-1}. This very low concentration of HCN cannot sustain contraction reactions to form complex biopolymers. For example, Sanchez et al. (1967) pointed out that adenine cannot be formed through polymerization of HCN, when the HCN concentration is less than about 10^{-1}–10^{-2} mol/L; in this case, HCN hydrolysis takes place rather than polymerization.

Following the discovery of hyperthermophile bacteria in the mid-oceanic ridge associated with a deep hydrothermal system (e.g. L'Haridon et al., 1995; Grassia et al., 1996), the submarine hydrothermal vents have been proposed to be a promising site for the origin of life, because hyperthermophile bacteria occurs near the root of the phylogenic tree by ribosomal RNA. In addition, considering the Hadean surface environment dominated by komatiite lava-flows on the surface, by which olivine-water reaction dominate to produce warm alkaline vents, like Lost City near the present Mid-Atlantic Ridge, driven by serpentinization of mantle materials, produce highly H_2-enriched water in a temperature range of about 40–90 °C (Kelley et al., 2001; Proskurowski et al., 2006). Such an aqueous environment has been regarded as a favorable site for the formation of organic matters. Thus, Russell et al. (1994), Russel and Hall (1997), and Martin and Russell (2003) proposed the idea that life originated in an alkaline hydrothermal vent at a redox, pH, and temperature-gradient between sulphide-rich hydrothermal fluid and Iron (II)-containing waters along the Hadean ocean floor, because they had known the importance of continuous electron flow as a key, since the Miller-Urey's experiments. The serpentinization of olivine (magnesium–iron silicate) with water is an abundant source of geological reducing power. These reactions occur at a 2–8 km depth beneath the ocean floor in a temperature range of 80–200 °C. Proskurowski et al. (2008) observed C_1 to C_4 hydrocarbons dissolved in hydrogen-rich fluids venting at the ultramafic-hosted Lost City hydrothermal field and showed their abiotic origin through Fisher–Tropsch type reactions, in which vapor phase mixtures of CO or CO_2 with H_2 occur in the presence of metal catalysts (Kugler and Steffgen, 1979; Anderson, 1984).

The ocean floors, however, lack a supply of necessary nutrients for life, which include nitrogen, phosphate, and potassium as major components of the life body (Maruyama et al., 2013). Concentrations of nitrogen-bearing inorganic molecules (e.g., ammonium and HCN) are found to be highly limited in hydrothermal vents. Although ammonium has been detected in submarine hydrothermal vents (Lilley et al., 1993; Lam et al., 2004), its concentration found to be less than mmol/L (i.e., insufficient to promote further reactions of complex biomolecules). Furthermore, there is few evidence of abiotic formation of amino-acid; although many authors have reported the detection of amino-acid from the fluid of the hydrothermal vents (Horiuchi et al., 2004; Takano et al., 2004; Klevenz et al., 2010; Lang et al., 2013; Fuchida et al., 2014), they are most likely derived from microorganisms living on the inner surface of the chimney.

As for HCN, so far, no reports of its detection have been made from submarine geothermal vents, though Mukhin et al. (1976) reported a trace of CN^- from on-land volcanic gas of the Alaid volcanoes in the Kamchatka islands. Furthermore, ocean floors covered by basalt are absolutely poor in phosphate and potassium (Maruyama et al., 2013). In summary, a mid-oceanic ridge hydrothermal system lacks nutrients (e.g., biologically accessible nitrogen, phosphate, and potassium). Even if these nutrients are available, the almost infinite dilution by sea water makes accumulation of biosynthetic molecules extremely difficult, in particular, for the primitive biological organizations, which do not have sophisticated membrane structures and material-uptake systems.

The final alternative theory of the origin of life, considered as a last resort in many respects, the interstellar and interplanetary space outside the Earth system has been proposed to form organic materials, since many biosynthetic precursors such as HCN, NH_3, and HCHO are detected in interstellar space through millimeter wavelength radio observations (Snow and Bierbaum, 2008). Ice and dust grains in the cold interstellar environments are continually bombarded by high-energy particles and radiation, producing complex organic molecules (Strazzulla et al., 1991), with >170 molecules discovered so far in the interstellar medium or circumstellar shells. Many more organic compounds, which include amino acids and nucleobases (Kvenvolden et al., 1970), have been detected in meteorites (Engel et al., 1997; Schmitt-Kopplin et al., 2010) and comets (Bockelee-Morvan et al., 2000).

Chyba et al. (1990), however, estimated the accretion rate of organic matter onto the Earth through asteroid and comet impact and found that it is at most 10^9 kg yr^{-1}, and more likely as small as 10^6–10^7 kg yr^{-1}, if the empirical constraints on the impact record are taken into account. As discussed above, this accretion rate is far less than what is required to achieve the necessary contraction reactions of biosynthetic precursors, such as HCHO or HCN, in order to continuously produce biopolymers. The situation is much worse, if a 100 bar-thick atmosphere during Hadean Earth is assumed (Abe and Matsui, 1986; Zahnle et al., 2007). In summary, although interstellar and interplanetary space is a good place to form and accumulate organic matter, impact-induced thermal destruction of the organic matter during its delivery to the surface of the Earth ultimately makes it highly questionable as the origin of life (Hashimoto et al., 2007).

Here, we present the nuclear geyser model as the promising site to lead to the emergence of first life, in which an underground natural nuclear reactor supplied a continuous flow of material and energy to bear primitive life. As can be seen in Table 1, energy flux in the form of ionizing radiation is as high as 10^{-2}–10^{-1} W cm^{-2}, which would be a promising site to harbor primitive life, as discussed below.