LIFE ON EARTH

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Summary

"The Universe is not only queerer than we suppose, it is queerer than we can suppose."
-J.B.S. Haldane

Although life may not be unique to Earth, and future explorations may yet reveal life elsewhere in the universe, life is without question the most awesome and the most incomprehensible phenomenon for those who seek to understand it. In order to understand the nature of the origin, distribution, and diversity of life on Earth in the past and the present, and, in order to predict its future, it is necessary to examine the forces that have shaped and influenced life in the past. Life has the capacity of responding and adapting to the dynamic environmental and physical forces that have changed both the Earth and life over the eons of time. This essay utilizes a paleoperspective approach in looking at the extraordinary history and diversity of life on Earth. Topics to be discussed will include the origin of life, evolutionary mechanisms and processes, biodiversity, and past global crises.

1. Emergence of Life

Notions have always been produced to account for the genesis of life, mind, and social order. Charles Darwin theorized that simple life evolved into complex life through a series of small beneficial changes which accumulated over time. But, just what is life and how did it originate? How did the complexity of life that we see on Earth today come into being? While many scientists agree that life had its humble beginnings as single-celled organisms, various questions still persist as to how these single-celled organisms began. See Chapter *Origin and Emergence of Life on Earth*.

Today, it is an acceptable and basic biological principle that life only can come from preexisting life (biogenesis). The geological history of Earth reveals, however, that early in the history of Earth, there is no evidence of life as indicated by fossils and, furthermore, the evidence indicates that the physical and chemical characteristics of early Earth would not have supported life as we understand it today. Excluding an "inoculation" of life on Earth from an extraterrestrial source, it must be concluded that life on Earth must have originated from the inanimate world. It is a premise accepted by most scientists that the origin of life on Earth can be studied by the application of scientific methodology to the historical, biological, and geological records, and to characterization of living organisms today. Although there are numerous theories and hypotheses concerning the origin of life, there is, as yet, no single, unifying theory.

A precise definition of life is fraught with difficulties. Dictionaries and biology textbooks fail to provide a satisfactory difference between life and non-life or define well what a living organism is. 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 (i) a store of genetic information… [and] (ii) …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." Defining life by describing its basic characteristics is also a common practice of biologists. Thus, living things, regardless of their amazing variety of shapes and forms, share the capacity to reproduce using genetic information, to develop and grow and to have the ability to maintain a stable internal environment despite changes in the external environment (homeostasis).

Figure 1. Life is not only the sum of all living forms but the complexity of their interactions that include the processes in atmosphere, hydrosphere, and even lithosphere.

Life also is characterized by specific structures, organization, and functions. Where and how did the DNA, RNA, proteins, and enzymes come together to produce living organisms? There is not universal agreement as to where life began and many theories have been proposed. Did life arrive on Earth from outer space, perhaps a remnant from ancient oceans on Mars carried to Earth by an asteroid? Did life originate near underwater hot lava vents? Other sources have proposed evaporating lagoons, freshwater reservoirs, molten base of glaciers, aerosols, and water, percolated deep layers of the crust, and others. It is even conceivable that several different environments have contributed to the origin of life. Wherever the location or locations, the single common denominator to all theories is the essential precondition of the presence of water in a liquid state.

Figure 2. The Archean and Proterozoic rocks contain numerous microfossils, but because only the shapes of the ancient bacteria are preserved we do not properly understand their genetic evolution. It resembles the situation when we can guess the function of computer only from hardware outlook without any software left.

The earliest record of life on Earth is bacterial fossils found in Precambrian rocks three and a half billion years old. These early life forms were single-celled, did not carry out photosynthesis and did not have a cell nucleus. These ancient unicellular organisms were at first autotrophs metabolizing carbon dioxide or hydrogen sulfide and later evolved into photosynthetic organisms and became able to live in other environments. It is thought that all subsequent life on Earth descended from these Precambrian creatures. Similar features of the genetic code and metabolism have been found in the Archaea, bacteria, and eukaryotic organisms. Eukaryotes are organisms which have a nucleus and other membrane-bound organelles and include the "higher" organisms such as plants, fungi, and animals in contrast to prokaryotes such as the Archaea and blue-green algae, which do not have a nucleus or other membrane-bound organelles.

The documentation of the evolution and the development of diverse life forms is reasonably inferred from the fossil record. Difficult as it may be for a plant or animal to be preserved as a fossil, several hundred thousand species already have been described and can be used to write a good "history" of life on Earth from the time of its first recorded instance.

Filling in the stages between the abiotic world and the first prokaryotic cells presents a much more difficult challenge, however. Given the chemicals that are characteristic of life today such as RNA, DNA, proteins, and enzymes, how did they originate and come together in the correct structures for the necessary functions of life? The chemical composition of all living organisms is remarkably similar. How did this come about?

There are different hypotheses to account for the origin of the chemicals that are used to serve as the building blocks for life. Most of the theories of the origin of life consider the presence of organic carbon as a necessary precondition for the emergence of life and that the presence of organic compounds must have preceded the origin of life. It has been hypothesized that the oceans contained a mixture of simple organic compounds (commonly referred to as a "primeval soup"). A half-century ago, Stanley Miller demonstrated that it was relatively easy to synthesize amino acids using gases thought to be part of the primeval atmosphere on Earth: methane, hydrogen, and ammonia. These gases are chemically inert at room temperatures but, with an input of energy, reactions take place. Miller utilized an electric current, reasoning that electrical discharges probably were available on the early Earth. His early studies yielded four different amino acids and he hypothesized that other chemicals and reactions could take place resulting in a chemical evolution leading to the actual origin of life. Subsequent experiments yielded additional amino acids as well as other biologically significant molecules including simple sugars. On the other hand, computer simulation models showed that some structures could proliferate and even evolve toward more complex structures whenever some conditions are fulfilled. These necessary conditions include the ability to replicate itself, heredity (transmission of information between generations) and "mutability" (possibility to randomly change this genetic information). Perhaps, life is inevitable given the right conditions.

How the first organic chemicals became organized enough to utilize energy to maintain and organize the structures and functions of life, including the vital capacity to reproduce the living organism, remain difficult and intriguing questions. The main problem concerning the origin of life is that relating to the origin of the genetic code: protein molecules cannot be copied and must be synthesized according to information stored in DNA, but that operation itself, as well as the replication of DNA, requires proteins. DNA cannot be copied without proteins and proteins cannot be synthesized without DNA, so how could such a self-supporting system originate? Maybe there was originally some structure that was able both to replicate and to catalyze the replication. RNA is a likely possibility for filling such a role since it can replicate itself and can direct the synthesis of proteins and other biochemicals. It also can act as a catalyst in various chemical reactions that transmit genetic information and control the expression of genes. RNA, thus, can be regarded as a key immediate precursor to the whole genetic machinery. And it also would have preceded DNA in evolution. See *Origin and Establishment of Life on Earth*.

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Bibliography

Cairns-Smith A.G. (1985). *Seven Clues to the Origin of Life: A Scientific Detective Story*, 131 pp. Cambridge: Cambridge University Press. [The "inorganic replicator" story. Life as an epiphenomenon of evolution of clay crystals.]

Dawkins R. (1982). *The Extended Phenotype: The Gene as the Unit of Selection*, 307 pp. Oxford: W.H. Freeman and Co. [Presentation of neo-Darwinian evolutionary theory.]

De Duve C. (1995). *Vital Dust: Life as a Cosmic Imperative*, 362 pp. New York: Basic Books. [The prebiotic soup version of the story.]

Ehrlich H.L. (1996) *Geomicrobiology*. Basel: Marcel Dekker. [View of life from a planetary perspective. The theory of geophysiology, of a planet controlled by feedback between biota and inorganic part of the planet. Coevolution of the planet and life.]

Eigen M. (1996). *Steps Towards Life: a Perspective on Evolution,* 173 pp. Oxford: Oxford University Press. [The theory of hypercycles.]

Gold T. (1999). *The Deep Hot Biosphere*. Berlin: Springer-Verlag. [Theory proposing vast resources of hydrocarbons existing in the Earth's crust; catalyses on active surfaces in high temperatures and pressures; the crust as the site of life's origin.]

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

Hsu K.J. (1982). Mass mortality and its environmental and evolutionary consequences. *Science*, **216**, 249–256. [A classic paper dealing with mass mortality, mass extinctions and fossilization. The concept of the depleted or so-called Strangelove ocean is derived from this publication.]

Kauffman S.A. (1993). *The Origins of Order: Self-organization and Selection in Evolution,* 709 pp. New York, Oxford: Oxford University Press. [Self-organizing processes as the basis of evolution. Behavior of complex systems at the edge between chaos and a frozen state.]

Kidwell S.M. (1998). Time-averaging in the marine fossil record: overview of strategies and uncertainties. *Geobios* **30**, 977–995. [This paper is a conceptual and process analysis of the taphonomy of death assemblages in nearshore and shelf settings as age-mixtures formed over thousands to tens of thousands of years.]

Lazcano A. (1997). Chemical evolution and the primitive soup: Did Oparin get it all right? *Journal of Theoretical Biology* **184**, 221–224. [This article gives information on the prebiotic soup version of the origin of life.]

Lovelock J.E. (1990). *The Ages of Gaia*. Bantam Books. [View of life from a planetary perspective. The theory of geophysiology, of a planet controlled by feedback between biota and inorganic part of the planet. Coevolution of the planet and life.]

Magurran A.E. and May M., eds. (1999). *Evolution of Biological Diversity*, 329 pp. Oxford: Oxford University Press. [Up-to-date review of evolutionary sources of biological diversity, speciation and extinction dynamics.]

McKinney M.L. (1989). Periodic mass extinctions—product of biosphere growth dynamics? *Historical Biology* **2**, 273–287. [This paper provides approaches for the modeling of self-regulated oscillations and extinctions of larger ecosystems, continuing the ideas of Tappan-Loeblich.]

Muller R.A. and MacDonald G.J. (1995). Glacial cycles and orbital inclination. *Nature* **377**, 107–108. [This paper deals with isotopical data and climate variations that show a 100 ka cycling that is caused by the previously ignored tilt of the earth's orbital plane and not by Milankovitch eccentricity. As the orbit changes, it passes through different parts of the sun's zodiacal ring, and encounters different regions of star dust.]

Oldfield F. (1999). The Past Global Changes (PAGES) project: a personal perspective. *Quaternary Science Reviews* **18**, 317–320. [This reflection provides good information (and/or deliberation) about major threads and subprojects, methods of the investigation, character of results, as well as the applicability of results and predictability of processes from this project.]

Playford P.E. and McLaren D.J. (1984). Iridium anomaly in the Upper Devonian of the Canning Basin, Western Australia. *Science* **226**, 437–439. [This paper documents increased content of iridium and other metals in early Famennian stromatolitic and weathering zones on partly emergent, extinct Frasnian reefs.]

Racki G. (1998). Frasnian-Famennian biotic crisis—Underevaluated tectonic control? *Paleogeography, Paleoclimatology, Paleoecology* **141**, 177–198. [This provides an application of the Cathles-Hallam model of fluctuating tectonic stress among lithospheric plates, including the massive effusions of basalts that may change sea level and Earth environments. Comparisons are also made with the ideas of F.E. Suess, nineteenth century.]

Raup D.M. (1991). *Extinction: Bad Genes or Bad Luck?*, 224 pp. New York: Norton. [A comprehensive overview of theories and facts about large extinctions and extinction dynamics]

Raup D.M. and Boyajian G.E. (1988). Patterns of generic extinction in the fossil record. *Paleobiology* **14**, 109–125. [Plots of global databases on extinctions of organisms are used to search for periodicities. A 26-million-year periodicity and others are postulated.]

Ricklefs R.E. and Schluter D., eds. (1993). *Species Diversity in Ecological Communities: Historical and Geographical Perspectives*, 414 pp. Chicago: University of Chicago Press. [The most important contribution to the theory of species diversity of communities. Overview of factors affecting diversity, ranging from local to geographical and historical ones.]

Rosenzweig M. (1995). *Species Diversity in Space and Time*, 436 pp. Cambridge: Cambridge University Press. [An excellent attempt to identify and explain the main large-scale diversity patterns from a general theoretical point of view. The general theory of species diversity is based on the assumption that area is a major factor affecting speciation and extinction dynamics and consequently almost all diversity patterns.]

Sepkoski J.J. Jr. (1992). Phylogenetic and ecologic patterns in the Phanerozoic history of marine biodiversity. *Systematics, Ecology, and Biodiversity Crisis* (N. Eldredge, ed.), pp. 77–100. New York: Columbia University Press. [This essay includes all the classic Sepkoski conclusions based on a structural view of the problem.]

Shukolyukov A. and Lugmair G.W. (1998). Isotopic evidence for the Cretaceous–Tertiary impactor and its type. *Science* **282**, 5390, 927–929. [This paper carefully documents the probability that the Chicxulub impactor was a carbonaceous asteroid similar to those which supplied Earth with carbonaceous chondrites of different metamorphic types. The alternative that the bolide was a comet cannot be refuted. Enhanced flux of extraterrestrial ^{3}He in sediments associated with the Chesapeake impact is also discussed.]

Strauss H. and Joachimski M. (2000). Response of the Ocean/Atmosphere System to Past Global Changes. *Chemical Geology, Special Issue* **162**. [This collection of papers discusses phoshorites, sulphur and carbon isotopes of Neoproterozoic/Cambrian times. Topics include high δ^{34}S values in nearshore areas as a result of overturn in ocean stratification, δ^{18}O evidence for Carboniferous and terminal Permian glaciations, etc.]

Valentine J.W. and Jablonski D. (1993). Fossil communities, Compositional variation at many time scales. *Species Diversity in Ecological Communities—Historical and Geographical Perspectives* (R.E. Ricklefs and D. Schluter, eds.), pp. 341–349. Chicago: University of Chicago Press. [This study exemplifies asynchronous and structured changes of communities with many characteristics of noncompetitive diffusion.]

Walliser O.H., ed. (1995). *Global Events and Event Stratigraphy in the Phanerozoic*, 340 pp. Berlin: Springer Verlag. [This is a basic monograph reviewing the results of the international project IGCP 216: Global Bioevents and Mass Extinctions. Ammonite faunas and eustacy are emphasized, together with outlines of ideas about "aging" of systems and organic groups.]

Wilde P. and Berry W.B.N. (1984). Destabilization of the oceanic density structure and its significance to marine extinction events. *Paleogeography, Paleoclimatology, Paleoecology* **48**, 143–162. [This is a truly classic study focused on mixing in the oceans, overturns of anoxic water and other significant changes in oceanic thermal transfer.]

Wilson E.O. (1994). *The Diversity of Life*, 406 pp. New York: Norton. [A famous and very popular book about diversity, from its origin and dynamics to its contemporary loss and consequent conservation issues.]

Biographical Sketches

Donald J. Nash was born in the United States in 1930. He received his B.S. in Zoology at the University of Michigan in 1951 and an M.A. in Vertebrate Paleontology at the University of Kansas in 1957. His Ph.D. degree in genetics was granted at Iowa State University in 1960 and his doctoral research involved studies of radiation biology and genetics. He has been a faculty member at Pennsylvania State University and Rutgers University and since 1965 has been at Colorado State University where he is currently a Professor of Biology. Dr. Nash is a Fellow of the American Association for the Advancement of Science and is the Executive Director of the American Association for the Southwestern and Rocky Mountain Division of the AAAS. His current research involves behavioral, developmental and genetic studies of mammals including humans. Particular emphasis is devoted to the study of neurological and developmental disorders. He has over 100 publications in the areas of genetics, behavior, and radiation biology.

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