Muriel Gargaud
Editor-in-Chief
Ricardo Amils
José Cernicharo
H. James Cleaves II
William M. Irvine
Daniele L. Pinti
Michel Viso
Editors

SPRINGER
REFERENCE

VOLUME 1
A–F

Encyclopedia of Astrobiology

Springer

Preface

Where do we come from? Are we alone in the Universe? Where are we going? These are the questions addressed by astrobiology – the study of the origin, evolution, distribution, and the future of life in the Universe.

Encyclopedias are unusual works. A quote from the prologue of one of the more famous early encyclopedias is instructive:

- "...the purpose of an encyclopedia is to collect knowledge disseminated around the globe; to set forth its general system to the men with whom we live, and transmit it to those who will come after us, so that the work of preceding centuries will not become useless to the centuries to come; and so that our offspring, becoming better instructed, will at the same time become more virtuous and happy, and that we should not die without having rendered a service to the human race in the future years to come". Diderot and d'Alembert, *Encyclopédie* (1751).[1]

Diderot and d'Alembert's eighteenth century *Encyclopédie* was indeed ground-breaking, but perhaps more remarkable is the degree to which their description resembles the modern concept of genetic inheritance and natural selection: a civilization's accumulated knowledge being analogous to the traits encoded in an organism's time-tested DNA genome. In many ways, the *Encyclopédie* addressed the goals of astrobiology; between the lines, we find aspects of what makes biology *biology.*

Encyclopedias have now existed for approximately 2,000 years, the first being Pliny the Elder's *Naturalis Historia*, which was a compendium of the knowledge available to a citizen of the Roman Empire as documented by the first century AD.[2] It contained ~ 20,000 facts from 2,000 sources written by 200 authors. The present volume contains an unknown number of "facts" (indeed, some of the content will likely be proven false, as science is a living, breathing accumulation of presently accepted knowledge, all subject to future revision), but it does include more than 1,700 contributions, references uncounted thousands of prior publications, and is written by 385 authors.

Modern encyclopedias are derived from the dictionaries of the eighteenth century. The two are similar in that both are arranged alphabetically and generally are the work of a team of expert contributors. They differ in that encyclopedias contain a deeper level of analysis of the included terms and attempt to cross-reference and place the assembled contents in a useful context.

The first encyclopedias attempted to cover all human knowledge. This is now impossible for a printed work because the body of human knowledge is presently growing exponentially, with no end in sight. Encyclopedias now exist for almost every definable field of study. A field requires a certain degree of maturity to have an encyclopedia, and conversely, the publication of an encyclopedia commonly records the birth of a definable field of study. Astrobiology is an interdisciplinary field, spanning geology, chemistry, physics, astronomy, biology, engineering, and computer science, to name only the core fields of study.

While some of these fields of research are fairly well mapped, many others are in rapid flux, and still others remain perennially enigmatic, awaiting future breakthroughs by the scientists of tomorrow. To this end, the *Encyclopedia of Astrobiology* is primarily aimed at younger scientists or scientists new to the field who wish to understand how their expertise coincides with current knowledge in other areas of study. It is hoped that the encyclopedia will serve to orient researchers to the current state of the art. A more in-depth discussion of many of the topic areas can be obtained by referring to college or graduate level texts or to the articles cited at the end of many of the entries.

Encyclopedias are snapshots of the state of knowledge at a particular time. In 1844, the book *Vestiges of the Natural History of Creation* was published anonymously (it was later found to have been written by Scottish publisher William Chambers) and created a public sensation.[3] It offered a sweeping and very secular view of the development of the Solar System, stretching from the nebular hypothesis to the development of man. While primitive by modern standards (it was, after all, based on state-of-the-art early nineteenth century science), it was in many ways remarkably similar to modern cosmology. In broad brushstrokes, it is the precursor to the worldview developed in Carl Sagan's *Cosmos*[4] and the grand view of myriads of habitable planets implicit in the Drake equation. The implication of *Vestiges* was simply this: the

Universe operates everywhere and at all times according to physical principles, and the evolution of matter is largely predictable and often progressive, proceeding from the simple to the complex.

Science has advanced dramatically since Chambers' book was published. It is truly a long way from Sir William Hershel's 40-ft telescope to the Herschel Space Telescope,[5] and from a Universe with seven known planets orbiting the Sun to one with more than 500 planets orbiting other stars. It is also a long way from the work of Black, Priestly, and Lavoisier[6] to SELEX technology and high-throughput automated chemical screening and analysis, and from Lyell's *Principles of Geology*[7] to plate tectonics and isotope geochemistry. Nonetheless, certain questions permeate the sciences across time and discipline. Woese's three domains of life[8] are direct descendents of Linnaeus' early classification scheme, and both are attempts to unify and classify terrestrial organisms. Darwinism has offered an underlying mechanism for doing so that has allowed for unification of the assorted observations of the living world. However, the question of whether terrestrial life is unique in the universe has fascinated mankind for millennia.

It was not until 1959, when NASA began funding the search for life in the Universe in its Exobiology program, that we at last achieved the technological prowess to try to answer this question.[9] The paleontologist George Gaylord Simpson famously noted shortly thereafter that Exobiology was a science "that has yet to demonstrate that its subject matter exists."

NASA's first exobiology grant was awarded to Wolf Vishniac for the construction of the Wolf Trap, a device for detecting bacteria on Mars. Due to size limitations, the device never flew, but various descendants have made the trip to Mars and returned various negative or tantalizingly ambiguous results. These results are, amusingly, either disappointingly or encouragingly ambiguous, depending on one's point of view. Despite remarkable progress in the sciences, humanity still has no answer to the question, "Are we alone?," though the question is in principle answerable. The search continues enthusiastically.

Why should we think there might be life elsewhere in the Universe? In 1960, the radio-astronomer Frank Drake developed his now-famous equation for estimating the number of communicating civilizations in the Galaxy:

$$N = R* \times f_p \times n_e \times f_e \times f_i \times f_c \times L,$$

where N is the number of civilizations in our galaxy for which communication might be possible, R^* is the average rate of star formation per year, f_p is the fraction of stars that have planets, n_e is the average number of planets that can support life per star with planets, f_ℓ is the fraction of the planets that can support life on which life actually develops, f_i is the fraction of those on which intelligent life develops, f_c is the fraction of those on which civilizations communicate using detectable signals, and L is the length of time these civilizations communicate.

When Drake unveiled his equation in 1960 and estimated that there were maybe ten communicating civilizations in the Galaxy, few of the parameters were known with any certainty; the rate of star formation was perhaps the only solid measurable value. Fifty years later, the flourishing search for exoplanets has placed the focus on the second value (notably, it now appears to be close to what Drake estimated, $\sim$ 50%). Hundreds of exoplanets have been found around other stars, and current technology allows the observation of even small planets. Theory suggests that the fraction of stars with Earth-like planets is somewhere near 10% (again, surprisingly, and a tribute to back-of-the-envelope calculations, not far from Drake's initial estimate).

The least well-known value is the question of how difficult is it for life to begin (one of the "perennially enigmatic" facts mentioned above). Based on present knowledge, the fraction of planets on which life actually emerges (f_l) could be anywhere from very, very close to 0 or far closer to 1. We simply do not know. On the ends of the spectrum, the scientific community is divided into two equally "hunch-"based camps: first, life is inevitable and is a cosmic imperative (where conditions are appropriate) and, second, the origin of life requires such a concatenation of improbable events that it is the scientific equivalent of a miracle.

On the one planet we know of with life, our own, putative evidence in the form of isotopically light carbon appears in the earliest known sedimentary rocks, suggesting life emerged relatively early in the history of the planet, although we do not know whether this took place 100 years or 700 million years after the planet formed. This implies that either something extraordinary happened on Earth, or that the origin of life is a mundane phenomenon on young planets, given appropriate chemistry, environmental conditions, and enough time. Radioastronomy has provided a glimpse of the chemical inventory of the cosmos which does appear to be universal. Spectral signatures of a veritable zoo of organic compounds suggest that the Universe is strewn with the potential precursors of life. Organic carbon (in the form of carbon monoxide) has now been observed as far back as 13 billion years ago, only some 700 million years after the birth of the Universe in the Big Bang. The picture emerging, reminiscent of Chambers' universe, is that physics and chemistry are the same everywhere in the Universe, and that the Earth, although remarkable in many respects, may not be unique.

As in any factorial equation, the most important values are the ones with the largest uncertainty. Two approaches could shed light on the "f_l problem": the duplication of the process in the laboratory or the discovery of life on another planet. It is difficult to say whether the first approach will ever succeed to anyone's complete satisfaction, given that the origin of life on Earth was a historical event that happened when no one was around to witness it. The second approach, while fraught with technological difficulties, is perhaps more promising. To that end, numerous instruments and space missions have been designed and launched to explore the Solar System and beyond. The spectral signatures of planets around nearby stars are being monitored for the characteristic signs of life such as the signature of disequilibrium chemistry in the form of the presence in their atmospheres of both oxidized and reduced gases.

While the answers to the vast questions that define astrobiology as a field of study are unclear, it is evident that answering them will require an interdisciplinary effort, stretching across international borders. One is hesitant to speculate what the answer to the question, "Are we alone?" will ultimately be. As good scientists, we should probably withhold judgment until the data are in. As better scientists, we must join hands and find the data. The editors of the *Encyclopedia of Astrobiology* hope that this volume will contribute to this effort.

The Editors

Notes

1. A complete English and French version of the *Encyclopédie* can be found at http://quod.lib.umich.edu/d/did/
2. For a complete English translation of Pliny the Elder's *The Natural History* by John Bostock see http://www.perseus.tufts.edu/hopper/text?doc=Plin.+Nat.+toc&redirect=true. A complete Latin version can be found at http://www.perseus.tufts.edu/hopper/text?doc=Perseus:text:1999.02.0138:toc&redirect=true
3. Chambers R (1994) Vestiges of the natural history of creation and other evolutionary writings. University of Chicago Press
4. *Cosmos* was a remarkable 13-part popular science series narrated by Carl Sagan which aired in 1980. Most if not all of the episodes can be viewed on line, and a book was spun off: Sagan C (1985) Cosmos. Ballantine Books
5. For a survey of the early developments in astronomy, see Lankford J (ed) (1996) History of astronomy: an encyclopedia, first edition. Routledge
6. For an excellent discussion of the early history of chemistry (including the work of Black, Priestly and Lavoisier) see Partington JR (1989) A short history of chemistry, 3rd revised edition. Dover Publications
7. Lyell C (2010) Principles of Geology: Being an Inquiry How Far the Former Changes of the Earth's Surface Are Referable to Causes Now in Operation. Nabu Press (March 1, 2010). Originally published in three volumes between 1830–1833
8. Woese C, Kandler O, Wheelis M (1990) Towards a natural system of organisms: proposal for the domains Archaea, Bacteria, and Eucarya. *Proc Nat Acad Sci USA* 87(12): 4576–4579
9. For an insightful recounting of the early history of NASA's early efforts in exo- and astrobiology (including discussion of the roles of Wolf Vishniac and Frank Drake) see Dick SJ, Strick JE (2005) The living universe: NASA and the development of astrobiology. Rutgers University Press

Foreword

Are we alone? Long an object of speculation or fiction, if not heresy, this question entered the field of science on November 1, 1961, at the National Radio Astronomy Observatory in Green Bank, Virginia, where a number of scientists, including Melvin Calvin, who had just been awarded the Nobel prize in chemistry for his work on photosynthesis, and the charismatic Carl Sagan, gathered at the invitation of a young astronomer, Frank Drake, to launch the Search for ExtraTerrestrial Intelligence (SETI) project. Since then, batteries of increasingly powerful radiotelescopes have been scanning space for messages sent out by some extraterrestrial civilization. So far in vain.

At the same time, in the wake of widening space exploration, a new discipline was born that has the distinctive peculiarity of having three names – exobiology, astrobiology, bioastronomy – and no as-yet-known object. The purpose of this new discipline is more modest than that of the SETI project: to detect signs of extraterrestrial life, not necessarily intelligent.

To guide this quest, we have available vast knowledge that has been gained in the last few decades concerning the basic mechanisms of life. This knowledge, in turn, has illuminated our concept of the origin of life. Even though we do not know how or under what conditions this phenomenon took place, we may safely affirm that if life arose naturally, which is the only scientifically acceptable assumption, its origin must have depended on "chemistry." By its very nature, chemistry deals with highly deterministic, reproducible events that are bound to take place under prevailing physical-chemical conditions. If even a very slight element of chance affected chemical reactions, there would be no chemical laboratories, no chemical factories. We could not afford the risk.

A conclusion that emerges from this consideration is that life, as a product of environmentally enforced chemistry, was bound to arise under the physical-chemical conditions that prevailed at the site of its birth.

This statement, at least, holds true for the early steps in the origin of life, until the appearance of the first replicable substance, most likely RNA. Once this happened, "selection" became added to chemistry, introducing an element of chance in the development of life. Contrary to what has often been claimed in the past, this fact does not necessarily imply that the process was ruled by contingency. There are reasons to believe that, in many instances, chance provided enough opportunities for selection to be optimizing, and, therefore, likewise obligatory under prevailing conditions.

Thus, in so far as chemistry and optimizing selection played a dominant role in the process, the development of life appears as the obligatory outcome of prevailing conditions. Hence the assumption that the probability of the appearance elsewhere in the universe of forms of life resembling Earth life in their basic properties is approximately equal to the probability of the occurrence elsewhere in the universe of the physical conditions that obtained at the site where Earth life arose.

In the eyes of many astronomers, this probability is very high. It is estimated that some 30 billion sunlike stars exist in our galaxy alone and that the total number of galaxies in the universe is on the order of 100 billion. This means, to the extent that our galaxy may be taken as a representative sample of galaxies in general, there may be some 3,000 billion sunlike stars in the universe. Unless our solar system should be the product of extremely unlikely events, the probability of there being planets similar to Earth (or to whatever celestial object served as the cradle of Earth life) seems very strong.

Recent findings are most encouraging in this respect, by revealing that planet formation is not a rare event, with more than 400 planets already identified around a number of nearby stars. Although no habitable Earthlike extrasolar planet has yet been found, this may be partly due to technical limitations. The prospects that, with improved technologies, such a planet may be discovered some time in the future are far from negligible. Signs of life on such a planet, although more difficult to detect, may likewise yield to technological progress.

As by now, the enormous research effort expended within the framework of the new discipline of exobiology-cum-bioastronomy-cum-astrobiology has already produced a wealth of new findings, in fields ranging from physics and cosmology to chemistry, biochemistry, and molecular biology. These findings have provided rich material for this Encyclopedia. Its editors and authors are to be commended for making this material widely available in easily accessible form.

Christian de Duve
14 January 2011

Reference

1. de Duve C (2005) Singularities landmarks on the pathways of life. Cambridge University Press, New York

Editor-in-Chief

Muriel Gargaud
Laboratoire d'Astrophysique de Bordeaux
CNRS and Université Bordeaux 1
2 Rue de l'Observatoire
33270 Floirac
France
Muriel.Gargaud@obs.u-bordeaux1.fr
Field: Astrophysics

Book Editors

Ricardo Amils
Laboratory of Extremophiles
Departament of Planetology and Habitability
Centro de Astrobiología (INTA-CSIC)
Ctra de Ajalvir km 4
28850 Torrejón de Ardoz
Madrid
Spain
ramils@cbm.uam.es
Field: Geomicrobiology

José Cernicharo Quintanilla
Department of Astrophysics
Centro de Astrobiología (INTA-CSIC)
Ctra de Ajalvir km 4
28850 Torrejón de Ardoz
Madrid
Spain
jcernicharo@cab.inta-csic.es
Field: Astrochemistry and Astrophysics

Henderson James (Jim) Cleaves II
Geophysical Laboratory
Carnegie Institution of Washington
Washington, DC 20015
USA
hjcleaves@ciw.edu
Field: Chemistry

William M. Irvine
Goddard Center for Astrobiology and
Astronomy Department
University of Massachusetts
619 Lederle Graduate Research Center
Amherst, MA 01003
USA
irvine@astro.umass.edu
Field: Astrochemistry and Planetary Science

Daniele L. Pinti
GEOTOP and Département des sciences de la Terre et de l'atmosphère
Université du Québec à Montréal
CP 8888, succ. Centre-Ville
Montréal, Québec, H3C 3P8
Canada
pinti.daniele@uqam.ca
Field: Earth Sciences

Michel Viso
Astrobiology
CNES/DSP/EU
Paris
France
michel.viso@cnes.fr
Field: Space Missions and Planetary Protection

Field Editors

Francis Albarede
Ecole Normale Supérieure de Lyon
46, Allee d'Italie
69364 Lyon Cedex 7
France
francis.albarede@ens-lyon.fr
Field: Early Earth Geochemistry

Nicholas Arndt
Maison des Géosciences LGCA
Universite de Grenoble
1381 rue de la Piscine
38400 St Martin d'Hères
France
nicholas.arndt@ujf-grenoble.fr
Field: Archean Geology

Hugues Bersini
IRIDIA
Université Libre de Bruxelles
Avenue Franklin Roosevelt 50
B-1050 Brussels
Belgium
bersini@ulb.ac.be
Field: Artificial Life

Carlos Briones
Laboratory of Molecular Evolution
Centro de Astrobiologia (INTA-CSIC)
Instituto Nacional de Técnica Aeroespacial
Carretera de Ajalvir, Km. 4
28850 Torrejon de Ardoz
Madrid
Spain
brioneslo@inta.es
Field: Genetics and Evolution

Steven Charnley
Astrochemistry Laboratory
Solar System Exploration Division, Code 691
Science and Exploration Directorate
NASA Goddard Space Flight Center
Greenbelt, MD 20771
USA
steven.b.charnley@nasa.gov
Field: Interstellar Medium (gas phase)

Therese Encrenaz
LESIA
Observatoire de Paris
92190 Meudon
France
therese.encrenaz@obspm.fr
Field: Outer Solar System and Comets

Felipe Gómez
Laboratory of Extremophiles
Department of Planetology and Habitability
Centro de Astrobiologia (INTA-CSIC)
Ctra de Ajalvir km 4
28850 Torrejon de Ardoz
Madrid
Spain
gomezgf@cab.inta-csic.es
Field: General Biology

Gerda Horneck
DLR German Aerospace Center
Institute of Aerospace Medicine, Radiation Biology
51170 Koeln
Germany
gerda.horneck@dlr.de
Field: Microbiology in Space

Emmanuelle Javaux
Geology Department
University of Liège
17 allée du 6 Août B18
Sart-Tilman Liège 4000
Belgium
EJ.Javaux@ulg.ac.be
Field: Traces of Life

Lisa Kaltenegger
Harvard University
MS-20 60 Garden Street
Cambridge, MA 02138
USA
lkaltenegger@cfa.harvard.edu
Field: Planetary Atmospheres

Kensei Kobayashi
Grad. School of Engineering
Yokohama National University
79-5 Tokiwadai
Hodogaya-ku, Yokohama 240-8501
Japan
kkensei@ynu.ac.jp
Field: Chemistry

David W. Latham
Harvard-Smithsonian Center for Astrophysics
60 Garden Street
Cambridge, MA 02138
USA
dlatham@cfa.harvard.edu
Field: Extra Solar Planets

Juli Pereto
Institut Cavanilles de Biodiversitat i Biologia Evolutiva
and Departament de Bioquímica i Biologia Molecular
University of Valencia
Evolutionary genetics group
APDO. 22085
46071 València
Spain
pereto@uv.es
Field: Biochemistry

Nikos Prantzos
Institut d'Astrophysique de Paris
98bis Bd Arago
75014 Paris
France
prantzos@iap.fr
Field: Nucleosynthesis

Sean Raymond
Laboratoire d'Astrophysique de Bordeaux
CNRS and Université Bordeaux1
2 rue de l'Observatoire
33270 Floirac
France
raymond@obs.u-bordeaux1.fr
Field: Planetary Formation and Dynamics

Daniel Rouan
LESIA
Observatoire de Paris, CNRS, UPMC, Université
Paris-Diderot
5 place Jules Janssen
92195 Meudon
France
daniel.rouan@obspm.fr
Field: General Astrophysics

Tilman Spohn
DLR - German Aerospace Center
Institute of Planetary Research
Rutherfordstraße 2
12489 Berlin
Germany
tilman.spohn@dlr.de
Field: Inner Solar System and Asteroids

Steven Stahler
Department of Astronomy
University of California
Berkeley, CA 94720
USA
stahler@astro.berkeley.edu
Field: Stars Formation

Stephane Tirard
Centre François Viète d'Histoire des Sciences et des
Techniques EA 1161
Faculté des Sciences et des Techniques de Nantes
2 rue de la Houssinière, BP 92 208
44322 Nantes CEDEX 3
France
Stephane.Tirard@univ-nantes.fr
Field: History of Sciences