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Volume II

With a Foreword by Antonio Lazcano

and 42 Tables and 215 Figures Including Photos and Plates, 44 in Color

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« Voyez-vous cet œuf ? C'est avec cela qu'on renverse
toutes les écoles de théologie et tous les temples de la terre. »

Denis Diderot (*Entretien avec d'Alembert*)

Foreword

Long before the idea of spontaneous generation was incorporated by Jean-Baptiste de Lamarck into evolutionary biology to explain the first emergence of life, the possibility that other planets were inhabited had been discussed, sometimes in considerable detail, by scientists and philosophers alike. More often than not, these were speculations that rested on the idea of a uniform universe but with little or no empirical basis. Today our approaches to the issue of life in the Universe have changed dramatically; neither the formation of planets nor the origin of life are seen as the result of inscrutable random events, but rather as natural outcomes of evolutionary events. The interconnection between these two processes is evident: understanding the formation of planets has major implications for our understanding of the early terrestrial environment, and therefore for the origin of living systems.

Although it is tempting to assume that the emergence of life is an unavoidable process that may be continuously taking place throughout the Universe, it is still to be shown that it exists (or has existed) in places other than the Earth. With the exception of Mars and some speculations on Europa, prospects for life in our own solar system have been strongly diminished. Although there is evidence the early Martian environment was milder and may have been similar to the primitive Earth, today its surface is a deep-frozen desert, constantly bathed by short-wavelength ultraviolet radiation. This highly oxidizing environment has rendered any hypothetical biosphere extinct or has limited it to few restricted underground niches well below the surface, where brine aquifers appear to be present. I am one of those sadly convinced that the balance of evidence suggests that life in our planetary system is confined to our own planet. As shown by the debates sparked by the announcement that the Allan Hills 84001 meteorite included traces of ancient Martian life, we also lack a well-defined consensus regarding the criteria by which we could rapidly recognize evidence of extraterrestrial biological activity.

Recognition that meteorite impacts may have led to an intense exchange of rocky ejecta between the inner planets during the early phases of the solar system has led some to discuss the possibility that life on our planet may have an ultimate Martian origin. It is somewhat amusing to see that discussions on panspermia, i.e., the transfer of organisms from one planet to another, are periodically resurrected without providing any detailed explanations of the ultimate mechanisms which may have led to the appearance of life in extraterrestrial habitable environments. It is true that the high UV-resistance of different prokaryotic species at the low temperatures of deep space, the likelihood of artificial or directed transport of microorganisms by probes sent to other bodies in the solar system, and the recognition of the Martian origin of some meteorites have given additional support to the panspermia hypothesis. However, this only shifts the problem to a different location, and most researchers prefer to study the origin of life within the historical framework of an evolutionary analysis that assumes that it took place on Earth.

As shown by the chapters that form this volume, nowadays the genealogy of life can be extended back to the origin of the chemical elements, continues with the evolution of stars and the formation of planets, and continues further with the synthesis of organic compounds that are found in comets and meteorites, which show that during the time of formation of the Earth and other planets the synthesis of many organic compounds which we associate today with living systems was taking place. Although we do not know how the transition from the non-living to the living took place, today the phylogenetic analysis of genomes can provide us with a historical record that very likely can be extended prior to the divergence of the three extant cell lineages. Most of the modern scenarios start out with relative simple organic molecules, now known to be widely distributed, which are readily synthesized, and hypothesized to undergo further evolutionary changes leading into self-maintaining, self-replicating systems from which the current DNA/protein-based biology resulted. Although many open questions remain, it is reasonable to conclude that life is the natural outcome of an evolutionary process, and that it may have appeared elsewhere in the Universe.

The distinguished American evolutionist George Gaylord Simpson once wrote that "exobiology is still a science without any data, therefore no science." Can the same be said today of astrobiology? The idea that life is the result of a rare chance event has been replaced by an evolutionary narrative, according to which biological systems are the outcome of a gradual but not necessarily slow process that began with the abiotic synthesis of biochemical monomers and eventually led to self-sustaining, self-replicating systems capable of undergoing Darwinian evolution. There is no compelling reason to assume that such processes took place only on the Earth. The timescale for the origin and early evolution of life and the ease of formation of amino acids, purines, and other biochemical compounds under a relatively wide range of reducing conditions, together with the abundance of organic molecules throughout space, all speak for natural laws conducive to the emergence of life in extraterrestrial environments where similar conditions prevail.

Yet, the role of historical contingency cannot be discounted. As the French philosopher Pascal once remarked, had Cleopatra's nose been different, the course of history may have changed. Precellular evolution was not a continuous, unbroken chain of progressive transformations steadily proceeding to the first living systems. Many prebiotic cul-de-sacs and false starts probably took place. While it may be true that the transition to life from non-living systems did not require a rather narrow set of environmental constrains, we cannot discount the possibility that even a slight modification of the primitive environment could have prevented the appearance of life on our planet. However unpalatable this conclusion may be, life may be a rare and even unique phenomenon in the Universe. In fact, today we have no evidence of extraterrestrial life, and we should not forget that it is like democracy: everybody likes the idea and speaks about it, but no one has really seen it.

Mexico City, February 2006 *Antonio Lazcano*

Preface

This is the second book dedicated to the origin(s) and development of life on Earth and possibly elsewhere in the Universe. It continues and supplements *Lecture in Astrobiology, vol. 1* published in 2005. The main goal of these volumes is to present the current state of knowledge concerning the environmental conditions and the processes leading to the appearance of life, and to establish the parameters indicative of biological activity on ancient Earth and eventually on other planetary bodies.

This book summarizes the lectures presented by selected speakers during Exobio'03, Ecole d'exobiologie du CNRS held in September 2003 in Propriano, Corsica. Just as in this volume, the field of exobiology is by nature multidisciplinary. It discusses the *bio-geo-physico-chemical* conditions required for the origin, development and evolution of life on planet Earth. Consequently, it addresses also the possibility that forms of life may exist (or have existed, or will exist) elsewhere in the solar system or in the rest of the Universe. These themes are often referred to during the in situ exploration of Mars and Titan or the ongoing search for distant exoplanets.

Recent geological investigations and in particular the discovery of the 4.4–4.3 Ga old Jack Hills zircons in Australia, demonstrate that part of the conditions required for the emergence of life existed on Earth shortly after the end of the accretion period. The first chapters deal with the different processes responsible for the establishment of the primitive environments on the young Earth. The stellar genesis and the distribution mechanisms of the key chemical elements (C, O, Si, Ca, Fe) available for the formation of the planets are discussed. An attempt is made to unravel the precise chronology of the astronomical and geological processes, which from the planetary accretion to the development of the crusts have paved the way to an environment propitious for life. Isotopic data obtained from various mineral phases in meteorites as well as the frequency and intensity of asteroid and comet impacts constrain these events.

So far, life seems directly linked to the presence of liquid water. However, it is now demonstrated that it can flourish in a wide variety of terrestrial environments, some at first sight highly inhospitable. The fact that liquid water most likely existed at the surface of Mars several billion years ago raises the challenging and so far unanswered question of the birth and development of life on this planet. Therefore, it also triggers discussions about its preservation and complete extinction due the geological evolutionary path followed by Mars. An analog might be provided by mass extinction events on Earth. The ongoing studies of Titan, which its atmosphere and surface could represent, according to some authors, a "laboratory of prebiotic chemistry", demonstrate the diversity and high complexity of the available planetary conditions. The cases of Mars and Titan directly address the concept of habitability; a notion that appears to be different (but somehow complementary) for the astronomer and the biologist. However, a favorable environment alone is not sufficient for life; the essential chemical building blocks must also be present. This particular aspect is considered in two chapters focused on the modeling of the type of molecules existing in interstellar clouds and planetary atmospheres, and on the regulation of life by planetary setting. In a completely different approach, clearly indicative of the inner intricacy of the essence of life, its artificial form is discussed, as it represents the ultimate concept of habitability and evolution inside a computer program.

This book was written for a large public of scientists as well as students, interested in the different challenges presented by the origin of life, its development and its possible existence outside the realm of Earth. It includes several appendices and an extensive glossary, to complement or update the reader's knowledge in the many disciplines covered. The different chapters are condensed versions of the animated discussions held in Propriano by a community of astronomers, geologists, chemists, biologists and computer scientists, all sharing the common goal to establish and evaluate potential scenarios leading to the appearance and development of life. This book attempts to convey the enthusiasm, the vigor, and the richness of the debates generated when specialists from a variety of disciplines gather their strength to address a specific and challenging theme. Dogmas break apart, and new paths are explored as everyone may come to question some basic principles of their own speciality and must integrate in his/her thinking, knowledge and principles gained from several other disciplines. The astronomer must then learn to reason as a biologist, and the chemist must assimilate geological parameters; the ambition of this book is to promote this broad scientific trespassing.

The editors wish to thank every author, who in his own way contributed a piece of knowledge to what remains an inextricable puzzle, whose complexity increases with every new discovery in one field or the other. The work and the patience of the reviewers is acknowledged; their contributions greatly improved the manuscripts.

Muriel Gargaud
Philippe Claeys
Hervé Martin

From *left* to *right*: Hervé Martin (geochemist), Muriel Gargaud (astrophysicist), Philippe Claeys (geologist)

Contents

1 Stellar Nucleosynthesis

Nikos Prantzos

1.1 Introduction

The theory of nucleosynthesis emerged around the middle of the twentieth century as a result of rapid progress in our understanding of three different fields:

1. The composition of the Sun and the solar system
2. The physical conditions prevailing in the interiors of stars during their various evolutionary stages
3. The systematic properties of nuclei and nuclear reactions

The idea that all nuclei are synthesized in the hot stellar interiors was promoted by the British astronomer Fred Hoyle in the 1940s. On the other hand, at about the same period, the Russian physicist George Gamow argued that all nuclei were produced in the hot primordial universe[1], by successive neutron captures. However, it was rapidly shown that in those conditions it was extremely difficult to synthesize anything heavier than ^{4}He. Moreover, observations in the 1950s showed that although all stars have similar amounts of the light (and most abundant) elements H and He, they may differ considerably in their heavy element content. It was clear then that heavy nuclei had to be produced *after* the Big Bang, in successive stellar generations, which progressively enriched the galaxies.

In the following, a brief account is presented on the basic ideas underlying nucleosynthesis. Emphasis is given (Sects. 1.4 and 1.5) on nucleosynthesis in massive stars, which synthesize most of the abundant heavy elements (C, O, Si, Ca, Fe, etc.) that are important for the formation of terrestrial planets and for the emergence of life.

[1] The name *Big Bang* was ironically given to the theory of the hot early universe by Hoyle, who promoted instead the *steady state theory* for the universe. Hoyle was proven to be wrong in his cosmological views, but correct as to the origin of the elements; the opposite happened with Gamow.

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