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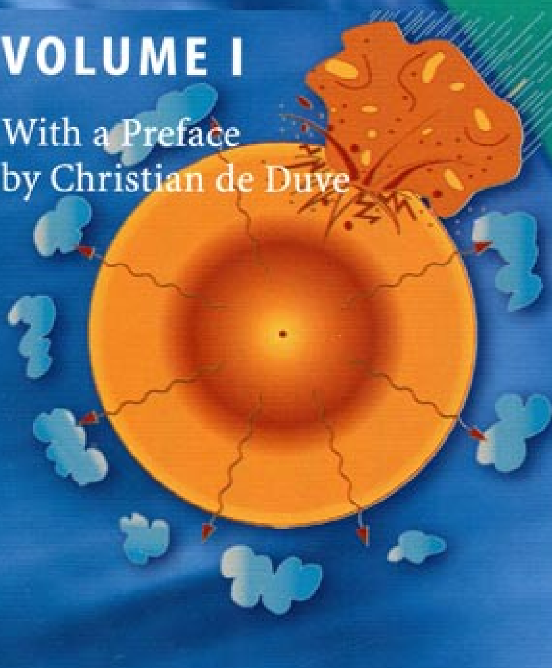
Lectures in Astrobiology

VOLUME I

With a Preface
by Christian de Duve



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Advances in Astrobiology and Biogeophysics

Gargaud · Barbier · Martin · Reisse (Eds.)

Lectures in Astrobiology I

Based on the material delivered at several summer schools, this book is the first comprehensive textbook at the graduate level encompassing all aspects associated with the emerging field of astrobiology. Volume I gathers a first set of extensive lectures that cover a broad range of topics, from the formation of the solar system to the quest for the most primitive life forms that emerged on the early earth.

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Foreword

Astrobiology, also known as bioastronomy or exobiology, refers to a vast area of scientific research. The formation of the solar system, its accretion and the formation of the planets, the origin of the molecules out of which living beings are made, the traces of present and past life within the solar system and elsewhere, as well as the search for extra-solar planets, are all part of astrobiology. And the above list is not exhaustive.

For obvious reasons, astrobiology is a field without the traditional barriers between astronomers, chemists, physicists, geologists, and biologists or between experimentalists and theorists, observers and those who model the observations. As such, a single researcher cannot possess all the knowledge necessary to be an "astrobiologist". One can even go a step further and say that while astrobiology clearly exists as a field of scientific research, there are no astrobiologists. Astrobiology exists at a higher level of organization where the knowledge is not that of an individual but that of a research community whose members all share the same interest for the fundamental questions concerning the emergence of life, its evolution, and how life is distributed on Earth and throughout the universe. Each person contributes in piecing together this vast puzzle through their knowledge and their experimental and theoretical tools.

As often, if not always, when treating questions dealing with the past or with a sort of "elsewhere" where one cannot go and that one can only study indirectly, we must be satisfied with plausible scenarios rather than clear proof or other certainties. In this way, the strategy of the astrobiologist is similar to that of an archeologist or a paleontologist. There exists, however, major differences between the path of a chemist interested in the origin of life, and thus in prebiotic chemical evolution, that of a biologist wanting to follow time back starting with current life, and that of a paleontologist searching for the traces of primitive life and its evolution and extinctions.

While paleontologists have some hard data at hand (fossils and other physical traces), the situation is very different for chemists, who are obliged to build a plausible scenario for the appearance of life based on hypotheses developed by specialists in other fields (composition of the primitive terrestrial atmosphere, addition of extraterrestrial organic material, etc.). For the most part, these hypotheses are unverifiable. The biologist, on the other hand, tries to use phylogenetic tools to find and understand LUCA, the first common ancestor who must have been preceded by other micro-organisms with no descendants.

Similarly, there is an important difference between the strategies of a geologist, expert in the transition between the Tertiary and Cretaceous periods, and the planetologist who would like to describe the Earth during the period of intense meteoritic bombardment. The former disposes of observations and measures (iridium content, sediment ashes, shocked quartz, etc.), which provide a reasonable explanation for the great biological Cretaceous Tertiary crisis caused by a major meteorite impact. The latter only has access to indirect data based on observations of lunar craters but also simulations, which are of course based on theoretical models.

Since every scientist has a limited area of expertise, the scenario that he/she proposes can only be validated by the constraints and parameters that he/she knows and masters. Such an individual strategy can thus lead to as many scenarios as there are researchers. A multidisciplinary approach has the advantage of subjecting each individual proposition to a much larger number of constraints. This naturally leads to the rejection of "weak" scenarios and to the emergence of more robust hypotheses. For example, it is pointless for a chemist to invoke the role of a prebiotic chemical reaction if the conditions needed for the reaction to occur are completely incompatible with the primitive Earth conditions determined by the planetologists. This simple example illustrates the importance of interdisciplinary discussion for all those who consider themselves to be astrobiologists. The CNRS summer schools such as Propriano in 1999 and 2003 and La Colle-sur-Loup in 2001 have contributed to strengthening the dialog within the French scientific community.

The goal of the first summer school, Exobio'99 in Propriano, was to provide participants with an objective image of what we know today about the early Earth conditions – the oceans, the proto-continents, the atmosphere, and even the climate – but also of what we know about the solar system during the first billion years of its history. Some stages in the chemical evolution that may have occurred on the young planet Earth, with a different solar radiation, less intense in the visible part of the spectrum but much more intense in the RX region were also discussed during the first summer school. The discussion then moves towards the biological evolution, the early stages of which are still very poorly understood. The problems related to the exploration of Mars and Titan were then addressed.

The second summer school, Exobio '01 in La Colle-sur-Loup, was more oriented towards the chemistry, molecular biology, biochemistry, and biological evolution of early Earth. Its main theme was the study of organisms referred to as extremophiles, which could provide information on the nature of the first unicellular organisms that populated the young oceans. Among the specific topics addressed were the autoformation of biological membranes, the possible origins of the homochirality of the constituents of living beings, the protometabolisms that may be inferred from the study of metabolisms, and the possible role of ribozymes before the emergence of catalysis by proteinic enzymes.

The texts that follow represent the first volume of the series "Lectures in Astrobiology" and are the result of the first two schools. The chapters were written for readers already familiar with the general topic of the origin of life and life "elsewhere" but not to the extent to which each specialist is in his own discipline. As such, they are meant as much for students as for established scientists seeking to broaden their horizons in the vast field of the origins of life. We hope these texts will initiate vocations and incite researchers and students specialized in one of the individual fields to join the broad forum of astrobiology. It is undeniable that the questions forming the basis of astrobiology are among the big questions that humanity has asked itself since its inception and which recent decades have attempted to answer; answers that seem more and more plausible although necessarily partial.

Acknowledgements

This book is the product of a multidisciplinary community, the members of which all question the knowledge from their disciplines at origin in order to build together the complex structure, which this area of research represents. One needs a very open mind as well as the ability to question ones ideas through the recent discoveries in other fields.

A group of international reviewers and ourselves have read the set of texts that follow. The final versions of these texts, after multiple rewritings and long discussions, sometimes required the opinions of five or six specialists.

We would therefore like to thank all of the authors who have accepted these remarks, criticisms, and multiple discussions warmly, but also all of the "specialist reviewers" who, through their expertise, have contributed to the general coherence of this work.

Last but not least, the editors call upon the reader's indulgence concerning some (or many!) misusages of the English language; English is not the mother tongue of the large majority of authors.

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First Part Introduction

Researches related to the origins of life can develop in two different directions: they can look towards the past and try to determine how life appeared on Earth, or they can explore present-day Universe in the hunt for life. Both ways proceed by using the same strategy: research of "favourable" conditions for life to appear. These conditions are the necessary prerequisites for prebiotic chemistry to occur. Of course, until now, nobody has been able to create life but, nevertheless, chemists determined the necessary conditions to generate amino acids, purine and pyrimidine bases and many other "small" molecules. They also know how to obtain (small) polypeptides and even how to create membranes.

Very often, many plausible prebiotic scenarios have been tested and, as several experimental procedures are able to lead to the same results, there is no unique solution. These different procedures permit minimal requirements to be established in terms of pressure, temperature, pH and reactants, which are necessary to obtain some of the main components (molecules as well as supramolecular systems) of living species. For instance, liquid water is a parameter that appears crucial for prebiotic chemistry and life development. Such a condition allows both thermodynamic and compositional constraints to be fixed. Of course, the basic elements for life (C, O, H, N, etc.) must also be available.

This is why planetologists develop intensive researches in order to determine if liquid water is or was present on planets and satellites of the Solar System (Mars, Europa ...). Moreover, the research of extrasolar planets becomes a very important and attractive challenge and the recent discovery of some extrasolar planetary atmospheres appears fundamental in the research of sites favourable for life development. For the Earth's and the other solar planets, the atmosphere origins (as well as the origin of water and C-, O-, N-, H-bearing molecules) are assessed to be endogenous or/and exogenous. Consequently, it becomes critical to determine the respective importance of endogenous and exogenous processes. In the exogenous case, matter is assumed to come from other parts of the Solar System and to have been transferred to Earth surface by comets, asteroids, meteorites and micrometeorites. These are the reasons why astrobiology is deeply interested not only in various aspects of cosmology and nucleosynthesis but also in the accretion process of the Solar System and more generally of planetary systems around stars. How elements and even molecules, initially present in the protosolar nebula, were redistributed and transformed during accretion is also a problem of major interest.

On the other hand, geological and biological investigations on Earth showed that autotrophic life can develop without light energy, as proved by life development associated to submarine black smokers. These hydrothermal vents are genetically linked to the internal Earth heat production and then to plate tectonics. This points to the possibility for life to develop not only because of solar energy but also due to planetary internal energy. On Earth, plate tectonics lead to a bimodal repartition on altitudes (ocean vs. continent). The possible discovery of a bimodal altitude distribution on Mars provides a strong argument in favour of an early plate-tectonic activity and also appears as a fundamental element for research of early life on this planet. Similarly, the possibility to have submarine hydrothermal vents on Europa, one of the satellites of Jupiter, is an exciting possibility. Evidence for the discovery of life in the Solar System or better on exoplanets, would demonstrate that the emergence of life does not result from the succession of highly improbable and complex events that occurred only on Earth. On the contrary, it would show that more simple processes are involved in the appearance of life, processes able to develop and to be reproduced in several places in the universe.

Looking to Earth past could appear easier as we are sure that at least one time in Earth history all conditions for life development were realised. Unfortunately, this is the only certainty we have and as we look farther into the past more the record of traces of life is tiny and ambiguous. Indeed, very old rocks (older than 3.8 Ga) are not very abundant and even if they are preserved they have been transformed by tectonic and metamorphic processes. The debate around Isua (3.85 Ga) traces of life is a perfect illustration of the difficulty to obtain a clear and unambiguous interpretation of geological records. Strategies are now being developed in order to clearly and unambiguously identify very old fossil traces of life.

In addition, some parameters such as atmosphere and also ocean compositions are drastically different today from what they have been on early Earth. Similarly, due to Earth cooling, terrestrial dynamics changed in the course of time, generating rocks such as komatiites that are no longer produced. Moreover, it is not clearly established when plate tectonics began to operate on Earth. Some scenarios for life development imply alternation of dry and aqueous periods, which means that emerged continents existed but we do not possess obvious evidences of emerged continents before 3.5 Ga. This does not indicate that they did not exist but it adds a greater level of uncertainty in the life-emergence scenarios.

This is why, in order to discuss the conditions prevailing on Earth at that time, researches develop towards the oldest preserved rocks. Unfortunately, rocks older than 4.0 Ga are still poorly known, so that modelling and simulation are still more or less the only ways to discuss and reconstruct the first 500 Ma of our planet.

Second Part Introduction

Chemical evolution, which started very early in our Universe, is not only a preliminary but also an essential step to any biological evolution. All the discussions concerning a hypothetical RNA world evolving towards a DNA world is based on the assumption that deoxyribose derives from ribose or, at least, that the replacement of ribose by deoxyribose was an important step in biological evolution. Many other examples of the interdependence between chemical evolution and biological evolution are known.

Unfortunately, we have no molecular fossils or relics of the prebiotic world and our knowledge about molecular evolution during the prebiotic period is based on models and scenarios. These scenarios themselves are based on hypotheses concerning the physico-chemical conditions present at the surface of the young Earth. They are also supported by experimental simulations and by indirect observations. Indeed, interstellar clouds that can be observed today are probably not very different from the protosolar nebula and chondritic and micrometeoritic matter that we can study in our laboratories today are probably similar to the chondritic or cometary matter that fell on the young Earth in large quantities during the prebiotic period. LUCA (our last universal common ancestor) was most probably a unicellular entity with a membrane, a metabolism, a reproduction capability and therefore a genetic code. LUCA itself was most probably not the most primitive form of life on Earth. Chemists and biologists must introduce constraints into the scenarios they suggest for the transition steps from nonlife to life. These constraints are based on what we know about the chemical elements and their reactivity, about the physicochemical laws, and very importantly, about the conditions prevailing on the young Earth when the transition occurred. The study of extreme biotopes on Earth, such as the ices above the Vostock Lake or the vicinity of oceanic black smokers, yields information about the diversity of life and also about the eventual universal requirements for life.

Together with astronomers, planetologists and geologists, biologists and chemists involved in exobiological studies participate in the elaboration of these models. As already mentioned, the chemist has no relics, no molecular fossils of the prebiotic period but he/she is the only one who can perform experimental simulations to help a model progress. The biochemist and the biologist are the only ones who work with living species, they know how living species have evolved and they are ready to take the risk to extrapolate towards the past: their approach could be described as a top-down approach while the chemists have a bottom-up approach. The hope (or better the dream) is that, one day, chemists and biologists could reach a similar conclusion about what LUCA looked like!

For the chemist, as for all "specialists" involved in exobiology, the most important contribution to the field can only come from their capacity to interact efficiently with other specialists. Exobiology is probably the best example of an interdisciplinary science: all natural sciences but also mathematics and informatics participate to its development. The next ensemble of chapters is a clear example of the work of chemists, biochemists and biologists, working in different fields but searching to contribute to the understanding of what remains an important problem: the emergence of life from nonlife.