3

The Biosphere: A Thermodynamic Imperative

Karo Michaelian
Instituto de Física, UNAM
Mexico

1. Introduction

The publication of "On the Origin of Species" by Darwin in 1859 set the stage for the emergence of a new paradigm. No longer was biology accredited to the whim of an omnipotent mystical being; for the first time the diversity of life was seen as the result of a plausible physical mechanism which led to complex organisms and species from simpler common ancestors. Darwin's theory assumed a fierce battle for survival of the individual against the hostile biotic and abiotic components of its environment. This fight for survival suggested an implicit metaphysical "will to survive" programmed within each organism, which, together with variability in reproduction, provides sufficient elements for natural selection to drive the evolutionary process. Such a process would lead to ever more apt forms of organisms until reaching what Darwin considered to be a state of "near perfection". The biosphere, under this paradigm, was considered to be an emergent system, the result of the sum of the many individual or collective struggles for survival.

The annunciation of the theory of Gaia by Lovelock (2005) in the 1970's added a completely new dimension to the biosphere. No longer was life subjected to the unrelenting demands of the environment, but living organisms, collectively or individually, could, in fact, alter their physical environment, in such a manner that seemed to be beneficial to their survival. It was found, for example, that organisms had transformed the Earth's atmosphere in such a manner that sunlight could penetrate through to the surface where it was needed by biology. Organisms even regulated the temperature of Earth's surface to keep it comfortable for themselves, and to ensure the presence of the vital liquid water in the biosphere. This biotic regulation of Earth's temperature to within the range for liquid water seemed remarkable considering that the Sun's integrated luminosity had increased by as much as 30% since the very beginnings of life on Earth (Sagan and Chyba, 1997).

Gaia theory was enlightening, it pointed out the many biological controls over the environment; from limiting the maximum concentration of salt in the oceans, and oxygen in the atmosphere (thereby avoiding higher concentrations at which spontaneous combustion occurs) to promoting plate tectonics that has allowed a diversification of ecosystems. From the optics of Gaia, biology was seen to be coevolving together with its abiotic environment. However, an enigmatic question arose, "towards what was the biosphere evolving?" Proponents of the Gaia theory claimed that evolution of the biosphere was proceeding in such a manner so as to provide better conditions for life, and greater stability for all living systems. In the most assertive interpretations of Gaia, the Earth itself was considered as one great living organism practicing homeostatic auto-regulation.

Critics of the Gaia theory countered that the tenets of the theory were in contradiction to those of Darwin's theory of evolution through natural selection. In particular, they argued that evolution was affected by natural selection operating at the individual level, not at the higher coupled biotic-abiotic levels that Gaia theory was claming. How could the biosphere as a whole, or even more enigmatically, the Earth as a whole (in the strongest interpretation of Gaia), be subjected to a kind of natural selection when there was no competition between distinct co-existing biospheres or co-existing Earths? This led to the annunciation of the "problem of the evolution of a system of population of one – the biosphere" (Swenson, 1991).

Proponents of the Gaia theory valiantly contested their critics, explaining Gaian dynamics on the basis of Darwin's theory of evolution through natural selection operating at the organismal level. Lovelock presented his now famous "Daisy World" model to show how Earth's surface temperature could be regulated to optimal values for the daisies by a variant gene that coded for either dark or light colored daisies. Meanwhile, more and more evidence was accumulating (much of it contributed by Lynn Margulis and her collaborators, Margulis; 1986) demonstrating that organisms do, and indeed always have, regulated their environment.

A progressive paleontologist, Gould (2002), saw the problem not in explaining higher level selection from within the Darwinian framework, but in the limitation of the Darwinian theory itself. Arguing his view in "The Structure of Evolutionary Theory", Gould (2002) states (p. 699) "This perspective implies a striking limitation upon the strictly Darwinian style of extrapolative and gradualistic selection that the Modern Synthesis promulgated as an adequate explanation for evolution at all scales of time and effect. … Once again, we grasp the need for independent macroevolutionary theory…".

Apart from the difficulty of explaining evolution on all hierarchal levels and the co-evolution of a coupled biotic-abiotic system, Darwinian Theory runs into other troubles. For example, there is no doubt that biotic systems are evolving through some kind of natural selection, but the answer to the question of "*what* is natural selection actually selecting?" remains elusive. Even though philosopher Karl Popper(1902-1994) recanted on his original criticism of *survival of the survivors* tautology in the theory of evolution, he still referred to it as a "metaphysical research program" (Popper, 1978), and there still remains a large amount of circularity of argument in Darwin's theory. This circularity cannot be removed from the theory unless a physical foundation for evolution through natural selection can be clearly identified.

Perhaps the most glaring deficiency of Darwinian Theory, however, is its lack of comment on the origin of life itself. Although Darwin expressed in private that life may have started "in a warm little pond" (Darwin, 1887) no experimental or theoretical extrapolation of the Darwinian paradigm to the molecular level has ever produced important insights into life's origin.

This chapter presents an argument for a new paradigm for the biosphere based on the thermodynamic theory of open systems (known as *non-equilibrium* or *irreversible, thermodynamics)* and in particular, on the statistical mechanics of open systems which eventually must provide the foundation for the thermodynamic theory. There are good reasons to believe that life and evolutionary processes occurring within the biosphere can be grounded in thermodynamic theory. First, thermodynamic laws are the most universal of all laws, often referred to as the "laws of laws"; they are derived from fundamental symmetries existing in Nature. There is no doubt that these laws apply to biological processes, since biological processes are composed of chemical, electrical, mechanical, and transport, processes, all of which, indisputably, are under the dominion of these basic symmetries and therefore under the imperative of thermodynamic law. Second, there is empirical evidence for a natural evolution of biological systems to particular stable end states which depend on both the boundary and the initial conditions of the system, similar to the very dynamics driving the evolution of abiotic non-equilibrium processes. Moreover, these end states, known as *stationary states* in non-living systems and as *stasis* in living systems, share similar stability characteristics (Michaelian, 2005).

This chapter argues that biotic and abiotic irreversible processes thermodynamically couple in such a way so as to increase the overall entropy production of Earth in its solar environment. It is suggested that the biosphere arose as a thermodynamic imperative that coupled life and biotic evolution to abiotic irreversible processes in order to remove impediments to greater global entropy production of Earth. It analyzes how biological processes are thermodynamically coupled with abiotic processes within the biosphere. (The term "biosphere" in this chapter is taken to mean that greater entity composing the processes of life, the lithosphere, atmosphere, and hydrosphere.) Examples of biotic-abiotic coupling are; biology catalyzing the hydrological cycle (Michaelian, 2009a, Michaelian, 2011b), and biology catalyzing ocean and wind currents, and the carbon cycle.

Such a thermodynamic view of the biosphere provides an explanation of many intriguing biotic-abiotic associations discovered while accessing the Gaia hypothesis (Lovelock, 2005). It also provides a framework for explaining the observed co-evolution of life with its environment, and for the resolution of the paradox of "the evolution of a system of population one – the biosphere" (Swenson, 1991). Perhaps most importantly, however, it offers a simple physical reason for the origin of life based on entropy production through ultraviolet (UV) light dissipation into heat by RNA and DNA during the Archean (Michaelian, 2009b; 2011a).

Keywords: Biosphere, non-equilibrium thermodynamics, thermodynamic dissipation theory of the origin of life, UVTAR, entropy production, Darwin, Gaia.

2. Co-evolution of the biotic with the abiotic through the thermodynamic imperative

Darwin's theory of evolution through natural selection lacks sufficient elements to explain the origin, persistence, and evolution of the biosphere. In order to understand the biosphere and its evolution, it is first necessary to recognize that biological processes in the biosphere are thermodynamically coupled to abiotic processes, and then understand how biosphere evolution is driven by increases in the entropy production afforded to the Earth through the origin and coupling of its constituent irreversible processes.

No irreversible process, life and the hydrological cycle included, can arise and persist without producing entropy. Entropy production is not incidental to the process, but rather the very reason for its existence. A fundamental characteristic of nature is the search for routes to greater global entropy production, often building on pre-existing routes by coupling new irreversible processes to existing ones. Onsager (1931) has shown how diverse irreversible processes can couple in order to remove impediments to greater global entropy production (Morel and Fleck, 1989). In general, the more complex the dissipative structuring in space and time, i.e. involving many coupled irreversible processes with embedded hierarchal levels and interactions of long spatial and temporal extent, the greater the overall entropy production in the systems interaction with its external environment (Onsager, 1931; Prigogine et al., 1972; Lloyd and Pagels, 1988).

Non-equilibrium thermodynamics shows (Prigogine, 1967) that the entropy production of a system is of a bi-linear form of generalized forces, X , times generalized flows, J , i.e.

$$\frac{dS}{dt} = \sum_i X_i J_i \tag{1}$$

where the index i runs over all irreversible processes operating in the system. These processes can be, amongst others, flows of mass, heat, or charge, chemical reactions, and photon absorption and dissipation. In ecosystem processes, individuals can be considered as units of entropy production and exchange. The forces X_i are then associated with the populations p_i of species i , and the flows J_i with the flows of entropy (Michaelian, 2005). In this thermodynamic view, selection of a particular irreversible process, or the coupling of irreversible processes, is contingent on increasing the global entropy production of Earth in its solar environment. In general, it is not the individual organism's entropy production, in isolation of all others (if this could even be imagined), which is relevant to selection, but instead the increase in the total entropy production of all coupled processes in the Earth system (the change in the sum of Eq. (1)). However, entropy production is an extensive (additive) quantity and the individual terms $X_i J_i$ are often positive (although not necessarily so if two or more processes occur within the same macroscopic region; in this case a term may be negative as long as a coupled term is positive and of greater magnitude, see (Prigogine, 1967)). Therefore, in this thermodynamic framework, selection based on increases in entropy production can occur at any level, including that of the individual or the biosphere.

In this top-down thermodynamic view, organisms should not be seen as individual entities endowed with a meta-physical “will to survive” competing against others and their environment, but instead as local thermodynamic flows which arise in response to local (on the relevant scale) thermodynamic forces which define their environment. The local thermodynamic potentials providing the forces are created by other irreversible processes dissipating thermodynamic potentials on a still higher level, and so on up until reaching the highest hierarchal level of the Earth in its solar environment. The moment that a local thermodynamic potential wanes, or becomes depleted, the organism (irreversible process spawned) created to dissipate this potential will “suffer”, or go extinct. Organisms (irreversible flow processes) on whatever scale, therefore, have higher probability of survival if they are attached to large, robust and stable thermodynamic forces (gradients of potentials). Life, in general, appears to be directly attached to the greatest thermodynamic potential influencing Earth; the solar-space photon potential. As equation (1) above indicates, stronger forces, or stronger flows, imply greater entropy production.

Thermodynamic selection, however, is not “instantaneous”; both biotic organisms and abiotic processes have the ability to adapt to a changing thermodynamic potential. Biotic organisms adapt through their organismal plasticity (e.g. the ability to migrate, or their ability to survive off different thermodynamic potentials - heterotrophy) or through their genetic apparatus and reproduction (plasticity on the species level). In contrast, abiotic processes have an inherent plasticity, for example, a change in size or direction of a hurricane, in response to a change in the size or direction of a temperature gradient. In this thermodynamic view the process is not “striving to survive”, it is rather a flow responding to a changing thermodynamic force. The Gaia theory speaks of “life shaping the environment to its own benefit”, but the thermodynamic view sees all life coupled to many higher level thermodynamic processes (both biotic and abiotic) which are together evolving to greater levels of global entropy production. It is these higher level potentials that are the creators, deformers, and selectors of those irreversible dissipating processes that we may call abiotic or biotic organisms.

The underlying thermodynamic foundations for evolution are the same for both abiotic and biotic irreversible processes. However, there are differences in mechanism which make them appear very distinct. The difference appears to be related to the nature of the thermodynamic potential that they arise to dissipate. Biotic organisms, in their majority, dissipate directly the photons arriving from the sun. Covalent interactions between the atoms of the organic molecules provide energy gaps compatible with the quantum energies of visible and UV photons. These molecules, when in water, can thus absorb and dissipate efficiently to heat the incident solar photon (hence the coupling of life to the water cycle). If not in water, the molecules remain for a longer time in an excited electronic state where they are vulnerable to destruction through photo-reactions, as well as to radiative decay and other less dissipative means of de-excitation (Middleton et al., 2009). These non-central covalent interactions have directionality properties which allow a great, almost inexhaustible, variety of distinct molecular configurations for pigments that absorb from the far UV to the far infrared (Gatica, 2011).

This diversity of organic molecular configurations allows for a genetic apparatus of biotic individuals that provides information storage and a retrieval system that accumulates information about the other irreversible processes and thermodynamic potentials in the environment. This endows individuals and species with great plasticity in responding (Darwinians would say “adapting”) to changes in the thermodynamic potentials of their environment.

Abiotic processes, on the other hand, tend to dissipate secondary heat gradients in which the relevant quantum energy packets are of much lower energy than those of visible or UV photons. Most of the solar photons intercepted by abiotic organisms are in the infrared. Abiotic organisms are usually “glued” together through central and weak hydrogen bonds (e.g. the interaction between water molecules) or through central van der Waals forces. These interactions have no directionality properties, and, therefore, lead to low diversity at the molecular level. This precludes a microscopic molecular genetic code and limits the “organism’s” ability to accumulate information about the thermodynamic potentials or other irreversible processes operating in their environment. However, information is nevertheless transmitted at a more macroscopic level, as, for example, in the distribution of ocean surface water temperatures which “remembers” the history of prior recent hurricanes (and other irreversible heat flow processes) and constrains the birth and evolution of new, future hurricanes.

3. Onsager's principle and entropy production in the biosphere

There is an underlying physical basis for expecting nature to evolve towards greater entropy production. Onsager showed that irreversible processes arise and couple to reduce impediments to greater global entropy production of the system (Onsager, 1931; Morel and Fleck, 1989). Onsager's principle should not be confused with the Maximum Entropy Production Principle (MEPP) which suggests that of all possible evolutionary paths, the system will take that particular path which maximizes the entropy production. Onsager's principle simply states that the appearance of a new irreversible process cannot be expected unless the global entropy production of the system increases. Since the Earth system is a complex non-linear system with many thermodynamic potentials generated in a hierarchy of embedded levels, many paths exist in phase space for dissipating the imposed solar photon potential, each path in phase space is separated from others by energy, momentum, or angular momentum barriers (the conserved quantities for classical systems). The actual path taken will depend, because of the non-linearity, very sensitively on the microscopic initial conditions and subsequent perturbations, and there is, therefore, no reason why the chosen path has to be the one of maximum entropy production. While the "maximum entropy production principle" may one day be validated as a probabilistic principle, this principle, at least in its present formulation and at the level of complexity of the biosphere, is not relevant here since we neither have ways of distinguishing the microscopic initial conditions of the Earth system, nor can we recognize and compile the history of subsequent external perturbations that the system experienced. The possibility that we will be able to count and analyze all possible paths available in phase space appears even further remote. Note that there is in principle no absolute maximum to the amount of entropy production of the Earth system. Infinite entropy production would result if the incident photons were converted into infinitely long wavelength photons (constrained, perhaps, by the finite temperature of outer space, the "size" of the Universe, and quantum aspects).

In principle, the thermodynamic framework could be used to predict which individuals, species, ecosystems, clades, or biospheres have higher probability of appearance and survival, however, since almost all irreversible processes occurring on Earth are coupled at many spatial and temporal levels, the Earth system cannot easily be separated into parts. Exceptions are cases in which coupled irreversible processes act on vastly different time scales. In these cases, the entropy production due to the part of short characteristic time scale can be used as a local predictor for the direction of evolution. In practice, however, few processes can be effectively isolated, and it is just as impractical to obtain a prediction for the direction of evolution from this framework as it is from the Darwinian principle of natural selection (of the "fittest").

However, by replacing "selection of the fittest" with "selection of irreversible processes leading to greater global entropy production" the thermodynamic framework avoids the tautology inherent in traditional evolutionary theory. Within the Darwinian framework, selection on a higher level than the individual, e.g. species, populations, communities, ecosystems, etc., is generally attributed to some kind of "emergent" behavior of a complex many-body system. However, it is well known that non-equilibrium "emergent behavior" results from the dissipation of an underlying gradient, a thermodynamic potential. The general struggle for existence leading to evolution through natural selection has not been associated with such a potential and this leads to a certain tautology in Darwinian Theory.

In the following section, an important example is given of how biology is coupled to a particular abiotic irreversible process, the water cycle, and how this coupling augments the entropy production of the Earth system.

4. Biology, solar photons, and the hydrological cycle

All irreversible process, the hydrological cycle included, arise and persist to produce entropy. The steps of the hydrological cycle contributing to the global entropy production are;

1. Sunlight reaching the Earth's surface is absorbed on both biotic and abiotic material and rapidly dissipated into heat, particularly if this occurs on organic material in water. This step contributes to the greatest amount of entropy production in the Earth system, about 63% of the total. Most of the remaining entropy production is due to photon absorption and dissipation on the gasses of the atmosphere (Peixoto et al., 1991, Michaelian, 2011b). Note that if there were no water in the region of photon absorption then the surface of Earth would radiate energy into space at shorter wavelengths or conduct or convect energy to the atmosphere at higher temperature, implying less dissipation and therefore less entropy production. The availability of water in the region also leads to the second step in the water cycle;
2. Heat absorbed by the water, particularly at the surface, converts liquid water into water vapor (the latent heat of vaporization). Water vapor expansion into the greater volume of the atmosphere, and its diffusion into the atmosphere, produce entropy. The cooling of Earth's surface produced by the removal of the latent heat of vaporization implies a more red-shifted black-body surface radiated spectrum.
3. Water vapor is less dense than dry air and so rises to the cloud tops. This diffusion process generates more entropy. As the water vapor rises, its heat is given off to the surrounding air column. This spawns other irreversible processes such as winds, tornadoes and hurricanes, all of which dissipate these secondary heat gradients and therefore generate further entropy.
4. At the cloud tops, at roughly -14°C, the water vapor condenses and releases the heat of condensation into the atmosphere. Much of this energy is then directly radiated into space in a roughly black-body spectrum of -14 °C. Condensation would seem to cancel the entropy production of evaporation (step (2) above), but this condensation occurs at a significantly lower temperature than does the evaporation. The net entropy produced by evaporation-condensation cycle can be roughly calculated as $dS = dQ(1/T_c - 1/T_s)$, where dQ is the heat of vaporization and T_c and T_s are, respectively, the temperature of emission of the energy dQ by condensation at the cloud tops, and the temperature of absorption by liquid water of this energy at the surface of Earth.

Indirectly, the water cycle also leads to entropy production through clouds which are blown over land masses, allowing water to travel inland and provide the essential element for life (particularly trees and plants). This life reduces Earth's albedo due to the organic molecules that absorb and dissipate solar radiation. Old, climax, forests correspond to the regions of lowest albedo on Earth. A greater portion of Earth's surface is thus rendered available for greater entropy production.

5. The origin of life

Darwin foresaw the possibility of a physical theory for the origin of life when he suggested that life could have started in a "warm little pond, with all sorts of ammonia and phosphoric salts, lights, heat, electricity, etc. present, so that a protein compound was chemically formed ready to undergo still more complex changes" (Darwin, 1887). However, nothing in his theory of evolution through natural selection suggests just how life may thus have originated. Many later attempts were made to adapt the Darwinian paradigm of competition to the molecular, or chemical, level, but these attempts have so far been unsuccessful

Most experiments on the origin of life have been carried out in near equilibrium conditions and look for the spontaneous appearance of an auto-catalytic chemical process. However, the mere hope of observing the origin and persistence of an irreversible process such as life without duly considering its thermodynamic function of entropy production is nothing short of expecting a miracle.

If the absorption and dissipation of high energy photons from the sun is the major thermodynamic function performed by life today, then it is plausible that this was also its function in the Archean some 3.8 billion years ago from when there is evidence that life began. Earth's atmosphere at this time was more transparent in the ultraviolet since there was no ozone or oxygen in the atmosphere (Cnossen et al., 2007), and more opaque in the visible. The sun was also perhaps up to 10 times more intense in the far ultraviolet than it is today, principally due to a higher rotation rate. It is then probable that life arose to dissipate photons in the UV and only later developed pigments in the visible when the atmosphere cleared of organic haze and sulfuric acid clouds and became more transparent at these wavelengths. Both RNA and DNA absorb strongly in the UV at 260 nm and dissipate this energy rapidly into heat when they are in water.

These facts have led me to propose a thermodynamic dissipation theory for the origin of life (Michaelian, 2009a, 2011b). In this theory, the reproduction of RNA and DNA is promoted by the entropy production due to dissipation of UV photons by these organic molecules while they floated on the surface of water bodies. Based on the ratio of the concentrations of ^{16}O and ^{18}O isotopes found in sediments of this age, it has been surmised that the ocean surface temperatures were around 80 °C when life began. This is close to the denaturing temperature of intermediate sized DNA fragments. An "ultraviolet and temperature assisted mechanism for replication" (UVTAR) of these first molecules of life can therefore be imagined: Once Earth's surface temperature dropped below the denaturing temperature of RNA or DNA, then during the day, particularly in the afternoon, absorption of UV, visible, and infrared light on the ocean surface would increase the temperature to beyond the denaturing temperature, and the double strands of RNA or DNA would separate into single strands. At night, the two single strands could act as templates for the formation of complementary strands thus providing a new generation of RNA or DNA. This process bears resemblance to a now standard laboratory procedure to amplify (multiply) DNA known as "polymerase chain reation" (PCR).

Biotic evolution in the Archean, as it is now, was driven by increases in the entropy production due to photon dissipation. As the seas cooled further still, it became selectively advantageous for the RNA and DNA molecules to code for aromatic amino acids such as tyrosine and tryptophan that could act as UV photon antennas to augment the local temperature enough to permit denaturation in the late afternoon. The cooling of the ocean surface was thus probably the first promoter of information storage in DNA and RNA.

An experiment is now underway at the Institute of Physics at the UNAM to determine if a PCR-like process can be carried out with a UV light cycle replacing the normal temperature cycling in PCR. If this is successful, the next phase of the experiment would be to attempt amplification without the enzyme polymerase. Although this will certainly slow down the process considerably, other inorganic catalyzers, such as magnesium ions, could have been present and it must be remembered that the first DNA or RNA segments could have been subjected to billions of PCR-like cycles before life as we know it initiated.

6. Conclusions

Arguments have been given to suggest that biology should be considered as a set of irreversible process embedded within, and coupled to, other abiotic irreversible processes, and it is this whole of processes which defines the biosphere. The biosphere and its evolution are the result of a thermodynamic imperative which drives the Earth system towards increases in the global entropy production, in accordance with Onsager’s principle. This is achieved principally, but not exclusively, by the organic pigments which absorb and dissipate the incident solar high energy photons into heat in the presence of water at the surface of the Earth. The coupling of the hydrological cycle to biology is thus a natural consequence of this thermodynamic imperative, and it is most probable that this association existed since the time of the first appearance of life on Earth (Michaelian, 2009b, Michaelian, 2011a). No longer should the biosphere be considered as a simple emergent system resulting from individual fights for survival, as Darwinian Theory proposes. Nor should the biosphere be considered as a greater organism, egoistically controlling its environment to increase its own stability, or that of its living components, as Gaian Theory proposes.

This thermodynamic view has the advantage of avoiding tautology in evolutionary theory by identifying a physical and universal foundation for evolution; that of increasing the global entropy production. It allows for selection on all hierarchal biotic levels, and even on coupled biotic-abiotic levels. The solution to the problem of “the evolution of a system of population one” becomes trivial under this framework. There is also an indication, remaining to be investigated further, that this framework could explain stasis and the punctuation of stasis in biological evolution (Gould, 2002) on the basis of thermodynamic stationary states and out-of- equilibrium phase changes, respectively. Finally, this thermodynamic framework provides a plausible explanation for the origin of life on Earth by tying RNA and DNA reproduction, and life’s subsequent dispersal into practically all environments, to greater global entropy production.

7. Acknowledgements

The author is grateful for the financial support of DGAPA-UNAM, grant number IN112809.

8. References

Cnossen, I., Sanz-Forcada, J., Favata, F., Witasse, O., Zegers, T., and Arnold, N. F.: The habitat of early life: Solar X-ray and UV radiation at Earth's surface 4–3.5 billion years ago, J. Geophys. Res., 112, E02008, doi:10.1029/2006JE002784, 2007.

Darwin, F., ed. 1887. "The life and letters of Charles Darwin". London: John Murray. Volume 3. p. 18

Gatica Martínez, J., "Contribution of Cyanobacteria to Earth's Entropy Production", Bachelors thesis, UNAM, 2011.

Gould, S. J., "The Structure of Evolutionary Theory", Cambridge, Havard University Press, 2002.

Lloyd, S. and Pagels, H. M.: Complexity as thermodynamic depth, Ann. Phys.. 188, 186–213, 1988.

Lovelock J. E.: Gaia: Medicine for an ailing planet. (2nd ed.) Gaia Books, New York, 2005.

Margulis, L. and Sagan, D., "Microcosmos: Four Billion Years of Microbial Evolution", New York, Summit Books, 1986.

Michaelian, K., Biological catalysis of the hydrological cycle: life's thermodynamic function, Hydrol. Earth Syst. Sci. Discuss., 8, 1093-1123, www.hydrol-earth-syst-sci-discuss.net/8/1093/2011/ doi:10.5194/hessd-8-1093-2011, 2011b.

Michaelian, K.: Thermodynamic dissipation theory for the origin of life, Earth Syst. Dynam., 2, 37–51, 201. doi:10.5194/esd-2-37-2011, 2011a.

Michaelian, K.: Thermodynamic Function of Life. 2009a, (PDF) arXiv. http://arxiv.org/abs/0907.0040.

Michaelian, K.: Thermodynamic Origin of Life. 2009b, (PDF) arXiv. http://arxiv.org/abs/0907.0042.

Michaelian, K.: Thermodynamic stability of ecosystems. Journal of Theoretical Biology 237, 323-335, 2005.

Middleton, C. T., de la Harpe, K., Su, C., Law, Y. K., Crespo-Hernández, C. E., and Kohler, B.: DNA Excited – State dyanmics: from single bases to the double helix, Annu. Rev. Phys. Chem., 60, 217–239, 2009.

Morel, R. E., Fleck, G: Onsager's Principle: A Unifying Bio-theme. J. Theor. Biol., 136, 171–175, 1989.

Onsager, L.: Reciprocal Relations in Irreversible Processes. I., Phys. Rev., 37, 405–426, 1931.

Peixoto J.P., Oort A.H., de Almeida M., Tome A.: Entropy budget of the atmosphere. J. Geophys. Res. 96, 10981--10988, 1991.

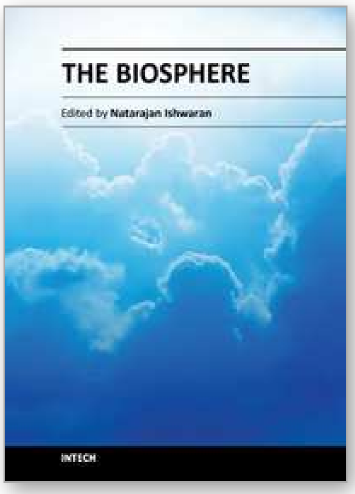
Popper, K.: Natural Selection and the Emergence of Mind, Dialectica, 32, no. 3-4, 339-355, 1978.

Prigogine, I., Nicolis, G., and Babloyantz A.: Thermodynamics of evolution (I) Physics Today, 25, 23-28; Thermodynamics of evolution (II) Physics Today, 25, 38–44, 1972.

Prigogine, I.: Thermodynamics of Irreversible Processes, Wiley, New York, 1967.

Sagan, C. and Chyba, C.: The Early Faint Sun Paradox: Organic Shielding of Ultraviolet-Labile Greenhouse Gases, Science, 276, 1217–1221, 1997.

Swenson, R.: End-directed physics and evolutionary ordering: Obviating the problem of the population of one. In "The Cybernetics of Complex Systems: Self-Organization, Evolution, and Social Change", F. Geyer (ed.), 41-60. Salinas, CA: Intersystems Publications, 1991.



The Biosphere

Edited by Dr. Natarajan Ishwaran

ISBN 978-953-51-0292-2
Hard cover, 302 pages
Publisher InTech
Published online 14, March, 2012
Published in print edition March, 2012

In this book entitled "The Biosphere", researchers from all regions of the world report on their findings to explore the origins, evolution, ecosystems and resource utilization patterns of the biosphere. Some describe the complexities and challenges that humanity faces in its efforts to experiment and establish a new partnership with nature in places designated as biosphere reserves by UNESCO under its Man and the Biosphere (MAB) Programme. At the dawn of the 21st century humanity is ever more aware and conscious of the adverse consequences that it has brought upon global climate change and biodiversity loss. We are at a critical moment of reflection and action to work out a new compact with the biosphere that sustains our own wellbeing and that of our planetary companions. This book is a modest attempt to enrich and enable that special moment and its march ahead in human history.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Karo Michaelian (2012). The Biosphere: A Thermodynamic Imperative, The Biosphere, Dr. Natarajan Ishwaran (Ed.), ISBN: 978-953-51-0292-2, InTech, Available from: http://www.intechopen.com/books/the-biosphere/the-biosphere-a-thermodynamic-imperative

INTECH
open science | open minds

InTech Europe
University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
www.intechopen.com

InTech China
Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821