

Biodata of **Luísa Pereira**, **Telma Rodrigues**, and **Francisco Carrapiço**, authors of “*A Symbiogenic Way in the Origin of Life.*”

Luísa Pereira was born in Lisbon, Portugal (1969) and has a B.Sc. in Biology and Geology (Education) from the University of Lisbon (1996). She teaches at the secondary school Fernando Lopes-Graça, Parede (Portugal), and in 2009 obtained a Master Degree in Earth and Life Sciences. In 2006, she attended the “6th European Workshop of Astrobiology (EANA’06)” in Lyon, France. Recently (2009), she was an invited speaker at the international conference “Evolution today and tomorrow, Darwin evaluated by contemporary evolutionary and philosophical theories,” organized by the Center for Philosophy of Sciences of the University of Lisbon, where she presented a communication on the post-neo-Darwinian approach to the origin of life.

E-mail: luisamadalena@gmail.com

Telma Rodrigues was born in Lisbon, Portugal (1977) and has a B.Sc. in Biology and Geology (Education) from the University of Lisbon (2000) and a Master Degree in Earth and Life Sciences from the same university (2005). She is currently a teacher at a secondary school in Portugal (Dr. José Afonso, Seixal), and simultaneously, she has been developing several projects in astrobiology education and public outreach. She has been responsible for the Astrobiology Project at the same school for the past 5 years. She also has participated in several congresses on astrobiology in Europe and the United States, enhancing the role of education and public outreach in the studies of the origin of life.

E-mail: telmarodrigues@oniduo.pt



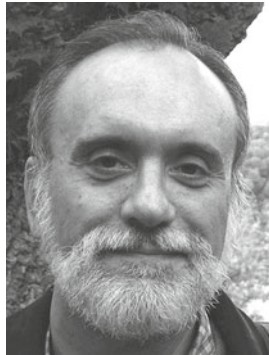
Luísa Pereira



Telma Rodrigues

Dr. Francisco Carrapiço was born in Lagos (1951), Portugal, and has a B.Sc. in Biology from the University of Lisbon, a Ph.D. in Cell Biology (1985) from the same university, and a postdoctoral from the Arizona State University, USA. Assistant professor at the Faculty of Science of the University of Lisbon, and researcher at the Center for Environmental Biology, his main field of research is Symbiomics, namely, the *Azolla-Anabaena*-bacteria symbiotic system. He has been involved in several projects in Portugal, Europe, Africa, and Latin America. He is also doing research work on the post-neo-Darwinian perspective of evolution, with emphasis on the origin of life and in the symbiogenic approach to this evolutionary process. He also has participated in several congresses on astrobiology in the United States and Europe, focusing on the topic of symbiogenesis and the origin of life.

E-mail: fcarrapico@fc.ul.pt



A SYMBIOGENIC WAY IN THE ORIGIN OF LIFE

LUÍSA PEREIRA¹, TELMA RODRIGUES², AND FRANCISCO CARRAPIÇO³

¹*Escola Secundária Fernando Lopes-Graça, 2775-200 Parede, Portugal*

²*Escola Secundária Dr. José Afonso, 2840-268 Seixal, Portugal*

³*Departamento de Biologia Vegetal, Faculdade de Ciências, Centro de Biologia Ambiental e Centro de Filosofia das Ciências, Universidade de Lisboa, 1749-016 Lisboa, Portugal*

1. Introduction

The scientific question relating to the origin of life remains, so far, without a consensual answer. The advanced theories essentially highlight a Darwinist or neo-Darwinist approach to the problem, preventing a more global and comprehensive overview, which could be made possible through consideration of other principles, namely symbiogenic ones. The notion of a dynamic and systemic Earth, with natural interdependent and interrelated subsystems, with life in all environments and ecological niches, even in the extreme ones, reveals an evolution of life in close relation with the primitive Earth's geochemical contexts. Under extreme and adverse environmental conditions, life chooses cooperative and synergistic strategies, establishing symbiotic relationships. The extremophile organisms, besides broadening the limits of the known life, instigate new reflections about life beyond Earth. Astrobiology is a privileged eye scoping the very dimensions of the origin, evolution and distribution of life in the Universe. The study presently being carried out, which concerns, among others, extremophile organisms and the search for earthly extreme extraterrestrial environments, analogous to the primitive ones on Earth, is of high importance. Besides characterizing the Earth's primitive environments, it also reinforces the exogenous models of the origin of life.

2. Symbiogenesis, the Stepson of Evolution

In the nineteenth century Louis Pasteur raised the fascinating question of the historical origin of life: "Because life can originate only from preexisting life, it has a history and therefore an origin, which must be understood and explained by chemists" (Brack, 2007 in Horneck and Rettberg, 2007, 2). Also, in 1859, Charles Darwin proposed his theory of evolution by natural selection, explaining the origin of all species without the intervention of any supernatural power: current living beings resulted from a long biological evolution, beginning with a very

primitive and simple organism. Darwin also developed an approach toward the origins of life and, in 1872, advanced a natural solution based on a prebiotic chemical evolution, considering also the nature of the basic processes involved. Thus, abiogenesis was necessary for an evolutive conception, considering all inanimate matter and life a historical *continuum*, and explaining the emergence of the initial organism(s) (Fry, 2000). Despite Darwin's ideas, it was only in the twentieth century that evolution seriously entered into scientific studies on the origin of life.

Aleksandr Oparin and John Haldane established the guidelines of investigation for the field in the first two decades of the twentieth century. Since then those guidelines remained the main theoretical framework for the majority of models on the origin of life. Their hypothesis and almost all of the life's origin and prebiotic chemistry studies are divided into two contrasting hypotheses: metabolism first or replication first. Until now all research was based on classic Darwinian principles, guided by a strictly competitive and gradual evolution, without any cooperative or synergistic involvement. The Darwinian and neo-Darwinian perspectives have, so far, dominated the scene, but it is clear that they are not able to explain all the mechanisms and processes of evolution (Carrapiço et al., 2007).

Several contradictory solutions and many open questions emerge from the current models on the origin of life. The analysis of the current models and of the recent astrobiological data show underlying difficulties or dilemmas: metabolism *versus* replication, gradual *versus* saltitatorial process, the smaller time window currently accepted for the emergence of life, endogenous *versus* exogenous building blocks of life, the processes and constraints of the prebiotic chemistry, single *versus* multiple events and terrestrial *versus* extraterrestrial origin.

Oparin and Haldane's first scientific proposal is usually considered as the main source for the development of modern thought considering the origin of life, but in the beginning of the twentieth century, the Russian biologist, Constantin Merezhkowsky made a proposal for a natural origin of life, under the extreme conditions of the primitive Earth. Merezhkowsky was the founder of the symbiogenesis concept in 1909, defined as "the origin of organisms by the combination or by the association of two or several beings which enter into symbiosis" (Sapp et al., 2002, 425). He also highlighted the importance of extremophiles and extreme environments in the early stages and evolution of life. Since then, several authors, have made some innovative approaches including symbiogenic evolutive principles, and highlighting the symbiogenesis significance as a source of evolutive novelty: Barricelli (1957, in Fogel, 2006), Dubos and Kessler (1963), Dyson (1985, 1998), Chapman and Margulis (1998), Margulis (1999), Taylor (1999), Antonelli et al. (2003), Sapp (2003, 2004), Roossinck (2005, 2008), Carrapiço (2006), Ryan (2006), Bouchard (2007), Gontier (2007), Reid (2007) and Watson (2007).

Kutschera (2009a) suggests that Charles Darwin originally employed the term "struggle for life" with two meanings: *competition* but also *cooperation*. It was Heinrich G. Broon, a German paleontologist, who translated Darwin's metaphor exclusively into terms of *competition*. Kutschera's claim is supported by the fact that in a dictionary from 1893 the term *concurrency* used by Darwin had

several meanings, ranging from competition to cooperation. In this way, the term *concurrency (struggle for life)* would include competition but also cooperation. Kutschera (2009b) suggests an integrative model of macroevolution, where the Earth's systemic dynamics were responsible for the creation of new habitats and ecological niches. In a global scale, he considers wide environmental changes as responsible for an adaptative evolution, via directional selection. Symbiogenesis, natural selection, and the dynamic of the planet were the key factors causing and determining the course of evolution in an ever-changing Earth. The author considers that this aspect of reality was not considered either by Darwin or by the synthetic theory authors. Kutschera's ideas are also supported by Corning (2005), who considers the theory of evolution by natural selection a functional one, including functional effects (adaptations) of all kinds, and at various levels of the biological organization. This author argues that the functional effects produced, for instance, by an independent set of genomes, as symbionts or coevolving species, with the contingencies of survival and reproduction constitute the directive aspect of natural selection. The notion of "competition via cooperation" is a very important one, because those who cooperate best compete more successfully. Corning (2005) considers the synergies resulting from various kinds of cooperative interactions to be responsible for the evolutionary trend toward greater complexity. In his opinion, several authors recognized that symbiotic and cooperative relationships could provide, under some circumstances, a competitive advantage, to which we add, particularly in the extreme conditions of the primitive Earth. In 1995, the same author considered that complexity should be correlated with the functional synergies it produces.

Considering the role of synergies in the evolution of complexity, we must now turn to symbiosis. Anton de Bary (1878) presented the symbiosis concept as "the common life of different organisms." According to Dubos and Kessler (1963, 8) symbiosis must be considered as a creative manifestation of a general biological phenomenon where "...More remarkable is the fact that many symbiotic systems produce substances and structures that neither one of the two components produces when growing alone." In symbiotic relationships, the central aspect is the creation of evolutive novelty (metabolic, anatomical, and organismal), and the association depends not only on the intrinsic symbionts properties but also on the internal and external system environmental conditions (Carrapiço, 2006). Symbiosis is a robust phenomenon, offering many opportunities for ecological niche occupation in ways that would otherwise be unviable, and also for having highly relevant survival propensities (defense, protection, nutrition, motility, reproduction, communication). We believe symbiosis meets the criteria necessary to overcome the obstacle raised by Theodosius Dobzhansky, who in 1962 stated that "no theory of evolution leaving the mystery of adaptation unraveled should be acceptable" (Corning, 1995, 102). For Corning (1995), the synergies associated to symbiosis perform a leading role in complexity evolutions, being involved in first living organisms' emergence, in primitive prokaryotes mergers, and in the "progressive" temporal coevolution of aquatic and terrestrial ecosystems.

Symbiosis established a new vision of the organism and of evolution, markedly different from the neo-Darwinian view, and was contextualized by symbiomics, a new multi-transdisciplinary evolutive science field with contributions from biology, biochemistry, physiology, genetics, ecology, and evolution of biological systems and their interfaces. It places symbiogenesis in the evolutive context of a post neo-Darwinian perspective (Sapp, 2003), and before it, as a principle of evolution developed by Boris Kozo-Polyansky in 1924 (Kozo-Polyansky, 2010). The concept of symbiogenesis underlines the central role of interactions, in which individuality (new entity) emerges through incorporation (Margulis, 1999 in Carrapiço et al., 2007). Symbiogenesis will be the evolutive mechanism and symbiosis the vehicle through which that mechanism unfolds (Margulis, 1990; Carrapiço et al., 2007). It involves horizontal mergers, which can be rapid, and, usually, discontinuous, creating permanent and irreversible changes, forming the basis for evolutive novelty. Something new arises through merging, resulting in a unique or new metabolism or structure(s), which were not present before symbiosis. Thus, a new entity reveals behaviors previously unobserved in the separate components. The new entity can evolve vertically, but is always preceded by a horizontal merger between two or more entities (Gontier, 2007). Symbiogenesis states that the most probable cause for unexpected complex structures (dead or alive) lies in the association of lesser complicated parts (Dyson, 1997). The evolutionary changes can be explained by an integrated cooperation between organisms, where symbiosis acts as the rule in nature (Carrapiço, 2006).

Corning (2005) also argues that symbiosis has provided many opportunities for organisms to occupy ecological niches that otherwise would not be viable, and that symbiosis typically precipitates the coevolution of various facilitative adaptations, and that frequently involving more than two species. The author mentions three consequences of symbiosis for the science of complexity: fusion via symbiosis as a major mechanism of complexification, evolutionary complexification via fusion includes behavioral dynamic changes that precipitate new options for selection, and the coupling of separately evolved genomes creates a new selective unit that may or may not compete directly with other organisms.

3. A Symbiogenic Way to the Origin of Life

A new approach and vision are needed to solve this paradigm. Studies on the origin of life must focus on the physical and chemical principles and naturalistic mechanisms guiding and constraining its emergence. We must use both bottom-up and top-down approaches, and rely on data from several scientific fields, such as geochemical and geophysical data concerning primitive and nowadays' Earth and Solar System, fossil records, current Earth system dynamics, data from living forms interrelations and interdependencies, and the comprehension of the characteristics of complex living systems, among others. This will provide us with a more coherent picture for the understanding of the mechanisms that rule the evolution

in nature. We believe metabolic and genetic models explain the different aspects. We must look for the common processes and principles that ruled the prebiotic evolution and question how evolution proceeded in such adverse environmental conditions. We developed our proposal for a symbiogenic understanding of the origin of life based on three perspectives: the consideration of other evolutive mechanisms that would account for a more rapid evolution, the symbiogenesis theory; the leading role of astrobiology, and the notion of a systemic and dynamic planet Earth (Carrapiço et al., 2007).

How can we apply the symbiogenesis theory in order to improve our understanding of the origin of life, and its initial evolution? The symbiogenic concept allows an innovative approach to the origin and evolution of life, with applicability to life's initial stages, and capable of being a fundamental rule in life's establishment and development on Earth and elsewhere. We suggest a naturalistic explanation for the origin of life, through the evolution of complex and adaptive systems, with synergistic, cooperative and symbiogenic mechanisms, guiding chemical evolution through its constraints (Carrapiço et al., 2007). At the turn of the twenty-first century, proposals for universalizing symbiogenesis as an evolutive mechanism were advanced. As far as we know, the first proposal was made by the astrophysical Freeman Dyson, in 1985 (Dyson, 1998). More recently, Gontier (2007) developed the universal symbiogenesis concept. This author considers symbiogenesis as offering a complementary view of evolution, allowing cooperative and synergistic approaches. Gontier (2007) considers a universal and neutral framework for symbiogenesis. "Universal Symbiogenesis is the process whereby new entities are introduced because of interactions between (different) previously independently existing entities. These interactions encompass horizontal mergings and the new entities that emerge because of this are called symbionts. The process is irreversible and discontinuous (...) after symbiogenic processes have occurred, this newly evolved entity can again become the subject of selection" (Gontier, 2007, 174).

We believe this definition allows different phenomena to be regarded as symbiogenic, and that universal symbiogenesis provides us with a general analytical tool for the immense interactions among different entities, namely the prebiotic and biotic entities. The symbiogenesis concept, through universal symbiogenesis, can be applied to the prebiotic evolutive context, beyond the biotic one, as a new paradigm shift in evolution (Carrapiço et al., 2007). The science of complexity defies the selectionist hegemony, by arguing that such a long-term trend toward increasing complexity suggests the presence of additional mechanism(s) and Corning (2005, 94) shares this opinion when he argues: "The evolution of complexity has seemed to require something more than the random point mutations in an amorphous 'gene pool'. The long term toward greater complexity (...) seems to suggest the presence of some additional mechanism or mechanisms."

One main characteristic of the living world is that entities in varied combinations are prodigious novelty generators. Synergies of several kinds have a creative role in evolution, being a source of evolutive novelty. The functional

advantages associated with synergistic phenomena constitute a common functional principle as well as a cause for the complex functionally organized systems in “progressive” temporal evolution (Corning, 1995). So, symbiosis is a factor of evolutive change, giving rise rather suddenly to evolutionary novelty, challenging, in our point of view, the Darwinian and neo-Darwinian competition and gradualism (Carrapiço, 2006). Furthermore, synergy refers to the effects that parts (or individuals) cannot attain alone, being interdependent effects, resulting in different “wholes.” It resembles an “umbrella” for cooperative interactions, dealing with mutualistics and parasitic combinatorial effects, emerging from the aggregation of multiple incremental contributions of individual parts or organisms (Corning, 1995).

According to Watson (2007), symbiosis allows for the combination of pre-adapted genetic material enabling an evolutionary process, yet one algorithmically distinct from the Darwinian gradualist framework. In his opinion, there are different underlying algorithmic principles in evolution. Thus, we should expand the framework of evolution to include a greater range of algorithmic possibilities, and break the equivalence between evolution and gradualism. Using evolutionary computation the author shows that compositional evolution is capable of evolving certain kind of complex systems, specifically systems with modular interdependency that would be considered unevolvable under the gradualist framework. Correia (2010) has been developing interesting work in the area of computational evolution. According to the author, evolutionary algorithms (EA) have been used to model and study evolution, using different common evolutionary algorithm models. Some of the models are biologically inspired, including coevolution and, in particular, symbiogenetics. For the author, another area of computational evolution, which has allowed us to study basic principles of evolution and ecology dynamics, is the development of artificial life platforms for open-ended evolution of artificial organisms. According to Dyson (1997), in the mid-1950s, Barricelli proposed a computational symbiogenic model for the origin of life. From his work, Barricelli concluded that symbiogenesis accelerated evolution, by displaying a parallel processing of the genetic code, allowing a more efficient search for the sequences propelling the individual, and species, to a higher level of complexity, the key for evolutive success.

According to Correia (2010), an evolutionary algorithm (EA) is a simplified computational model of evolution. The author considers the implementation of coevolution (competitive or cooperative) in standard models. In cooperative coevolution, there are differentiated species that cooperate. The symbiotic models are based on a strong mutual dependency of two species with different genotypes, and any solution is achieved only by collaboration, that is, symbiosis, which is based on individuals of each species. In the author’s opinion, symbiosis and cooperative coevolution in general tend to improve EA performance in difficult problems. According to Correia (2010, 187): “Symbiosis brings the possibility of simultaneous speciation of some symbionts and diversity through the choice of different symbionts available in the populations of the two types. Also, it provides

some sort of scaffolding, helping to produce individuals that are able to perform on their own the tasks of former symbiosis.”

The majority of autocatalytic and self-organized phenomena are also open to natural selection, with functional synergy being the bridge connecting self-organization and natural selection (Corning, 1995). Although several authors consider that self-organization and natural selection are opposed to one another, and that the first diminishes the role of the second, others considered that self-organizing systems are not organized by an external force; instead, they believe that the causal dynamics are internal to the parts or participants and their interactions (Corning, 2005). According to the same author, this does not present any inherent conflict with the Darwinian Theory, and natural selection can also be a party to synergistic autocatalytic processes. The author goes further when stating that (Corning, 2005, 103): “It can be party to discontinuous (...) symbiotic functional fusions. And it can be a party, as well, to novelties that create new niches and mitigate competition.” Therefore, self-organization is an undisputed fact, and autocatalysis is compelling, especially in the early stages of evolution.

In our point of view, competition and cooperation can coexist in the same scenario of evolution, and probably take place in terms of discontinuous bursts of activity, depending on the internal and external conditions driving evolution. The same population can evolve using competitive and/or cooperative processes in a hypercycle evolutive scenario. A series of synergistic and cooperative effects produced a wide source of creativity and functional advantages that pushed the emergence of complex and functionally integrated biological systems through the evolution of self-organization, self-catalysis and higher complexity. It was only after this biochemical evolution of structures, which gained informational capabilities necessary to self-replication, that the Darwinian competition arose. The complexification in evolution implies the production of new forms (entities) and more powerful synergies. In this context, symbiogenesis creates new important selection units (symbioma) arising through the integration of varied parts and progressive differentiation of the whole, implying a competitive advantage and going beyond the traditional neo-Darwinian units of selection (Carrapiço et al., 2007).

In Corning’s (2005) opinion, the order that arises through self-organizing processes probably took place prior to selection. The author believes that the products of evolution were themselves increasingly important co-designers over time, in an interactive process. Thus, and regarding biological complexification, the wholes are more fundamental biological entities than parts. This means that, in the earliest stages of evolution, the parts only had directional consequences and selective value when combined into functional units.

As we already proposed, a symbiogenic scenario could have been responsible for the development of prebiotic processes toward primitive cells. The notion that the synergies associated with symbiosis had a leading role in the complexification was also suggested by other authors such as King (1977), Dyson (1985), Popa (2004), Matthews (1994), Matthews and Minard (2003), Frank (1995), Lee et al. (1997), Fernando (2005), and Carrapiço (2006). We consider that the

symbiogenic approach to the origin of life can be associated with Freeman Dyson's hypothesis on the origin of life, which are based on symbiogenic concepts and invoke Lynn Margulis ideas. Dyson (1985) synthesizes the metabolic and genetic visions of life's origin, supported by symbiosis, and proposes a prebiotic evolution accomplished by the independent formation of metabolic systems and self-replicating molecules, which evolved together. In a certain time, the metabolic systems became encapsulated in primitive amphiphilic vesicles, and in a specific time some of the molecules were synthesized first as parasites and later as mutualists and underwent evolution together. Later, the primitive self-replicating molecules joined them, first as parasites and then later as mutualists.

Shenhav et al. (2003) proposed a metabolic system to store and propagate information (compositional information), considering it fundamental to overcome the dogma stating that any transfer information mechanism inferior to base-pair templating is implausible. The authors suggested considering a mesobiotic entity (with primordial molecular assemblies, devoid of long catalytic biopolymers or long informational biopolymers and endowed with molecular and ensemble complexity) embodying primitive features from metabolism and replication. We believe that these mesobiotic entities could be the result of a primitive symbiosis between primitive metabolism and primitive replication molecules, as initially proposed in 1985 by Dyson.

A double origin of life involving metabolism and replication, accomplished in multiple origins on Earth, suggests a metabolism carrying the compositional information, and a replication of sequential information. Symbioses of these two kinds of entities led to a hybridization of their informational content. In a double origin the self-catalyzed and peptide-based metabolic systems emerged through successive symbioses between abiotic components and self-replicating and autocatalyzed molecules. This way, life emerged as two kinds, as metabolism and as genetic information, combined in a symbiotic fashion. The basic organic monomers required different component materials integration. Also, complex polymers were based in monomers fusions. Corning (1995) also considers autocatalysis and self-organization as preceding mutations and the most fundamental novelty source in the formative stages of evolution. Our ideas for a symbiogenic scenario of the origin of life are also supported by Popa (2004) and Woese's (2004) works.

Popa (2004) considers two major symbioses involved in the emergence of life. The first molecular symbiosis in the evolution of life resulted from the association of a frontier (primitive membrane) with a reflexive activity, based in an association or mutual assistance between two distinct characteristics (entities). Metabolism emerges from the coupled entities between a self-assembly process and a reflexive activity that stabilizes it. The reflexive activity was established by different synergisms and mutualisms through autocatalytic cycles and hypercycles that several other authors propose as leading to symbiosis emergence. Eigen et al. (1979, 1981, in Corning, 1995), proposed the hypercycles to explain how organic substances with increasing complexity could overcome the "complexity catastrophe," an example of synergy in evolution. According to King (1977), autocatalytic

chemical systems arise spontaneously, in an irradiated aqueous medium. Self-reproducing chemical particles, of any complexity, in a proper environment, have self-regulating properties, allowing for long-term survival. The environmental loss of materials, leading to continuous system decay, can be overcome through physical unions (symbiosis) involving different self-reproducing particles. Those unions create an increasing and irreversible complexity, leading to evolution in the chemical system. The author suggests an evolution through spontaneous successive symbiosis. Thus, successive prebiotic symbioses changed simple autocatalytic particles in this way to primordial cells. According to Fernando (2005), if in a self-reproducing and autocatalytic cycle, with a fundamental organization, two previously independent autocatalytic replicating entities establish a physical union, still capable of autocatalysis, and with a low decay rate, then symbiosis can still be viable in an environment with scarce resources, even if the symbiont growth rate is slower than any of the component parts. The failure in establishing symbiosis can result in deficits, and will be a central problem for metabolism and template replication origins. Bouchard (2007) argues that a careful examination of the evolutionary strategies found in many obligate symbiotic associations validates a view of fitness that is not to be understood in reproductive terms, but in ecological ones. He suggests that complex symbiotic systems can have an emergent fitness value described in terms of differential persistence of the community. In our opinion this vision of persistence is in agreement with the symbiotic relation importance in the withstanding of extreme environmental condition and novel ecological niches occupation (Carrapiço et al., 2007).

We believe in abiotic peptides that assisted a symbiosis with nucleic acids, leading to a primitive translation apparatus emergence. This way, encapsulated entities, analogous to modern cells emerged, based on a nucleic acid organization. According to Woese (2004) an imprecise and primitive small primordial genome replication emerged, with simple and primitive cellular designs, of modular nature, permissive and ill-defined, subjected to an unrestricted Horizontal Gene Transfer (HGT). This HGT would not disturb cellular organization to collapse. The components with certain form/function could be replaced by rough equivalents, the primitive representatives of some of the actual specific enzymes that could have only a specific class reaction. This is a period of ephemera organismal genealogy. For the author, these primitive cells had an essentially communal evolution, with a reticulate and cooperatively collective pattern of evolution. At which point we add hybridization, symbiosis, and synergisms, being the base of a multileveled communication world. This way of looking at the emergence of life supports the notion of multiple origins in strait correlation with the geochemical contexts, natural constraints, and environmental conditions. The progenote proposed consisted in an open community of very diverse primitive cellular entities with intense symbiotic associations, antagonisms, and competition, and with a rapid and reticulate pattern of evolution. Another piece of evidence for the widespread nature of these initial and universal synergistic and cooperative interactions, through symbiogenic mechanisms, can be found in microbial mats and

stromatolites. The latter forms one of the first examples of a communal ecological strategy, based on cooperative and synergistic mechanisms, for surviving in the primitive Earth extreme environmental conditions (Carrapiço et al., 2007).

An experiment dealing with symbiotic organisms' survival in space conditions showed that symbiosis, together with synergistic and cooperative principles, is a useful and power strategy for survival in extreme environmental conditions. Experiments performed in the BIOPAN-5 facility, in the European Space Agency (ESA), studied the lichen *Rhizocarpon geographicum* survival fitness when facing space conditions. Ascaso et al. (2006) believe this kind of symbiotic organism could represent model organisms for interplanetary transference. Although they observed several ultrastructural changes, they conclude that fungal and algal cells survive in space conditions. Another example of how symbiotic relations can allow the survival and thriving of life in extreme environmental conditions can be seen in the marine invertebrate *Riftia pachyptila*, a giant tube worm (Annelida) found in the hydrothermal submarine vents.

We are convinced that an origin and initial evolution of life approach should include the symbiogenic perspective, in a more communicational sense. Communal synergistic and cooperative strategies certainly occurred in prebiotic evolution. The symbiogenic approach to the emergence of life contributes to the development of the astrobiological knowledge, as it is able to provide innovative perspectives on the study of life's appearance and development on Earth and elsewhere. We agree with Trainer et al. (2006) that life is an emergent and global phenomenon on Earth and not an isolated one, occurring in a specific place. We think it was also a naturalistic process that occurred in several places and times, in a quick step-by-step process with evolutive jumps within a small geological "time window." Its emergence was subject to physical-chemical constraints, intimately correlated with different geochemical contexts and environmental conditions. The symbiogenic universal principals favored an increasing and irreversible diversity and complexity, in balance with the primitive Earth's natural conditions. It was also supported by self-assembly, self-catalysis, liquid water, and basic organic compounds. According to Lehto (2007), we can conceive several locations for the different emergence steps toward life as being locally or temporally separated. This way, several of the different scenarios proposed for life's origin by different theories could be integrated in a convergent approach to the problem (Carrapiço et al., 2007).

Our planet can be considered as an open ecological system, with natural subsystems (lithosphere, atmosphere and hydrosphere), also open and interdependent, with constant exchanges of matter and energy between them and the universe, which evolve and cooperate in order to keep Earth in a dynamical equilibrium. We must consider that this dynamic planet functioning was also present in the primitive Earth. The fourth natural system is the biosphere; it crosses all the others and is supported by their interactions. In contemporary Earth, we observe an immense diversity, biological and environmental, with huge facets, interactions, synergistic phenomena, and antagonisms, in a variety of environmental conditions, some of which are considered extremes. Certainly, in the

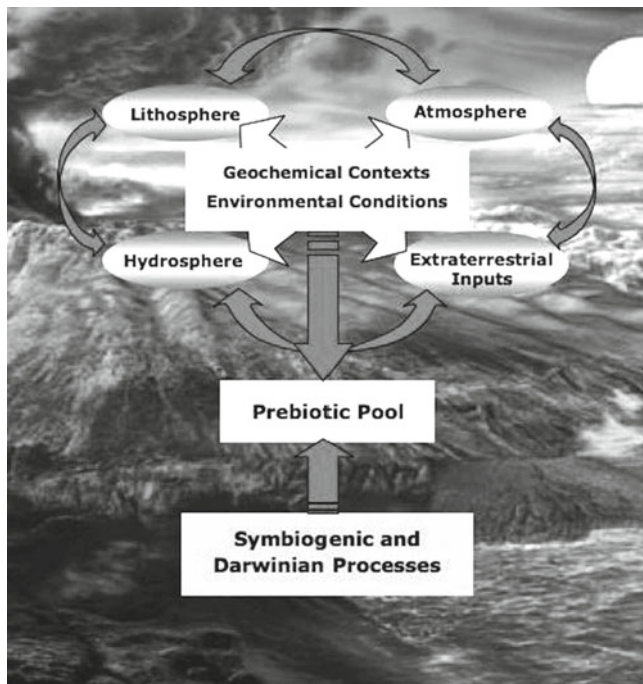


Figure 1. Diagram of the possible interactions within the primitive earth prebiotic environment (Carrapiço et al., 2007). (Backup image adapted from http://www2.uol.com.br/sciam/imagens/materia/abre_terra.jpg).

primitive stage, diverse chemical transformations and interrelations between the natural systems also occurred, with important transition phases in their interfaces, translating their current interdependencies (Fig. 1).

The three natural Earth subsystems, synergistically with extraterrestrial sources, provided an abundant input of organic compounds to prebiotic evolution. We assume a diverse reality in the primitive Earth, with different environmental characteristics, and multiple ecological niches, with different organic compounds concentrations. Several authors have already suggested some possible locations for the emergence of the first living systems, namely volcanic fissures, mineral superficies, deep sediments, shallow lagoons, hydrothermal vents and springs, intertidal zones, and ocean surface, aerosols surfaces, and in the subsurface. The existence of several changing habitats in the prebiotic Earth, with semi-permeable geographic frontiers, posed environmental challenges that resulted in increasing complex and diverse entities. So, cooperative, synergistic and communicational processes were responsible, using terrestrial and extraterrestrial materials, for the creation of a large prebiotic pool, closely related to geochemical contexts and environmental conditions, and with intense interactions within.

According to Woese (2004) we also believe in life's emergence being accomplished through multiple origins, in different times and environments, displaying a variety of selective contexts, which optimized symbiogenic processes in the promotion of creative novelty (Carrapiço et al., 2007).

4. A New Starting Point?

The symbiogenic approach within an astrobiological context is based in several tenets. A currently debated question is the definition of life. According to *The Astrobiology Primer* (2006), a definition of life based only in extant living forms fails in not considering earlier life forms that preceded current cellular life. Also, NASA's definition of life only considers evolution through competitive processes, excluding symbiogenic processes, and thus not reflecting the natural world's reality. The majority of scientists agree that no single parameter can, by itself, define life, as life emerged from multiple mechanisms acting in concert. According to Kolb (2007), to define life as a phenomenon, we must understand its origin and evolution from abiotic matter, through RNA World and Last Universal Common Ancestor (LUCA). We agree, but we also believe, like Popa (2004, 3, 5, 13, 158), that for the understanding of life as a phenomenon we must consider that life is a complex system, far from equilibrium, delimited from exterior by a frontier, with vast information, with capabilities of self-assembly, self-catalysis, self-organization, self-reproduction, and evolution. It has a metabolism in its own right and homeostasis. It fights against dynamical equilibrium, and uses external sources of energy and nutrients. Its functioning is based in antagonisms, but also in synergistic and cooperative principles, as living beings establish associations and communicate with others.

We believe this proposal for a symbiogenic origin of life has the ability to overcome several of the difficulties highlighted previously. It is a possible way to articulate different theories, valid in specific Earth contexts, and is supported by natural processes, reinforcing the role of the extraterrestrial contributions to the prebiotic chemical pool on Earth, deals with the metabolism-replication dilemma, and puts different primitive environmental conditions in close relation with the existent geochemical contexts. These lines can guide future work, but for that it is necessary to adopt a more cooperative and communicational approach underlying a multidisciplinary scientific work, the reconsidering of positions concerning this field, and the time and place to give, with an open mind, more coherence and meaning to all the work done until now (Carrapiço et al., 2007).

Where to look for future answers? It would appear to be necessary to dedicate more time to the detection of extraterrestrial life, new prebiotic chemistry experimental work, to embrace artificial life studies, and computational simulations with a symbiogenic perspective, extremophile studies, and space exploration. In 2000, Fry said: "It is plausible to speculate that the weight given in the

future to metabolic versus genetic models will be largely decided by experimental work.” Ten years later, we are facing a possible starting point to the beginning of a new era in the studies on the origin of life. An era that probably will result, according to the Gibson et al. (2010), in a better understanding of the nature of life itself. These authors were responsible for the creation of a bacterial cell controlled by a chemically synthesized genome. The authors designed, synthesized, and assembled a genome starting from digitized genome sequence information and its transplantation into a *Mycoplasma mycoides* cells that were controlled only by the synthetic chromosome.

Gibson et al. (2010) state that the only DNA in the cells was the designed synthetic DNA, including “watermark” sequences and other designed gene deletions and polymorphisms, and mutations acquired during the building process. The new cells have expected phenotypic properties and are capable of continuous self-replication and of logarithmic growth. In the discussion of the results obtained, the authors refer to such a cell controlled by a genome assembled from chemically synthesized pieces of DNA as a “synthetic cell,” even though the cytoplasm of the recipient cell is not synthetic. The properties of the cells controlled by the assembled genome are expected to be the same as if the whole cell had been produced synthetically; the authors consider that the DNA software builds its own hardware. According to the authors “if the methods described here can be generalized, design, synthesis, assembly, and transplantation of synthetic chromosomes will no longer be a barrier to the progress of synthetic biology” (Gibson et al., 2010, 56). These authors anticipate that their work will continue to raise philosophical issues, with broad societal and ethical implications. We agree with this point of view, not only with regard for a scientific theory on the nature of life, but also for the symbiogenic origin of life and initial evolution studies.

We think this experimental work illustrates a practical application of the symbiogenesis concept to the artificial life using live material. This achievement poses several questions regarding the origin of life itself. In the domain of artificial life, we would like to remember the work of Nils Barricelli referred to previously. For this author, the software analog in the living world is a self-replicating DNA molecule. Most of this software is parasitic (symbiotic), depending upon metabolism, which favors the analogies to life. Barricelli also considers that languages are the key to the evolution of self-reproducing structures with greater complexity, through the cooperation of simpler parts. We believe this experimental work represents a very important breakthrough in the origin of life studies. The analogies of software replication (genetic) and hardware metabolism, the fact that they need each other, and their interdependency, are in agreement with the notions of coevolution and symbiogenesis (Dyson, 1997).

According to Correia (2010), when considering artificial life and evolution, perhaps, the most interesting results of artificial life environments are the emergence of evolutionary processes and ecological dynamics equivalent to those observed in nature, such as host-parasite relations and punctuated equilibrium,

among others. The author considers it very significant that such macroscopic effects are observed both in natural and artificial environments. We agree with the author opinions when saying (Correia, 2010, 189): “Computational evolution has opened new possibilities of exploring biology by allowing us to liberally build models that may go beyond what we currently know in natural organisms”; “Both EA and artificial life evolution, in software platforms or in robots, can be put to use in testing current or new biological models.”

Perhaps we should remember the symbiogenic origin of life theories mentioned previously. Remember that in the primitive Earth there were probably several processes resulting in amphiphilic vesicles and that Matthews (1994), and Matthews and Minard (2003) advanced a symbiogenic idea for the nucleotides endogenous formation on the primitive Earth. According to this model, membrane material – carboxylic acids, carbohydrates, and polypeptides – accumulated in lakes and oceans, while on land polyamides could have been the original dehydrating agents directing the synthesis of nucleosides and nucleotides from available sugars, phosphates, and nitrogen bases. Most significant would have been the parallel synthesis of polypeptides and polynucleotides arising from the dehydrating action of polyamides on nucleotides. Metabolic material – hardware – thus arose separately from genetic components – software – as proposed by Freeman Dyson. Subsequent interfacing, perhaps with the help of clays, then produced the first replicating protocells (Carrapiço et al., 2007). On our dynamic planet, this polypeptide-polynucleotide symbiosis mediated by polyamides may have set the pattern for the evolution of protein-nucleic acid systems controlled by enzymes, the mode characteristic of life today. In 2003, Matthews refers that from hydrolysis of hydrogen cyanide (HCN) polymers, there is some evidence for peptidic structures. Also, hydrolysis/pyrolysis gives rise to nitrogen heterocycles, including purines and pyrimidines found in nucleic acids today. According to the author, some recent experimental results are consistent with this model of HCN polymer chemistry playing an essential role in the origin of life (Carrapiço et al., 2007). Reinforcing this idea, Martins et al. (2008) report the discovery of extraterrestrial nucleobases in the Murchison meteorite.

The role of viruses should also be considered in the origin and initial evolution of life as proposed in 2010 by Villarreal and Witzany. The authors consider that viruses had an evolutionary role and are the predecessors of cells as polyphyletic. Following the ideas of Woese (2004), they propose the coexistence of several LUCAs, as quasispecies based and reticulated. This is a strong argument in favor of our symbiogenic envision since we postulate the existence of several LUCAs, several lineages in the way to life, via symbiotic interactions. The primitive Earth was a natural laboratory where those ephemeral lineages emerged, and where RNA genomes existed, probably, before the DNA ones. This way, varied contributions of the Lipid World and of the RNA World should be considered together in the establishment of the initial roots of the tree of life and with a reticulated pattern of evolution.

5. Concluding Remarks

The symbiogenic approach to chemical and biological evolution should be seriously considered. We believe that competition and cooperation can coexist in the same scenario of evolution, and probably take place in terms of discontinuous bursts of activity, depending on the internal and external conditions that drive evolution. It means that the same population can evolve using competitive and/or cooperative processes during the time and space of a hypercycle evolutive scenario. We believe that cooperative and synergistic processes were responsible, using terrestrial and extraterrestrial materials, for the creation of a large prebiotic pool, closely related to geochemical contexts, and intense interactions within. Most likely, a series of synergistic and cooperative effects produced a wide source of creativity, and functional advantages that pushed the emergence of complex and functionally integrated biological systems, through the evolution of self-organization and autocatalysis. It was only after this biochemical evolution of structures, which produced the informational capabilities necessary to self-replication, that the Darwinian mechanisms could arise. This way of perceiving the emergence of life follows the proposals regarding life's initial evolution in which the progenote proposed consisted in an open community of very diverse primitive cellular entities with intense symbiotic associations, antagonisms, and competition, and with a rapid and reticulate pattern of evolution. We believe this symbiogenic approach should be considered in the understanding of chemical and biological evolution. This contributes to the development of astrobiological knowledge, enabling other perspectives on the study of life's appearance and development on Earth and elsewhere. It is also necessary to reconsider symbiosis as a general mechanism in heredity and development, in addition to gene mutations and recombination, as a source of evolutionary innovation, and to hold symbiotic processes as one of the main bases of biodiversity and evolution on Earth. This idea implies also the central role of interactions, in which individuality (new entity) emerges through incorporation. It involves horizontal mergers, which can be rapid, and, usually, discontinuous, creating permanent and irreversible changes, the ground for evolutive novelty. Something new arises through merging, being a unique or new metabolism or structure(s), which was not present before symbiosis (Carrapiço et al., 2007). In this context, we can consider this entity as a new taxonomic novelty or even as a new level of biological organization. Thus, biology must take into account this reality, integrating symbiosis, not only as a factor of evolutionary change, but also as a taxonomic element in the organization of the living world (Carrapiço, 2010).

According to Fry (2000) the "arch and scaffold" model constitutes a metaphor to analyze the origins of life theories. Following this idea we suggest that the synergistic, cooperative, and symbiogenic interactions between the prebiotic entities provided the way for the establishment of the physical and chemical scaffolds the author talks about. In our perspective, those scaffolds or supports were based

on symbiogenic principles, which together with physical and chemical prebiotic constraints, the geochemical context compatibility and environmental conditions, channeled evolution, leading to the currently established domains of life. Although there are different models to explain the origin of life, they reveal complementary aspects of the same reality applied to the primitive Earth. Thus, a more cooperative and communicational work is necessary to help reveal the so far hidden answer(s) and for the search of life elsewhere. Astrobiology, being a multi-transdisciplinary science, has the conditions to be the primary actor leading this enterprise and to implement this paradigm shift.

Finally, we believe that an experimental model for the symbiogenic approach to life's origin will come up. Artificial life's simulations may lead the way: digital primordial soup, the EvoGrid is being developed, through the adaptation of an open source molecular dynamics simulator, to allow artificial nature to take its course, to model the *prebiotic* chemical environment and search for emergent self-organization (Damer et al., 2009).

6. Summary

The scientific study of the origin of life remains one of the greatest unanswered scientific questions in the twenty-first century. This study must integrate and articulate the contributions from diverse scientific fields, such as biology, geology, chemistry, geophysics, and astronomy, among others. The transdisciplinary work that is being done in astrobiology becomes fundamental to a scientific comprehension of life's origin, including the conditions and processes of the primitive Earth. Different evolutive mechanisms have been put forward, but the general acceptance of a smaller "time window" for life's emergence has led other researchers, while not ignoring the role of natural selection and the notions of gradualism and competition, to look for other and complementary evolutive mechanisms, which could explain a more rapid evolution. Innovative approaches have eliminated the traditional dichotomy metabolism and replication, such as the double origin of life, developed by the astrophysicist Freeman Dyson, in 1985. More recently, other authors have put forward new evolutive mechanisms, involving cooperation and synergisms. In 2003, Jan Sapp has conceptually integrated symbiogenesis in the symbiomics domain, which became a new evolution theory, one that is post neo-Darwinian. These concepts had their origin in the principles developed by Constantin Merezhkowsky, in 1909, and Kozo-Polyansky, in 1924, which gave symbiosis a determinant role in evolution. These ideas were strengthened by the universal symbiogenesis concept, developed in 2007 by Nathalie Gontier. The inclusion of symbiogenic principles in the comprehension of life emergence, and the contribution from the latest astrobiology developments must be considered in the current life origin studies. A symbiogenic approach toward the origin of life becomes imperative, leading to a broader comprehension of a phenomenon that can be emergent and global.

7. Acknowledgments

A special word of gratitude to Benjamin Farrand and Helena Carrapiço for the English revision of the text.

8. References

- Antonelli PL, Bevilacqua L, Rutz SF (2003) Theories and models in symbiogenesis. *Nonlinear Anal Real World Appl* 4:743–753
- Ascaso C, Los Rios A, Wierzchos J, Risueño C, Horneck G, De La Torre R, Sancho LG (2006) Ultrastructural features of *Rhizocarpon geographicum* symbionts after exposure to space at Biopan-5 facility. In: Abstracts from 6th European workshop on astrobiology, Ecole Normale Supérieure de Lyon, France, October
- Bouchard F (2007) What is a symbiotic superorganism and how do you measure its fitness? In: Abstracts of the ISHPSSB meeting, University of Exeter, UK, 25–29 July, pp 45
- Brack A (2007) Astrobiology: from the origin of life on earth to life in the universe. In: Horneck G, Rettberg P (eds) Complete course in astrobiology. Wiley-VCH Verlag GmbH & Co.KGAA, Stuttgart, pp 1–22
- Carrapiço F (2006) The origins of life and the mechanisms of biological evolution. *Proc SPIE* 6309:63090O-1–63090O-5
- Carrapiço F (2010) How symbiogenic is evolution? *Theory Biosci* 129(2–3):135–139
- Carrapiço F, Pereira L, Rodrigues T (2007) Contribution to a symbiogenic approach in astrobiology. *Proc SPIE* 6694:669406–1–669406–10
- Chapman MJ, Margulis L (1998) Morphogenesis by symbiogenesis. *Int Microbiol* 1:319–326
- Corning PA (1995) Synergy and self-organization in the evolution of complex systems. *Syst Res* 12(2):89–121
- Corning PA (2005) Holistic darwinism. Synergy, cybernetics, and the bioeconomics of evolution. The University of Chicago Press, Chicago
- Correia L (2010) Computational evolution: taking liberties. *Theory Biosci* 129(2–3):183–191
- Damer B, Newman P, Gordon R, Barbalet T (2009) The EvoGrid: simulating pre-biotic emergent complexity. <http://www.evogrid.org/>. Accessed September 2010
- De Bary A (1878) Ueber symbiose. – *Tageblatt* 51. *Versamml. Deutscher Naturforscher u. Aerzte. Cassel* 1878:121–126
- Dubos R, Kessler A (1963) Integrative and disintegrative factors in symbiotic associations. In: Nutman PS, Mosse B (eds) Proceedings of the thirteenth symposium of the Society for General Microbiology, London, pp 1–11
- Dyson F (1985) *Origins of life*. Cambridge University Press, Cambridge
- Dyson GB (1997) *Darwin among the machines. The evolution of global intelligence*. Perseus Books, Cambridge
- Dyson F (1998) *Evolution, society, science and the universe*. Darwin College/Cambridge University Press, Cambridge
- Fernando C (2005) The good symbiont. In: Caparrere MS, Freitas AA, Bentley PJ, Johnson CG, Timmis J (eds) *ECAL 2005, LNAI, 3630*. Springer, Berlin, pp 695–704
- Fogel DB (2006) Nils Barricelli – artificial life, coevolution, self-adaptation. *IEEE Comput Intell Mag* 1(1):41–45
- Frank SA (1995) The origin of synergistic symbiosis. *J Theor Biol* 176:403–410
- Fry I (2000) *The emergence of life on earth. A historical and scientific overview*. Free Association Books, London
- Gibson DG, Glass JI, Lartigue C, Noskov VN, Chuang R-Y, Algire MA, Benders GA, Montague MG, Ma L, Moodie MM, Merryman C, Vashee S, Krishnakumar R, Assad-Garcia N,

- Andrews-Pfannkoch C, Denisova EA, Young L, Qi Z-Q, Segall-Shapiro TH, Calvey CH, Parmar PP, Hutchison CA III, Smith HO, Venter JC (2010) Creation of a bacterial cell controlled by a chemically synthesized genome. *Science* 329:52–56
- Gontier N (2007) Universal symbiogenesis: an alternative to universal selectionist accounts of evolution. *Symbiosis* 44:167–181
- King GAM (1977) Symbiosis and the origin of life. *Orig Life Evol Biosph* 8(1):39–53
- Kolb VM (2007) On the applicability of the aristotelian principles to the definition of life. *Int J Astrobiol* 6(1):51–57
- Kozo-Polyansky B (2010) Symbiogenesis. A new principle of evolution. Translated from the Russian edition (1924) by Victor Fet. Fet V, Margulis L (eds). Harvard University Press, Cambridge
- Kutschera U (2009a) Struggle to translate Darwin's view of concurrency. *Nature* 458:967
- Kutschera U (2009b) Symbiogenesis, natural selection, and the dynamic earth. *Theory Biosci* 128(3):191–203
- Lee DH, Severin K, Yokobayashi Y, Ghadiri MR (1997) Emergence of symbiosis in peptide self-replication through a hypercyclic network. *Nature* 390:591–594
- Lehto K (2007) From molecular evolution to cellular life. In: Horneck G, Rettberg P (eds) Complete course in astrobiology. Wiley-VCH Verlag GmbH & Co.KgaA, Stuttgart, pp 85–120
- Margulis L (1990) Words as battle cries: symbiogenesis and the new field of endocytobiology. *Bioscience* 40(9):673–677
- Margulis L (1999) The symbiotic planet. A new look at evolution. Orion Books, London
- Martins Z, Botta O, Fogel ML, Sephton MA, Glavin DP, Watson JS, Dworkin JP, Schwartz AW, Ehrenfreund P (2008) Extraterrestrial nucleobases in the Murchison meteorite. *Earth Planet Sci Lett* 270:130–136
- Matthews CN (1994) The HCN world: establishing protein-nucleic acid life. The Alexander Ivanovich Oparin 100th anniversary conference, Miramare, Trieste
- Matthews CN, Minard RD (2003) Prebiotic and extraterrestrial chemistry of hydrogen cyanide polymers. In: Abstracts of the workshop on cometary dust in astrophysics, Crystal Mountain, Washington, 2003, pp 46
- Popa R (2004) Between necessity and probability: searching for the definition and origin of life. Springer, Berlin
- Reid RGB (2007) Biological emergences. Evolution by natural experiment. The MIT Press, Cambridge
- Roossinck MJ (2005) Symbiosis versus competition in plant virus evolution. *Nat Rev Microbiol* 3:917–924
- Roossinck MJ (2008) Symbiosis, mutualism and symbiogenesis. In: Evolution of plant virus. Springer, Berlin, pp 157–164
- Ryan FP (2006) Genomic creativity and natural selection: a modern synthesis. *Biol J Linn Soc* 88:655–672
- Sapp J (2003) Genesis: the evolution of biology. Oxford University Press, New York
- Sapp J (2004) The dynamics of symbiosis: an historical overview. *Can J Bot* 82:1046–1056
- Sapp J, Carrapiço F, Zolotonodov M (2002) Symbiogenesis: the hidden face of Constantin Merezhkowsky. *Hist Philos Life Sci* 24:421–449
- Shenhav B, Segré D, Lancet D (2003) Mesobiotic emergence: molecular and ensemble complexity in early evolution. *Adv Complex Syst* 6(1):15–25
- Taylor TJ (1999) From artificial evolution to artificial life. PhD thesis, Division of Informatics, University of Edinburgh
- The astrobiology primer: an outline of general knowledge (2006) – version 1, education paper. Mary Ann Liebert, Inc, New Rochelle
- Trainer MG, Pavlov AA, DeWitt HL, Jimenez JL, McKay CP, Toon OB, Tolbert MA (2006) Organic haze on titan and the early earth. *Proc Natl Acad Sci USA* 103(48):18035–18042
- Villarreal LP, Witzany G (2010) Viruses are essential agents within the roots and stem of the tree of life. *J Theor Biol* 262:698–710
- Watson RA (2007) Compositional evolution and symbiosis. In: Abstracts of the ISHPSSB meeting, University of Exeter, UK, 25–29 July, pp 183–184
- Woese CR (2004) A new biology for a new century. *Microbiol Mol Biol Rev* 68(2):173–186