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Primordial Soup

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Synonyms

Prebiotic soup; Primitive broth

Keywords

Abiotic organic synthesis, Darwin's warm little pond, Oparin–Haldane, origin of life, primordial heterotrophs

Definition

The primordial soup is a generic term that describes the aqueous solution of organic compounds that accumulated in primitive water bodies of the early Earth as a result of endogenous abiotic syntheses and the extraterrestrial delivery by cometary and meteoritic collisions, and from which it is assumed that the first living systems evolved.

Overview

The term "primordial soup" and its synonyms are linked to the proposal of the heterotrophic theory of the origin of life, which was suggested independently in the 1920s by Alexandr I. Oparin, John B. S. Haldane, and few others. Based on the simplicity and ubiquity of fermentative reactions, Oparin and Haldane proposed that the first organisms must have been heterotrophic bacteria that could not make their own food but obtained organic material present in the primitive milieu. In order to support his proposal, Oparin appealed not only to astronomical observations that had shown that hydrocarbons and other organic material were present in meteorites and cometary nuclei, but also to the nineteenth century experimental syntheses of organic molecules by Wohler, Butlerow, and Mendeleyeev, among others (Lazcano 2010a).

Similar ideas were being developed independently at the same time by other researchers. Like Oparin, the British biochemist and geneticist John B. S. Haldane argued in 1929 that the origin of life had been preceded by the synthesis of organic compounds. Based on experiments by E. C. C. Baly, an English chemist who had reported the formation of amino acids and sugars as a result of the UV irradiation of a solution of CO_2 in water, Haldane suggested that the absence of oxygen in a CO_2-rich primitive atmosphere led to the synthesis of organic compounds and their accumulation in the primitive waters of the Earth, which he wrote had "the consistency of hot dilute soup." The discovery of phages led Haldane to argue that viruses represented an intermediate step in the transition from the prebiotic broth to the first heterotrophic cells (Farley 1977; Lazcano 2010a).

A Darwinian Warm Little Pond

In 1871, Charles Darwin mailed a letter to his close friend Joseph Dalton Hooker in which he mentioned Pasteur's work on the absence of spontaneous generation, and added that "It is often said that all the conditions for the first production of a living organism are now present, which could ever have been present. But if (and oh what a big if) we could conceive in some warm little pond with all sorts of ammonia and phosphoric salts,–light, heat, electricity &c. present, that a protein compound was chemically formed, ready to undergo still more complex changes, at the present day such matter would be instantly devoured, or absorbed, which would not have been the case before living creatures were formed."

However, the "hot dilute soup" concept formulated by Haldane developed independently of Darwin's warm little pond. During the first part of the twentieth century, most authors assumed, at least implicitly, that the origin of life had taken place in an aqueous environment. When Winslow Herschel discussed the consistency of colloids, which by then were assumed to explain many of the properties of protoplasm (Podolsky 1996), he wrote that "How many factors determine consistency is a matter of controversy, but the colloquial meaning of the word is well understood and may be illustrated by the description, from a recent novel, of 'Flanders mud after a thaw'. As the flow increased, the side of the trenches began to fall in; the earth thus mixed with the water thickened it to

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a consistency which might be liked to a very rich soup" (Herschel 1926).

There is nothing that suggests that Herschel, Haldane, or Oparin had read Darwin's remarks about the origin of life and the warm little pond. Darwin's letter was included by his son Francis as a footnote in the 3rd volume of his father's book *Life and Letters* published in 1887, but it was not until 1969 that Melvin Calvin published it in his book on chemical evolution (Calvin 1969), calling it to the attention of the origins-of-life community (Peretó et al. 2009). By then, the concept of a prebiotic broth and a heterotrophic origin of life, which had been developed by Oparin and Haldane within the framework of an evolutionary perspective, had gained considerable support from the development of a multidisciplinary research program on the emergence of the first living systems.

Defining the Soup

The proposal that life was the outcome of prebiotic chemistry and the evolution of precellular systems was further elaborated and refined by Oparin in a more extensive book that was published in Russian in 1936 and translated 2 years later into English (Oparin 1938). In his new book, Oparin suggested that the ► primitive Earth was a highly reducing milieu in which iron carbides of geological origin would react with steam to form hydrocarbons. Their oxidation would yield alcohols, ketones, aldehydes, etc., that would then react with ammonia to form amines, amides, and ammonium salts. The resulting protein-like compounds and other molecules would form a hot dilute soup, in which they would aggregate to form colloidal systems such as coacervates, from which the first heterotrophic microbes evolved. Others, like John D. Bernal argued that the compounds were concentrated on the surfaces of minerals like clays, where the higher density would favor their chemical interaction (Bernal 1944).

Experimental evidence in support of Oparin's proposal came first from Harold C. Urey's laboratory, at the University of Chicago, who had considered the origin of life in the context of his proposal of a highly reducing terrestrial atmosphere (Urey 1952). The first successful prebiotic amino acid synthesis was carried out with an electric discharge and a strongly reducing model atmosphere of CH_4, NH_3, H_2O, and H_2 (Miller 1953). The result of this experiment was a significant yield of a racemic mixture of amino acids, together with hydroxy acids, short aliphatic acids, and urea. One of the surprising results of this experiment was that the products were not a random mixture of organic compounds; rather, a relatively small number of compounds, most of which were of biochemical significance, were produced in substantial yield. The ► Miller–Urey experiment marked not only a new epoch in the study of the origin of life but also led to surprisingly rapid acceptance by the public of both the heterotrophic theory and the idea of a primitive soup (Bada and Lazcano 2003).

Was There a Primitive Soup?

Although it is generally agreed that free oxygen was absent from the primitive Earth, there is no agreement on the composition of the primitive atmosphere; opinions vary from strongly reducing ($CH_4 + NH_3 + H_2O$, or $CO_2 + H_2 + N_2 + H_2O$) to neutral ($CO_2 + N_2 + H_2O$). In general, nonreducing atmospheric models were favored by planetary scientists, while prebiotic chemists leant toward more reducing conditions, under which the abiotic syntheses of amino acids, purines, pyrimidines, and other compounds are very efficient. Prior to the recognition that organic compounds can be synthesized under the neutral conditions of a CO_2-rich atmosphere (Cleaves et al. 2008), the difficulties involved with the endogenous synthesis of amino acids and nucleobases have led to the development of alternatives.

In the early 1990s, Chyba and Sagan reanalyzed Oró's 1961 proposal on the role of cometary nuclei as sources of volatiles to the primitive Earth, and based on the chemical composition of carbonaceous meteorites proposed that the exogenous delivery of organic matter by asteroids, comets, and interplanetary dust particles could have played a significant role in forming the primitive soup, by seeding the early Earth with the compounds necessary for the origin of life (Chyba and Sagan 1992). On the other hand, proponents of an autotrophic theory of the origin of life (Wächtershäuser 1988) have dismissed the role of ► prebiotic synthesis and accumulation of organic compounds. However, since the FeS/H_2S combination is a strong reducing agent that has been shown to reduce nitrate and acetylene, induce the formation of peptide bonds between amino acids activated with carbon monoxide and (Ni, Fe)S (Maden 1995; Huber and Wächtershäuser 1998), and catalyze the synthesis of acetic acid and pyruvic acid from CO under simulated hydrothermal conditions (Huber and Wächtershäuser 1997; Cody et al. 2000), the role of Fe/S minerals is also compatible with a more general, modified model of the primitive soup in which pyrite formation is recognized as an important source of electrons for the reduction of organic compounds (Bada and Lazcano 2002).

There has been no shortage of discussion about how the formation of the primitive soup took place. However, it is likely that no single mechanism can account for the wide range of organic compounds that may have accumulated on the primitive Earth, and that the prebiotic soup was formed by contributions from endogenous syntheses in a reducing atmosphere, metal sulfide-mediated synthesis in deep-sea vents, and exogenous sources such as comets, meteorites, and interplanetary dust. This eclectic view does not beg the issue of the relative significance of the different sources of organic compounds, but it simply recognizes the wide variety of potential sources of organic compounds, the raw material required for the emergence of life (Bada and Lazcano 2009; Lazcano 2010b).

The Prebiotic Broth: A Risky Metaphor?

Synonymous terms like "primitive soup," "primordial broth," or "Darwin's warm little pond" have led in some cases to major misunderstandings, including the simplistic image of a worldwide ocean, rich in self-replicating molecules and accompanied by all sorts of biochemical monomers. However, nowadays, it refers to parts of the prebiotic environment where the accumulation and interaction of the products of abiotic synthesis may have taken place, including oceanic sediments, intertidal zones, shallow ponds, membrane-bound systems, freshwater lakes, and lagoons undergoing wet-and-dry cycles. The soup may have been semi-frozen, and glacial ponds where evaporation, eutectic separations, or other physicochemical mechanisms, such as the adherence of biochemical monomers to active surfaces, could have raised local concentrations and promoted polymerization (Bada and Lazcano 2009).

Given adequate expertise and experimental conditions, it is possible to synthesize almost any organic molecule. However, the fact that a number of molecular components of contemporary cells can be formed nonenzymatically in the laboratory does not necessarily mean that they were also essential for the origin of life, or that they were available in the prebiotic environment. The primitive soup must have been a bewildering organic chemical wonderland, but it could not include all the compounds or molecular structures found today in even the seemingly most primitive prokaryotes. It is possible that some compounds, including perhaps RNA itself, may not have been synthesized prebiotically, so their occurrence in living systems may have been the result of early metabolic syntheses.

The existence of different abiotic mechanisms by which biochemical monomers can be synthesized under plausible prebiotic conditions is well established. During the past few years, laboratory simulations of prebiotic synthesis have been developing models of specific detailed environments, including those that may have been provided by the surface of clays, small volcanic ponds, and liposomes. Our ideas on the prebiotic synthesis of organic compounds are based largely on experiments in model system, and the evidence suggests that the remarkable coincidence between the molecular constituents of living organisms and those synthesized in prebiotic experiments is too striking to be fortuitous. The robustness of this type of chemistry is supported by the occurrence of many of these biochemical compounds in the 4.5 billion-year-old Murchison carbonaceous chondrite and other carbon-rich meteorites, suggesting that similar synthesis took place on the primitive Earth (Miller and Lazcano 2002).

Conclusions

How the first life evolved is not known, but analysis of carbonaceous chondrites and the laboratory simulations of the primitive Earth suggest that prior to the emergence of the first living systems the prebiotic environment was endowed with (1) a large suite of organic compounds of biochemical significance; (2) many organic and inorganic catalysts (such as cyanamide, metallic ions, sulfur-rich minerals and clays); (3) purines and pyrimidines, that is, the potential for template-dependent polymerization reactions; (4) membrane-forming compounds; and (5) the availability of many possible sources of carbon and nitrogen for primordial heterotrophs. Once life appeared and biosynthetic pathways developed, the reservoir of organic material present on the Earth then shifted from one initially characterized by compounds of abiotic origin to one made up entirely of biologically derived components (Lazcano 2010b).

The existence of different abiotic mechanisms by which biochemical monomers can be synthesized under plausible prebiotic conditions is well established. Of course, not all prebiotic pathways are equally efficient, but the wide range of experimental conditions under which organic compounds can be synthesized demonstrates that prebiotic syntheses of the building blocks of life are robust, that is, the abiotic reactions leading to them do not take place under a narrow range defined by highly selective reaction conditions, but rather under a wide variety of experimental settings. Like other scientific metaphors, the term "primitive soup" is risky but useful, and has become a part of popular lore. For all the uncertainties surrounding the emergence of life, it appears that the formation of the prebiotic soup is one of the most firmly established events that took place in the primitive Earth.

See also

- ▶ Heterotrophic Hypothesis
- ▶ Miller–Urey experiment Au1

► Prebiotic Synthesis
► Primitive Earth
► RNA World

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