Philippine Studies: Historical and Ethnographic Viewpoints

Volume 12 | Number 3 Article 5

9-29-1964

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Recommended Citation
Varela, Miguel Maria (1964) "Origins of Terrestiral Life," *Philippine Studies: Historical and Ethnographic Viewpoints*: Vol. 12: No. 3, Article 5.
Available at: https://archium.ateneo.edu/phstudies/vol12/iss3/5

philippine studies

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Philippine Studies vol. 12, no. 3 (1964): 460–472

Origins of Terrestrial Life

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THE term "spontaneous generation" does not now have the same meaning it did two thousand years ago, or even two hundred years ago. Its meaning then was the presumed genesis of living organisms from lifeless matter as a contemporary process. Thus, in the sixteenth century, the physician Paracelsus reported as an observable fact the spontaneous formation of mice, frogs and turtles from such raw materials as water, air, straw and rotting wood. Today this theory is no longer held; it was dealt a fatal blow by the series of experiments conducted by Pasteur about a century ago.

The past ten years or so have, nevertheless, brought to the forefront of scientific discussion the problem of how life originated on this planet, and with it a revised version of the Aristotelian theory of spontaneous generation. Two developments in our times have provided stimulus for the problem and the hypothesis. The first is the rapid progress in the field of biochemistry, which has opened for us new methods of synthesis and new insights into the structure of biologically significant molecules. Scientists have likewise been able to form substances in the laboratory under conditions duplicating those of our primitive earth. Secondly, the growing interest in the space program has generated a whole new field of science called *exobiology*, the branch of the biological sciences interested in extraterrestrial life.[1] It is not surprising then that a renewed interest in the possible existence of life forms in outer space has brought back the old question of how life developed in the first place in our own earth.

The *panspermic hypothesis* attempts to answer this question by assuming that the vastness of interstellar space was at one time teeming with living spores or seeds; "astroplankton", as Haldane calls them. These seeds of life owe their motion to the impact of energy in the form of light rays. Life in other planets, so the panspermists say, could have been kept in a state of cryptobiosis (hidden life through some form of protective mechanism) and disseminated by cosmozoan transport from one planet to another. The Swedish chemist Arrhenius (+ 1927) was an enthusiastic upholder of this possibility, especially after learning that some of his contemporary scientists thought life could be coextensive with the entire cosmos both in time and space. This hypothesis assumes, therefore, that astroplankton is resistant to the damaging radiations of outer space, and to the extreme temperatures and the cold vacuum conditions prevailing in the space oceans of the universe. Today, however, we know that life as experienced on earth is unable to tolerate such a rigorous and extreme environment. Moreover, this "life from outer space" hypothesis, while accounting for the appearance of life on earth, does not explain how it originated in whatever planet it may have come from.

The *autotroph hypothesis* tries to explain the genesis of earth life by assuming that an autotrophic organism was the first form of life in our planet. An autotroph is defined as an organism capable of manufacturing its own food. Green plants today fall under this category. A serious objection to this hypothesis is that all the known chemical reactions taking part in food metabolism are very complex and require a complex organism to synthesize complex compounds from simple raw materials. Such a postulate seems improbable when we consider that the paleontological and biological studies of the

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[1] Exobiology is a science that still has to prove the existences of its subject matter, namely, life beyond our earth. See the critique of this new discipline by Dr. G. G. Simpson in *Science* 143 (1964), 769.

past few years point to Nature as advancing from simple to complex forms, and that organic forms grow in complexity only in the course of long spans of time through a series of many small changes. Complex organisms do not appear right away in simple surroundings.

In opposition to this autotrophic hypothesis is the *heterotroph* one which assumes that simple organisms were the first forms of life to appear. These earliest forms developed from non-life, and were incapable of producing their own food. At first sight this heterotrophic hypothesis may not seem to be different from the Aristotelian spontaneous generation, both postulating life from lifeless matter. A closer scrutiny, however, brings out the fact that whereas the hypothesis of spontaneous generation assumes the *sudden* formation *even today* of *complex* organisms, like rats and frogs, from non-living forms, the heterotrophic hypothesis upholds the *slow* evolution of very *simple* organisms from non-living matter under *special* environmental *conditions* which existed only billions of years ago.[2].

How were such heterotrophic organisms capable of obtaining their own food supply in the absence of autotrophic ones? To answer this rather difficult objection some clever assumptions have been proposed, particularly by two contemporary scientists, Haldane and Oparin. Other biochemists like Florkin, Calvin, and Ehrensvard have of late added their contribution of ideas to answering this and related questions. In spite of differences of opinion on matters of detail they show very close agreement on essential points. As Simpson points out[3] almost all biochemists today believe life on earth arose spontaneously from non-living matter. Such confidence is based on chemical experience which shall be briefly touched upon later on. Biological evolutionary processes, then, according to this modern conception of life, was preceded by *chemical* evolution. Schematically it may be represented thus:

Dissociated atoms → Micromolecules → Macromolecules
Precellular organisms → Cryptobiotic life → Exobiotic life

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[2] See G. Wald, "Innovation in biology", *Scientific American 199* (September 1958), 100-113.

[3] *Art. cit.*, p. 771.

During the first stage of chemical evolution the primeval hydrogen cloud originated in great abundance the elements of the Periodic Table[4] by a series of reactions: implosion, fusion, and fission. In the course of ages the highly reactive elements in this group combined to appear as "reduced forms", that is, as products of hydrogen. Methane, ammonia and water—all in the gaseous state—were therefore the basic ingredients, and together with free hydrogen made up the primitive atmosphere of our young earth. Methane or "marsh gas" (CH_4) is a colorless, odorless gas made up of four hydrogen atoms for every carbon atom. It is an example of a so-called "organic" compound. This group includes those carbon-containing substances that in earlier times were believed to be produced only by living organisms. The heterotroph hypothesis, on the other hand, assumes that such organic molecules existed on earth prior to the appearance of the first living forms.

Among the first experiments designed to test the assumptions of this hypothesis were those of Calvin and associates about thirteen years ago.[5] In 1951 they obtained significant amounts of formaldehyde ($HCHO$) and formic acid ($HCOOH$), two organic compounds, from irradiated water and carbon dioxide. Two years later, Stanley L. Miller, then a graduate student of Prof. Urey, performed an experiment which has become a milestone in the search for a solution of the genesis of earth life. At the time Urey was interested in the degree to which electrical discharges in the upper atmosphere may promote the synthesis of organic compounds. Under his direction Miller circulated continuously for a week a mixture of water vapor, methane, ammonia, and hydrogen. Notice that his raw materials were gases believed to be present in the primitive atmosphere of our earth. By the end of the week the water

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[4] The periodic table arranges the known chemical elements in a systematic grouping. Elements with like properties occur in related positions, as in horizontal or vertical sequence. In this way unknown elements can be deduced from their positions in the table. The elements are arranged in the order of increasing atomic number.

[5] W. M. Garrison, J. G. Hamilton, D. C. Morrison, A. A. Benson and M. Calvin, "Reduction of carbon dioxide in aqueous solutions by ionizing radiation", *Science 114* (1951), 416.

was found to contain a mixture of amino acids, and analysis by paper chromatography[6] revealed the presence of glycine and alanine, the simplest of amino acids, and the forms most prevalent in proteins.[7] Miller's experiment showed the possibility of a similar process having taken place in the early stages of emergent life on earth. Subsequent experiments were able to synthesize amino acids from simple starting materials by applying various forms of energy[8]. Energy in the form of heat, light, electricity, and alpha, beta, and gamma radiations broke up the chemical bonds of the primitive gases mentioned above and allowed the free atoms to recombine as amino acid molecules. These newly formed amino acids would then have been shielded from further changes in the vast expanses of ocean covering the earth.

Other investigators after Miller have worked in this field of duplicating primitive earth conditions in an effort to see whether they were favorable to the synthesis of organic compounds, and if so to what extent of complexity. Outstanding among them is the work of Prof. Sidney Fox of Florida State University and that of Dr. John Oro of the University of Houston, Texas. The investigations of Fox[9] have centered on the biogenesis of proteins and point to the possibility of obtaining protenoids by the thermal polymerization[10] of the

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[6] Paper chromatography is a method used in analytical chemistry to separate components of a mixture through their different affinities to adsorb on a porous substance like paper. The separated components can then be identified by the characteristic color they show after reacting with color-producing compounds.

[7] S. L. Miller and H. Urey, "Organic compound synthesis on the primitive earth", *Science 130* (1959), 245.

[8] S. W. Fox, *Organic Geochemistry* (New York: Pergamon Press, 1963), p. 36.

[9] S. W. Fox, "A chemical theory of spontaneous generation", *Aspects of the Origin of Life,* M. Florkin, ed. (New York: Pergamon Press, 1960), p. 148.

[10] Polymerization is the method in chemistry of producing large molecules (macromolecules) by a process of repetitive addition of the constituent units called monomers. These may be of the same or different sorts. Thermal polymerization forms polymers mainly through the application of heat energy.

18 amino acids. Proteins, we must remember, are the building blocks of living things and are giant molecules formed by the combination of amino acid molecules through the medium of the peptide link, the whole process being known as polymerization. In his experiment Fox heated a dry mixture of amino acids to temperatures sufficient to vaporize water; on cooling it he found that many of the amino acids had bonded together to form more complicated compounds. These complicated molecules he found to be very similar to proteins and therefore he called them "protenoids." These protenoids were found to have a tendency to form "microspheres" with dimensions in the bacterial range. Oro, for his part, has been able to synthesize adenine, a component of nuclear materials in cells, as well as biochemical intermediates of purines, also found in cell nuclei. These substances have been obtained by Oro from a simple organic compound, ammonium cyanide.[11]

At the Exobiology Laboratories of the National Aeronautics Space Administration in California, Dr. Ponnamperuma and his associates[12] are using various types of energy known to have existed in the primitive earth. The components of the primordial atmosphere are being subjected to the action of ultra violet light, electric discharges, ionizing radiations, and heat. Aside from attempting to synthesize in this way amino acids and the main constituents of proteins, the group is also attempting to form large molecules by polymerization.

> The results we have obtained so far are indeed very encouraging. Starting with primitive atmospheres, we have been able to synthesize several constituents of the nucleic acid molecule—the purines, adenine, and guanine, the sugars ribose and deoxyribose, the nucleoside adenosine and the nucleotide adenylic acid... Published results from several

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[11] J. Oro in *Annals of the New York Academy of Sciences* 108 (1963), 64. Lowe and his associates have reported that if we assume the existence of appreciable amounts of ammonium cyanide in the primitive earth, complex organic substances and macromolecules can be synthesized from it as one of the raw materials. See C. U. Lowe, M. W. Rees and R. Markham, "Synthesis of complex organic compounds from simple precursors", *Nature 199* (1963), 219.

[12] C. Ponnamperuma, C. Sagan and R. Mariner, "Synthesis of adenosine triphosphate under possible primitive earth conditions", *ibid. 199* 222.

laboratories thus demonstrate that the first and second stages of chemical evolution, namely, the inorganic and organic, can be satisfactorily retraced in the laboratory.[13]

Dr. Harada and Prof. Fox have likewise succeeded in synthesizing 14 of the common naturally occurring amino acids by using heat energy alone and an atmosphere duplicating that of primitive times.[14] Thermal energy alone had not been tried before because of the belief that it would not be enough to produce primordial synthesis. Harada and Fox, however, found thermal energy sufficient to effect multi-condensation of amino acids so as to yield some 18 of them. Moreover, this thermal energy brings about the formation of hydrocyanic acid, HCN, from two gases of the primitive atmosphere, methane and ammonia:

> In summary, simple gases are thermally convertible to most of the amino-acids common to protein in a way that is sequentially compatible with other aspects of the thermal theory of biochemical origins.[15]

Prof. Fox has also demonstrated experimentally[16] the possibility that amino acids polymerize and produce microspheres even in an environment of volcanic origin and in the presence of volcanic lava.

Thus, in our exposition of the possible development of living forms from biochemical precursors, we have reached the stage in which today duplicated laboratory conditions of primitive atmospheres have yielded synthetic macromolecules such as nucleosides and nucleotides from micromolocules like methane, ammonia, and water. The question now arises: How could such chemical compounds have joined together to form still more complex structures that would result in precellular organisms? One possible solution has been suggested by the Russian biochemist Oparin. He postulates the exist-

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[13] C. Ponnamperuma, "Chemical evolution and the origin of life", *ibid. 201* (1964), 340.

[14] K. Harada and S. W. Fox, "Thermal synthesis of natural amino-acids from a postulated primitive terrestrial atmosphere", *ibid.* 201, 335.

[15] *Ibid.*

[16] S. W. Fox, "Thermal polymerization of amino-acids and production of formed microparticles on lava", *ibid. 201,* 336.

ence of "coacervates," a word derived from the Latin word meaning clustered or grouped together. These coacervates are clusters of proteins or protein-like bodies, organized into droplets with the aid of a protective liquid environment. These protected droplets, under the influence of diffusion and the kinetic energy of the chemical molecules themselves, would collide with each other and surrounding organic materials to result in more stable and complex molecular structures. Coacervation, then, could have been a means not only of bringing together organic materials but of protecting them in the immense "hot dilute soup", as Haldane calls the primitive ocean conditions.

The experiments by Prof. Fox mentioned earlier substantiate Oparin's assumption, fòr under conditions simulating those of primitive times Fox observed that amino acids tend to string along together to produce proteinoids, amino acid chains resembling very much protein bodies. Using energy like that present in the primitive earth he found out that these complex chemicals tend to form still more complex biochemical bodies clustering as microspheres.

Aside from the energy the coacervates possessed from their surroundings in the form of heat, light, and electricity, they also in the course of their development utilized intramolecular energy, namely, that supplied by the chemical bonds which link together atoms and molecules. Some coacervate-like systems began to use this chemical-bond energy to develop, sustain and improve their molecular organization. This organization of energy by coacervates with protein-like components may have been the first step in the development of the first living cells. In the course of time these energized structures were capable of releasing their energy by a process akin to that of fermentation. Fermentation as a process obtains its energy source from organic molecules, but in the absence of oxygen, the element we have seen to be scarce in the primitive earth. As these heterotrophs utilized organic materials of the surrounding oceans they also acquired the capacity to transport them across the cell membrane.

The heterotroph hypothesis at this point may seem to some to have reached the end of the line, for we have reached the borderline between life and non-life and a definition of "life" should be forthcoming. Unless some notion of life is given it is most difficult to explain how those precellular biochemical structures made the jump to living cellular organism. The proponents of the heterotroph hypothesis, like all others working out a solution to the problem of life genesis on earth, modestly admit that an apodictic reply cannot be expected. At present all we can do in this regard is to suggest a possibility. Probably certain combinations of molecules within the coacervates would be more stable than others, thus enabling them to survive. Eventually, after long stretches of time, certain molecular combinations would produce reactions that gave off energy within the coacervate, thus stabilizing its internal environment, and creating conditions favorable to self-activity. Self-activity is one manifestation of living forms, but not the only one. The description of "living form" becomes more difficult the closer living and nonliving forms are to each other structurally and phylogenetically. It is not difficult, for instance, to distinguish life in such extremes as the horse and the tree, or even between an amoeba and a coacervate, but it is a puzzle still to distinguish a type of virus from true crystals. Some viruses are crystallizable, and may be preserved indefinitely in a laboratory vial without loss of activity. Others do not seem to be in need of food for energy purposes, and yet reproduce themselves. Are viruses then living organisms? The English biochemist Pirie summarizes the answer for us:

> Systems are being discovered and studied which are neither obviously living nor obviously dead, and it is necessary to define these words or else give up using them, and coin others. When one is asked whether a virus is living or dead the only sensible answer is 'I don't know'.[17]

The heterotroph hypothesis, rather than describe life in terms of a strict definition, subscribes to the idea that no sharp

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[17] N. W. Pirie in *The Microbe's Contribution to Biology,* A. J. Khuyver and C. B. Van Neil, eds. (Cambridge: Harvard, 1956), p. 162.

line can be drawn between living and non-living forms, and that life forms manifest a spectrum of increasing complexity from the viewpoint of structure. The Harvard biologist, Professor Wald, puts this question of the nature of life in a lighter vein:

> A curious thing about biology is that it flourishes as science of life without attempting to define it... What biologists do about life is to *recognize* it. If that seems slipshod procedure, I beg the reader, try to define your wife. You have no trouble recognizing her; I think you will grant the operation to be accurate and unequivocal. But define her? Well, that's the way it is with biologists and life.[18]

We shall conclude with four observations, the first three being attempts to answer some more objections against the heterotroph hypothesis. How was it possible for the organic syntheses required in the formation of micro and macromolecules to take place without the presence of catalytic substances called enzymes? We know that today's biochemical processes do need the presence of such reaction accelerators. This objection poses a dilemma, since enzymes are themselves proteins and consequently among the most complex components of living cells. The objection then would postulate the existence of a complex apparatus to exist in the cell even before the first cell is formed.

The objection vanishes when we recall that an enzyme is only a catalyst. All it does is change the *rate* of the biochemical reaction. It does not make anything occur which would not have happened without its presence. Without an enzyme as catalyst the biochemical processes would have taken place just the same, but at a tremendously slower rate. During those primeval times, however, time was not at a premium. Millions of years rolled by and things took them in their stride.

The second objection can be put this way: all these organisms postulated by the heterotroph hypothesis, whether molecular, precellular, or cellular, are all highly perishable. Even granted that during the long expanses of prehuman time now a carbohydrate molecule, now a protein molecule might

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[18] G. Wald, "Innovation in biology", *Scientific American 199* (September 1958), 110-111.

be formed, each of these molecules has only a transitory existence. How were they ever to accumulate, amid such perishability, and thus form an organism? In reply we are told that the stability of such organic substances was assured by a twofold preservation, from decay and from oxidation. They were preserved from decay by non-contamination with the cause of decay, namely, living organisms themselves. This possibility is, of course, most consonant with the heterotroph assumption that prebiotic forms preceded the emergence of living forms. Those organic substances were, likewise, preserved from oxidation because, in the opinion of geologists and astronomers today, the early earth atmosphere was oxygen-free. Oxygen existed then in "bound form", that is to say, as the oxide of hydrogen and metals. The same is true of carbon dioxide. It is believed today that most of the carbon on the earth during its early geological history existed as the element or in the form of metal carbides and hydrocarbons. This absence of free oxygen in the primitive atmosphere and the abundance of free hydrogen had also another beneficial effect on these prebiotic organisms. It allowed the high-energy sunshine helpful in the synthesis of amino acids to reach the earth's surface unobstructed by an oxygen shield, at the time it was most needed on earth. Our atmosphere seems to have contained no oxygen until living organisms placed it there by means of plant photosynthesis. Here we have a good illustration of how living organisms themselves can modify the physical environment, rather than adapting themselves to their surroundings.

The third objection has to do with a process of equilibration. We have just said that any process catalyzed by enzymes can occur in time without the enzyme. But the trouble is that organic reactions are reversible, that is to say, any chemical reaction catalyzed by an enzyme may go either forward or backward. What we truly achieve by time in these biochemical reactions is not completion but equilibrium, specially between two forces, synthesis atnd dissolution. Moreover, in the great majority of these processes the point of equilibrium lies far toward the side of decomposition, so that there is much more probability for spontaneous disintegration to occur than spontaneous generation, let us say, of protein or amino acid molecules. Today organisms manage to move the point of equilibrium toward synthesis only by the continuous expenditure of energy usually at great cost to their own surroundings. In terms of thermodynamics this means that the living organism acquires negentropy (negative entropy).[19] It must therefore produce a less random organization of its matter content and must also be capable of storing and replicating information, and this replicated information must eventually form part of the development of a new individual system like that from which it came. We can see, therefore, that this third objection is not by any means well understood and it also assumes the existence of forces still barely grasped by us.

We know that it is possible to protect molecules from disintegration by precipitation or by aggregation to other molecules. Modern biochemistry uses a good many of these precipitation and "trapping" reactions to foster syntheses. Some molecules simply by increased size seem to acquire a certain degree of resistance to dissolution. To illustrate, polypeptides and proteins, built up of amino acids, reveal much less tendency to disintegrate into their component units than do smaller compounds constituted of two or three amino acids. Moreover, many organic molecules have a second type of integrating force, a spontaneous impulse toward structure formation. Lecithins and cephalins, for instance, which are types of fatty molecules, spin themselves out in water forming well-shaped structures known as myelin figures. Myelin, by the way, is the fatty substance enveloping the nerve fibers, and acts much like the insulation in electric wires. The destruction of this myelin sheath results in the disease known as multiple sclerosis.

We are thus insinuating that *intra*molecular forces of dissolution may be opposed and contained by *inter*molecular ag-

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[19] Entropy is a thermodynamic function which describes quantitatively the disorder of molecular states. The second law of thermodynamics in its most generalized form states that all processes in nature tend to occur only with an increase in entropy. A more disordered state has a higher entropy than an ordered state.

gregations of various kinds. Although, therefore, the equilibrium between union and disunion of amino acids making up proteins is all to the advantage of disunion, yet the aggregation of the protein with itself or with other molecules might swing the equilibrium towards the formation of larger aggregates. Under such a scheme the protein would appear as an intermediate:

amino acids → protein → aggregate

Our final observation has to do with a few implications of those experiments and the heterotroph hypothesis. May life, then, be ultimately created in a test tube? Are we on the verge of producing a synthetic man? No scientist worth his salt would bother to answer such questions. The imaginary world that can be built up on the data and assumptions such as we have presented belongs to the domain of the science-fiction writer.

However, biopoesis, or modern spontaneous generation, at present does sound a feasible hypothesis. Its proponents, in the true scientific spirit, are not in any way dogmatic about their assumptions. They advance it as one *possible* and *probable* answer to the problem of the genesis of life on earth, but by no means deny that for the present it is a tentative solution showing more and more promise and consequently requiring further study. The hypothesis certainly brings us closer to the material causes of life on this planet and ought not necessarily contradict the revelation given in the sacred Scriptures[20]. Chemical evolution, moreover, may be a means of understanding better the theological truth that conservation is continued creation, and that divine activity *ab extra* is coordinated throughout all eternity. The hypothesis gives us indeed new intimations of order and harmony in the work of creation.

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[20] O. W. Garrigan, "The origin of life on earth", *The Catholic World 198* (February 1964), 286.