ORIGINS AND EVOLUTION OF LIFE

Devoted to exploring questions about the origin and evolution of life in our Universe, this highly interdisciplinary book brings together a broad array of scientists. Thirty chapters assembled in eight major sections convey the knowledge accumulated and the richness of the debates generated by this challenging theme. The text explores the latest research on the conditions and processes that led to the emergence of life on Earth and, by extension, perhaps on other planetary bodies. Diverse sources of knowledge are integrated, from astronomical and geophysical data, to the role of water, the origin of minimal life properties and the oldest traces of biological activity on our planet. This text will appeal not only to graduate students but also to the large body of scientists interested in the challenges presented by the origin of life, its evolution, and its possible existence beyond Earth.

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ORIGINS AND EVOLUTION OF LIFE

An Astrobiological Perspective

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Foreword

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Astrobiology, also known as bioastronomy or exobiology, is the study of the origin, evolution and distribution of life in the Universe. These are subjects which have been of interest to mankind throughout recorded history. Although questions of origins have most frequently invoked divine beings, non-supernatural speculation on these fundamental issues dates back at least to the Ionian school of pre-Socratic Greek philosophers. Anaximander, the successor to Thales, is reported as saying that all living creatures arose from the moist element (water) through the action of the Sun (Freeman, 1966), a prescient insight given current ideas that life as we know it requires water, that radiation acting on inorganic matter can produce the molecular components of life (amino acids, nucleic acids, etc.) and that the Sun is the ultimate energy source for almost all life on Earth. In fact, Anaximander seems to have gone further and suggested that human beings arose from fish-like creatures (presumably a natural result of life having originated in water).

Speculation about life beyond the Earth has also had a long tradition. Although Pythagoras himself is not known to have recorded his teachings, his school (in particular, Philolaus, *ca*. 400 BCE) is said to have written that the Moon appears Earth-like because it is inhabited with animals and plants (Dreyer, 1953). At roughly the same time the atomist school of Leucippus and Democritus taught that the Universe is infinite and contains innumerable worlds. Since Democritus is quoted as saying that 'There are some worlds devoid of living creatures or plants', presumably he believed some are in fact inhabited, and this view was explicitly stated by his later follower Epicurus (*ca*. 300 BCE). The atomist ideas are best known from the Roman poet and philosopher Lucretius (*ca*. 99–55 BCE), who firmly embedded the idea of an infinity of worlds in the atomist tradition. Also during Roman times Plutarch, better known for his biographies, raised in an essay the distinction between habitability and the actual presence of life; a distinction of fundamental importance in modern astrobiology (Dick, 1982).

Aristotle's rejection of the atomist theories ended most Western discussion of life beyond the Earth for the next millennium, although some medieval scholars such as William of Ockham (of the famous razor; *ca*. 1280–1347) argued that the omnipotence of God certainly allowed for the possible existence of other worlds like ours. Then, as the Renaissance began, Nicholas of Cusa (1401–1464) argued that 'Rather than think that so many stars and

parts of the heavens are uninhabited and that this earth of ours is peopled … we will suppose that in every region there are inhabitants'. Subsequently Johannes Kepler, arguing on the basis of its newly discovered moons, 'deduce[d] with the highest degree of confidence that Jupiter is inhabited' (Dick, 1982).

Islamic science had a considerable history of speculation about the evolution of species. Al-Jahiz (real name Abu Uthman Amr ibn Bahr al-Fuqaimi al-Basri) (*ca*. 780–*ca*. 869), an Afro-Arab descendant of an African slave, wrote that the effect of the environment can cause animals to develop new characteristics and can thus lead to new species (Sarton, 1975; Bayrakdar, 1983). Later, Nasir al-Din al-Tusi (born in 1201 in what is now Iran) apparently held an atomist-like view of the origin of life and also propounded ideas on the evolution of species (Alakbarov, 2001). Fakr al-Din al-Razi (1149–1209, in Iran) was an atomist as well and proposed that there are possibilities for other beings and other universes (A. Ragab, Harvard University).

In modern times ideas concerning extraterrestrial life have been expressed by many, including Huyghens and Fontenelle, while Percival Lowell built the Lowell Observatory in the USA primarily to investigate Mars, where he was convinced that the 'canals' were the work of an intelligent species. Modern scientific study of the origin of life perhaps began with the theoretical work of Oparin and Haldane and the laboratory experiments by Miller and Urey. Governmental funding for what was initially called exobiology was initiated in the USA shortly after the formation of NASA in 1958, with the aim of exploring the origin, evolution and distribution of life, and life-related molecules, in the Universe. The Exobiology Program included the Viking missions, intended specifically to search for evidence of life on Mars. At present the International Astronomical Union has a Commission (51) on Bioastronomy, there is an active International Astrobiology Society (ISSOL) and astrobiology societies or institutes exist in Spain, the USA, Japan, the United Kingdom, Australia, France, Italy and more generally in Europe.

Modern astrobiology encompasses the search for extant life, evidence of past life or evidence of prebiotic chemistry on Solar-System bodies; the search for and characterization of planets around other stars; the study of biologically relevant molecules in the interstellar medium and in primitive Solar-System objects such as comets, undifferentiated asteroids and some meteorites; the study of the origin, evolution and environmental constraints for life on Earth; and the search for intelligent signals of extraterrestrial origin. This book addresses all of these questions except the last one and also probes the complex issue of the definition of life. The authors are experts in the field, so that their work here will be a valuable resource for both students and established scientists in the many disciplines which contribute to astrobiology.

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Preface

This book aims at exploring several crucial issues related to the origin(s) and evolution of life in the Universe, starting from the only example of life known so far: terrestrial life. It is clear, though, that many of the circumstances that surrounded the emergence of life on Earth may have occurred, are occurring or will occur in other regions of our Galaxy or in other galaxies of our Universe. Therefore, the critical exploration of those conditions and the elaboration of models explaining the transition from the organic chemistry of the Universe to the biochemistry of terrestrial living forms are relevant at a much more global scale.

Just as with this volume, the field of astrobiology is by nature multidisciplinary. Astrophysicists, geologists, chemists, biologists, computer scientists and philosophers, as well as scientists working at the different interfaces between those disciplines, can all contribute to a better understanding of the processes and conditions that led to the emergence of life. The points of view and approaches of those different disciplines should not only superimpose, but also converge towards a unified explanation of the phenomenon of life in our Universe.

This book is an attempt to contribute to such an ambitious objective. It summarizes a series of lectures presented by selected speakers during two successive summer courses sponsored by the French Research Council (CNRS, Centre National de la Recherche Scientifique): *Exobio'05 and Exobio'07, Ecole d'exobiologie du CNRS*, which were respectively held in September 2005 and September 2007 in Propriano, Corsica (http://www.u-bordeaux1.fr/exobio07/).

The different chapters condense the animated discussions held in Propriano by a community of astronomers, geologists, chemists, biologists, computer scientists, philosophers and historians of science, all sharing the common goal of critically assessing potential scenarios for the origin of life on Earth and in the Universe. This book will attempt to convey the enthusiasm and richness of the debates that took place among those different specialists that gathered their strength to address a specific and challenging issue with an open mind. Under such an atmosphere, long-standing assumptions may be put into question, and lead to a stronger interdisciplinary basis, where the astronomer learns to reason as a biologist, or the chemist as a geologist. The ambition of this book is to reflect such broad

scientific trespassing and to make it accessible for the broader public as well as for teachers and master and PhD students.

The book is divided into eight major sections. Part I is introductory to the heart of the problem and gathers a series of chapters addressing the fundamental question of what life is and what kind of proxies are used to approach, in practice, a minimum life system by various disciplines. Michel Morange (Chapter 1) critically revisits the problem of the definition of life in its historical context and takes into account the epistemological challenges that it implies. Along a similar epistemological perspective, Dominique Lambert carries out a logical analysis of the cosmological anthropic principles, making a clear dissection of the underlying premises and assumptions. The following three chapters by, respectively, Céline Brochier-Armanet, Hugues Bersini and Bernard Billoud discuss the standards used to define the minimal cell from both biology and from computer sciences as well as the approach taken by computer scientists to mimic life.

Part II deals with the astronomical and geophysical constraints that led to the emergence of life on Earth and, perhaps, elsewhere in the Universe. It contains a series of chapters reviewing organic chemistry in the interstellar medium (Cecilia Ceccarelli and José Cernicharo) and meteorites (Sandra Pizzarello), as well as the astronomical setting allowing the right conditions for life to evolve (Matthieu Gounelle and Thierry Montmerle), including the formation of habitable planets (John Chambers) and galactic habitable zones (Nicolas Prantzos). Two additional chapters are devoted more specifically to the Solar System, with a chapter by Manuel Güdel and James Kasting on the influence of the young Sun on planets' atmospheres and a chapter by Gilles Ramstein about the evolution of climates on planet Earth.

One essential requisite for life as we know it is liquid water, which has incomparable properties, making it a solvent of choice for biochemical reactions. The three chapters of Part III explain why those properties are essential to life (Kristin Bartik *et al.*), how water intervenes in planet formation and evolution (Thérèse Encrenaz) and what the history of water on Mars has been like (Jean-Pierre Bibring).

The three chapters of Part IV are devoted to the very transition from inert matter to true living organisms, a fading frontier that is explored from both the bottom-up approach of prebiotic chemistry (Robert Pascal and Laurent Boiteau) and from the top-down approach of comparative genomics of extant organisms to deduce the features of more ancestral living forms (Antonio Lazcano). Juli Peretó details the fundamental, though complex, issue of the origin of metabolism and of how the first cells made a living, i.e. obtained free energy and organic matter to sustain themselves and reproduce.

Part V includes three key chapters to understand the molecular phylogenetic tools that allow for the retrieval of the genetic history of the extraordinary diversity of lineages of living organisms on our planet (Emmanuel Douzery) as well as crucial mechanisms with an increasingly recognized primordial role in evolution, namely, horizontal gene transfer (David Moreira) and symbiosis (Amparo Latorre *et al.*).

The three chapters of Part VI describe particular adaptations of life to some of the most challenging conditions: life under ionizing radiation and desiccation (Magali Toueille and Suzanne Sommer), which cause important damage to biological macromolecules, notably nucleic acids (Jean Cadet and Thierry Douki); and high salt (Giuseppe Zaccai).

Part VII deals with the kinds of traces that biological organisms can leave directly (their remains) or indirectly (through their activity on the immediate surrounding environment) in the fossil record and how these can be used to trace back and attempt dating of the oldest occurrences of life on our planet (chapters, respectively, by Frances Westall, Emmanuelle Javaux, Karim Benzerara and Jennyfer Miot, and Ken Takai).

Finally, Part VIII closes the book with two chapters by Jonathan Lunine and François Raulin and Richard Leveille on the interest in studying other systems different from Earth to tackle the possibility of finding life elsewhere in the Solar System or in the rest of the Universe.

We hope that the reader will enjoy this book as much as we have by putting together these insightful chapters on the origin of life from a multitude of scientific perspectives.