ORIGIN AND ESTABLISHMENT OF LIFE ON EARTH

A. Markoš
Charles University, Faculty of Sciences, Praha, Czechia

Keywords: life – definition, abiogenesis, theories of life origin, metabolism, genetic code, complex systems, planetary dimension

Contents

Summary

Life is a phenomenon which emerged on this planet as a result of very specific constellations of events. Cellular life emerged about 3.8 Gy ago as an outcome of many hypothetical steps: abiotic syntheses of organic compounds, protometabolism, emergence of replication, insulation into membranous compartments, etc.; the most enigmatic among these events may appear the establishment of genetic code. During the most part of evolution, the planetary dimension of life prevailed (represented by prokaryotic cells), followed by the appearance of multi-cellular eukaryotes in the late Precambrian.

1. Introduction

The enigma of life’s origin remains one of the most challenging problems of contemporary science. However clumsy the definition of life may be, we shall agree that “it” has a beginning and an evolution. Extensive research of geological and historical vestiges takes place, and sophisticated logical, computer, and chemical models have been built in the hope of revealing the mystery. In spite of many years of research and enormous progress, the answers available remain as unsatisfactory as those of seven decades ago, when Oparin proposed the first scientifically formulated theory. Due to paucity of concrete evidence concerning the early conditions on the Earth (and various planetary sub-compartments), even the simplest experiments aimed to understand early steps towards life remain biased by many uncertainties. As a result, interpolations made between the outcomes of such experiments on one hand and the contemporary life on the other quite often go beyond what is acceptable in established experimental sciences. After all, the problem transcends the scope of experimental sciences, which aim to reveal regularities, “laws” and general principles. Historicity, singularities, and extrapolation to unusual space-, and time-scales never make the situation easy for them. A further source of difficulties in such a trans-disciplinary project may lie in the absence of common language among sciences. Planetology, biochemistry, biology, science of complexity, thermodynamics, geochemistry, etc., each project their own view of affairs, but the superposition of these views is far from being satisfactory: many loose ends remain to be interconnected, many should be abandoned, and even more need be invented.

1.1 What is Life?

Difficulties begin with the attempt to define the very subject of our investigation—life. Even the most respectable dictionaries stay with vague definitions such as “a common property of living beings that make them different from non-living objects, enables them to feed, grow, and breed, etc., and becomes lost after their death”. Some of encyclopedic sources openly resign to the task and simply provide a list of life’s attributes. The same holds true for biology textbooks: no definition provides a satisfactory difference between life and non-life, life and mechanisms, life and “intelligent” machines, and life and complex evolving systems, etc. The main difficulty may reside in the fact that the definition should somehow incorporate structures and events occurring simultaneously at many spatial and temporal levels: maybe our language does not allow us to encompass them correctly.

A common attempt to escape such philosophizing and to remain firmly in the realm of science is to confine oneself not to life, but to the term organism. It’s meaning, however, is also very vague, and has wildly oscillated during last 200 years. On one pole we have a Kantian entity, which is an “organic product of Nature”. In contrast to a mechanical device (a machine,) such entity is its own cause and effect, is endowed not only with movement, but also with self-building forces, and with purpose; that’s it can take care of itself. On the other pole the term is a mere synonym for mechanism. Authors operating with the term organism usually do not bother with explanation. The reader is, then, left with fuzzy definitions like the following extracted from a few popular encyclopedia: “Any living thing;” “An organized body, consisting of mutually connected and dependent parts constituted to share a common life; the material structure of an individual animal or plant,” or “A form of life composed of mutually dependent parts that maintain various vital processes”. Such definitions will, of course, easily encompass machines, ecosystems, biosphere, and even dead bodies, and the nature of “vital processes” will remain unanswered. (On the other hand, one of them excludes fungi, protists, and bacteria.) Are there forms of life that are not organisms at the same time? We are left, as Kant was, with a mere list of properties: cellular organization, metabolism, genetic memory, and homeostasis etc.

A.G. Cairns-Smith has introduced a good operational definition of both organism and life: An organism is that which can take part in the processes of evolution through natural selection. For this it must have a dual constitution, namely:

1. A store of genetic information.
2. Phenotype.

Life is an informal term for the seemingly purposeful quality of evolved organisms. If organisms are prerequisites for evolution, "life" is rather a product of that process. This definition allows us to uncouple the evolution of "non-living" organisms from the commonly accepted attributes of the extant life (see below). It includes, however, two a-priori assumptions that may simply reveal an idiosyncrasy of our times: the genotype–phenotype dualism and a belief that all evolution can be reduced to a selection of molecular replicators.

A competing view can be summarized by the holistic slogan, coined by M.W. Ho: "Life is a process of being an organizing whole". This view accents the fact that life is a process coherent over a vast range of space- and time-scales. The whole body (be it a cell, a multi-cellular organism, or even more complex being) is thus "informed" across all space and time levels; information as well as energy is "non-local," it is shared by the whole body. Such a non-reductionist approach is somewhat alien to the discourse going on in contemporary biology. I feel, however, that it is necessary to stress also the interconnectedness of all hierarchical levels, with concomitant independent, (and emergent) behavior at each of them.

1.2 Rules of the Game

It is beyond hope to discuss here all ideas connected with the appearance of life. Our thoughts will be constrained to some scenarios plausible within the frame of experimental sciences; no creationist versions of life origins will be discussed. Furthermore, we shall suppose that the cradle of cellular life forms was on the Earth (i.e. life appeared as an indivisible part of the evolution of our planet). The theory of panspermy, which assumes that germs were brought to the planet from the outer space, will not be taken into consideration. We shall also leave out speculations about both, possible different forms that may reign somewhere in the Universe, as well as man-made creations (e.g. Artificial Life). Moreover, we shall assume that cellular forms of life have originated on the planet only once, i.e., we suppose the existence of the Last Universal Common Ancestor (LUCA). This assumption is reasonable because life's origin is highly improbable anyway, hence the whole event can be considered a singularity. Moreover, only a narrow time-window may have existed in the evolution of the planet, when conditions were favorable enough for the event to occur. Finally, origins of life may be impossible in the presence of other (competing because—they are—more highly evolved) forms of life.

We have to face uncertainties regarding the early history of the Earth. Except for common agreement as to her age—about 4.5 Gy, the available scenarios concerning her evolution considerably differ. How much organic carbon was brought in by planetismals, and what fraction of these compounds survived the initial warming of the planetary body? Was the planet molten completely or only partially? How complete was the primary fractionation of elements? How much organic carbon was brought in during cosmic bombardment that followed? What are the composition of the primordial atmosphere, hydrosphere, and lithosphere, and the following evolution of the planetary surface? What was the nature of pre-biotic syntheses, and how did they get enchained into the body of LUCA? All this brings too many degrees of freedom into the game.

We shall accept the opinion that 3.8 Gy old fossils found in the Isua formation (Greenland) represent fossils of genuine prokaryotic cells, (i.e. assume that life more or less comparable to contemporary life has established itself by that time). “Comparable” means that:

- It was already bound to the existence of cells and probably far away from the LUCA
- It ruled over a genetic memory based on DNA, and over a cellular “executive” based on proteins
- Its metabolism (including photosynthetic assimilation of CO_2) was fuelled by free energy of oxidation-reduction couples. Energy was transformed into two universal and mutually convertible energy currencies of the cell:
    1. Difference of electrochemical potentials of ions across a membrane.
    2. Energy of chemical bonds in a “macroergic” compound—usually the molecule of ATP. Energy liberated from these sources (by discharge of the difference of electrochemical potentials, or by splitting high-energy bonds) can be coupled to all processes requiring energy.

The oxidation-reduction couples were—by means of biogenic photosynthesis—already connected to, and boosted by, the incoming energy of solar light.

Evolution of life has from the very beginnings been both molecular and, at the same time, planetary phenomenon: the totality of the process cannot be described and understood from any single level of description. The planetary dimension of life tends to be quite neglected. Moreover, there is a large gap in the study of life history. Investigations on life origins tend to be concentrated to the relatively short initial period of planetary history, whereas the evolutionary theory is highly centered to multi-cellular eukaryotes, i.e. to the last half billion of years. The periods of three billions of years in between attracts little attention—and namely this, the longest period of life evolution, is marked for its planetary dimension. During this period, enormous work has been invested in rebuilding the planetary surface, and firm grounds have been established for planetary homeostasis to become controlled, as I believe, by biotic factors. The evolution of the planet and evolution of life go hand in hand from the very beginning, and deeper insight into processes that mould this co-evolution should cast more light on the very beginnings of this relationship.

2. The Playground

As is the case for all historical phenomena, also for life it holds that the present state is an outcome of many possible (or thinkable) trajectories. The “real” one is only to be guessed and tentatively reconstructed not only from extrapolations based on present forms of life, but also from interpretation of paleontological, and cosmological vestiges. The interpretation of such vestiges is by no means equivocal, and several competing and mutually exclusive interpretations are in circulation at present. In this part of our discussion, we shall focus attention on factors recognized by contemporary science as basic prerequisites for the origin of life: the sources of organic carbon and of energy (and of their development) the emergence of the genetic code, the emergence of complexity through evolution, and, finally, the emergence of cellular life.

2.1 Where on Earth?

What was the putative "biotope" which enabled life to establish itself? For the pioneers of abiogenic theory, the open ocean seemed to be an obvious candidate. Its masses, according to their views, served as a reservoir of organic matter ("primordial soup," whatever its origin was, see the next paragraph). An enormous body of evidence has been accumulated since in favor of many different locations, e.g. evaporating lagoons, fresh-water reservoirs, active surfaces of various nature, hydrothermal vents, molten base of glaciers, aerosols, water, and percolated deep layers of the crust, etc. Salinity, high (or low) temperatures or pressures needed for catalysis, the presence of active surfaces or of special configuration of catalytic matrices, solar radiation or the absence thereof, oxidation-reduction potential, and many other factors were proposed for, or against, a particular hypothesis. As all such niches may have existed in parallel, a "division of labor" cannot be ruled out, either. The mainstream life (from LUCA onwards) can easily be considered as a merger of different parallel pre-biotic processes. Multiple streams leading to cellular life may have originated in different environments, and contributing to different aspects of the emerging life. Perhaps the single common denominator to all theories is the essential precondition of the presence of water in a liquid state.

3. The Source of Organic Carbon

The contemporary life is tightly coupled to the existence of very complex organic compounds. At the surface layers of contemporary Earth, the most frequent form of carbon is CO_2 and/or carbonates; most deposits of organic carbon present in Earth's crust are usually interpreted as fossilized remnants of living beings. The synthesis of organic compounds is totally ensured by living beings, phototrophic or chemolithotrophic. No known mechanism (except human technologies, of course) can perform "abiotic" reduction of CO_2 to organic compounds today. Was, then, organic carbon a necessary precondition for the emergence of life? If so, how did organic compounds appear on the abiotic planet? If not, what were the first "inorganic" forms of life?

Most of the theories of the origin of life consider the presence of organic compounds, as indispensable from its very beginning, i.e. the presence of organic compounds must have preceded the origin of life.

The original supply of organic compounds could have originated in open space, and be brought to the planet during the accretion process. It is well known that chondrites (a type of meteorites) contain substantial amounts of organic compounds in great assortment; the presence of a great variety of organic compounds in high quantities was also confirmed (by spectroscopy) in outer space. Estimates of the contribution of this cosmic store to the birth of life vary considerably depending on what model of the early evolution of the planet has been adopted. Some authors assume that upon accretion the planet became molten, which would necessarily destroy any organic compound present originally. Even if so, organic compounds could have been brought in during a subsequent phase of extensive "bombardment" of the planet by planetismals.

Recently, however, the postulate of molten Earth has been put in doubt, and T. Gold coins a theory assuming huge deposits of organic carbon, of cosmic origin. According to the theory, hydrocarbon (mostly methane) deposits in the depth of 100–300 km, existing up to our days, gave rise, in the past, to most "fossil" fuels (petrol, gas, anthracite, and kerogen,) and also supplied the emerging life with both building blocks and energy, to run organic syntheses.

Another set of theories explains the origin of organic compounds starting with "inorganic" Earth, with atmospheric carbon as a source of organic syntheses. Originally, it was assumed that the primordial atmosphere was highly reducing, containing compounds like methane, ammonia, water, hydrogen, and hydrogen cyanide, etc. It was shown experimentally that electric discharges in such mixtures lead to synthesis of a broad variety of organic compounds, i.e. carboxylic acids, amino acids, formaldehyde etc. However, no nucleotides—building blocks of nucleic acids—and no organic compounds containing phosphate were obtained. According to this scenario, after some time, the oceans would bear a mixture of simple organic compounds ("primordial soup,") and chemical interactions among them would establish some kind of primitive metabolism leading to building blocks of living beings.

Recently it has been commonly accepted that the primitive atmosphere was only mildly reducing, consisting mainly of CO_2, nitrogen, and water. In such mixture electric discharges are not energetic enough to reduce CO_2; therefore a photo-reduction driven by UV photons, with ferrous ions as electron donors, has been postulated. (Such a mechanism would also explain the enigma of the origin of banded iron ore deposits.) The process would also lead to a "soup" of a kind.

There also exist "no soup for starters" scenarios:

In one approach, concomitant unfolding of primitive metabolism as well as CO_2 assimilation is supposed, usually on two-dimensional surfaces of some sort (a primeval "pizza," to continue with the analogy), e.g. on the surface of pyrite crystals.

Even more radical is the theory coined by A. G. Cairns-Smith. He suggests that the first organisms were inorganic, self-replicating crystals. In such case the first evolution may or may not have been accompanied by the accumulation of organic compounds: organic syntheses may have appeared only later, as processes catalyzed by already present crystal "organisms." Cairn-Smiths uses an analogy of building a stone arch. You need a scaffold to build it, but when ready, you will not easily decipher the nature of the scaffold. In this analogy contemporary replicators and the DNA–protein represents the “arch,” whereas self-replicating clay crystals are the long-abandoned scaffolds.

-
-
-

Bibliography

Cairns-Smith A. G. (1985). *Seven Clues To The Origin of Life. A Scientific Detective Story*. Cambridge University Press [The “inorganic replicators’” story].

Dawkins R. (1982). *The Extended Phenotype*. Freeman and Co.; Maynard Smith J. (1996) *Evolutionary Genetics*. Oxford University Press. [Presentation of neo-Darwinian evolutionary theory].

de Duve C. (1995). *Vital Dust. Life As A Cosmic Imperative*. Basic Books. [The pre-biotic soup version of the story.].

Eigen M. (1996). *Steps towards life. A Perspective On Evolution*. Oxford University Press. [The theory of hypercycles.].

Gold T. (1999). *The Deep Hot Biosphere*. Springer. [Theory of vast resources of hydrocarbons existing in Earth’s crust. The crust as the site of life origin.].

Ho M.W. (1993). *The Rainbow And The Worm. World Scientific*. [A holistic view of life processes coherent through many space-, and time-scales. An attempt to define the essence of the living on those premises.].

Poole A. M., Jeffares D. C., and Penny D., (1998) *The Path From The RNA World, Journal of Molecular Evolution* **46**, pps. 1–36. [A model of evolution from the late stages of the RNA world to modern cellular life as we know it today.].

Kauffman S. A. (1993). *The Origins of Order. Self-Organization And Selection In Evolution*. New York, Oxford: Oxford University Press. [Self-organizing processes as a basis of evolution. Behavior of complex systems at the edge between chaos and a frozen state.].

Lovelock J. E. (1990). *The Ages of Gaia*. Bantam Books; Ehrlich H.L (1996) *Geomicrobiology*. Basel: Marcel Dekker.; Westbroek, P. (1992). *Life as a Geological Force*. Norton. [View of life from a planetary perspective.].

Wächtershauser G. (1988). *Before Enzymes and Templates: Theory of Surface Metabolism. Microbiological Reviews* **52**, pps. 452–484; Wächtershauser G. (1990). *Evolution of the First Metabolic Cycles, Proceedings of the National Academy of Sciences of the USA* **87**, pps. 200–204. [The “pre-biotic pizza” version of the story. The role of pyrite formation as a driving force, as well as matrix, for the primitive metabolism.].

Biographical Sketch

Anton Markoš was born in 1949 in Czechoslovakia. In 1972, he graduated in biology at the Faculty of Sciences, Charles University, Prague. In 1977 he received his PhD at the same institution, in cell physiology. Since 1977, he has been a faculty member of the University. From 1979–1994 he worked in cell biology; since 1994 member if the Center of theoretical study, a joint institution of the Charles

University and the Czech Academy of Sciences; since 1998 associated professor of the Department of philosophy and history of sciences. Presently working and teaching in theoretical biology, especially on problems of morphogenesis and evolution. Books: *Emergence of Living Shape* (1997, in Czech), and *Readers of the Book of Life* (2000, in Czech; English version forthcoming in the Oxford University Press).