Planets and Life: The Emerging Science of Astrobiology

Astrobiology involves the study of the origin and history of life on Earth, planets and moons where life may have arisen, and the search for extraterrestrial life. It combines biology, biochemistry, paleontology, geology, planetary sciences, and astronomy. This textbook brings together world experts in each of these disciplines to provide the most comprehensive coverage of the field currently available. Topics cover the origin and evolution of life on Earth, the geological, physical, and chemical conditions in which life might arise, and the detection of extraterrestrial life on other planets and moons. The book also covers the history of our ideas on extraterrestrial life and the origin of life, as well as the ethical, philosophical, and educational issues raised by astrobiology. Written to be accessible to science students and scientists from diverse backgrounds, this text will be welcomed by advanced undergraduates and graduates who are taking astrobiology courses, as well as by practicing scientists who desire a comprehensive introduction to this emerging and exciting field.

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Planets and Life

The Emerging Science of Astrobiology

Edited by

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and

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Où finit le teléscope, le microscope commence.
Lequel des deux a la vue la plus grande?
[Where the telescope ends, the microscope begins.
Which of these has the grandest view?]

Victor Hugo (*Les Misérables*, 1862)

If the planets be inhabited, what a scope for folly;
if they not be inhabited, what a waste of space.

Thomas Carlyle (1795–1881)

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Preface

The emerging field of astrobiology encompasses a daunting variety of specialties, from astronomy to microbiology, from biochemistry to geology, from planetary sciences to phylogenetics. This is both exciting and frustrating – exciting because the potential astrobiologist is continually exposed to entirely new ways to look at the world, and frustrating because it is difficult to understand new results when venturing outside the confines of one's own specialty. There are now many excellent popular books on astrobiology, but a scientist wants more details and more sophistication than these afford. Where can an astronomer without any formal biology since high school learn the basics of cellular metabolism? Or the principles of evolution? Or notions about alternative forms of life? And where can a microbiologist with little physics and no astronomy learn the basics of how a planetary atmosphere works? Or how the Earth formed? Or how planets are detected around other stars? This book is designed to fill these needs.

We have endeavored to cover all the important aspects of astrobiology at an advanced level, yet such that *most* of the contents in *every* chapter should be understandable to anyone versed in any relevant science discipline. We envision our youngest readers to be science majors near the end of undergraduate study or the beginning of graduate study. And at the other extreme, we aim to serve scientists who haven't taken an academic course for forty years, but are intrigued by the nascent field of astrobiology. Readers should find this volume a challenging, yet accessible, way to get "up to speed" and "up to date" on the many facets of astrobiology.

While we anticipate that this book will be used for courses in astrobiology, and while it has a definite pedagogical aim, it is *not* in fact a textbook in the usual sense. A textbook, unlike this volume, would have chapter-end problems, uniformity of style, methodical development of concepts, and less idiosyncratic coverage of the various aspects of astrobiology. On the other hand, a single-author textbook of astrobiology, which must range over a multitude of disciplines, cannot carry the authority of the chapters herein.

Astrobiology at the University of Washington (UW) began with a graduate seminar offered in 1996, organized by us and also called "Planets and Life." This led three years later to establishing a graduate Astrobiology Program (depts.washington.edu/astrobio), largely funded by the IGERT (Integrative Graduate Education and Research Traineeship) program of the US National Science Foundation (NSF). As we struggled with how best to train astrobiologists in a limited time, the need for a book such as the present volume became evident. Our students obtain "normal" Ph.D.s in their home departments, but on top of that they complete various requirements for a Certificate in Astrobiology (see Chapter 28). The goal of the UW Astrobiology Program is to produce scientists who are firmly rooted in one of the disciplines that contributes to astrobiology, but also to expose each student to the other relevant disciplines: their fundamental questions and how they approach answers, their culture, and their terminology. We create intellectual and social connections between the disciplines to foster the asking of entirely new sorts of questions and their eventual answer. This all flies in the face of modern science, which usually drives its participants to ultra-specialization. If astrobiology is to succeed, however, the proverbial pendulum needs a push back towards synthesis, not unlike the synthesis that spawned molecular biology a half century ago (Section 28.1).

The individual chapters have been written by experts in the various specialties and leaders in shaping astrobiology today. We have asked authors to focus not on a standard review of their field, but on an introduction to the basics of the field and how problems are approached. In this way the scientific and educational value of the chapters should endure longer than usual. We have not tried to enforce too strict a uniformity in the styles of writing except for our Prime Directive: all jargon must be defined and most of each chapter must be understandable by nonexpert scientist readers. Whether we have succeeded will be judged by biologists learning about the subsurface ocean world on Europa, and by astronomers grappling with the RNA world on early Earth.

Sociologists chart the rise of new scientific disciplines through the appearance of textbooks, journals, and degree programs. So it is with emerging astrobiology. Below we give an annotated list of the astrobiology books and other resources that might be used as advanced texts or references at this time (although some are unfortunately far too expensive for even a professorial budget, let alone a student's!). The books are in order of usefulness and financial accessibility.

An endeavor such as this book does not happen without the aid of many persons and institutions. We and the UW Astrobiology Program have profited from the support of the University of Washington, NSF, and NASA. We also especially thank Arthur Whiteley and his eponymous Center for providing a marvellous scholarly retreat in the San Juan Islands where major portions of this book were edited and written. The NASA Astrobiology Institute and the UW directly supported the production of this book. Our astrobiology graduate students commented on chapter drafts (and are co-authors of three chapters), and have in essence taught us how we need to teach this new discipline. Linda Khandro and Nancy Quensé have also provided essential help through the years.

We thank especially those authors who have done what we asked and when we asked, and yet then been patient with wayward fellow authors and the editors in the face of delays. Cambridge University Press has also exhibited the patience of Job. WTS is extremely grateful for the supportive environment created for "The Book" by Barbara Sullivan. JAB would like to acknowledge the support of and helpful discussions with Jody Deming.

Resources for advanced astrobiology

Books

Existing astrobiology textbooks for *non*-science majors are listed in footnote 2 near the end of Chapter 28.

Lunine, J. (2005). *Astrobiology: A Multi-Disciplinary Approach*. San Francisco: Addison Wesley. Comprehensive and challenging textbook by a planetary scientist for advanced science undergraduates and graduate students.

Schulze-Makuch, D. and Irwin, L. N. (2004). *Life in the Universe*. New York: Springer. Excellent treatment of the nature of life, its properties, alternative types of life, and biosignatures; suitable for nonexperts.

Chela-Flores, J. (2001). *The New Science of Astrobiology: From Genesis of the Living Cell to Evolution of Intelligent Life*. Dordrecht: Kluwer. Idiosyncratic look by a physicist at life in a cosmic context; suitable for all scientists.

Horneck, G. and Baumstark-Khan, C. (eds.) (2002). *Astrobiology: The Quest for the Conditions of Life*. Berlin: Springer. Most chapters (by individual authors) are an outgrowth of a 2001 workshop on astrobiology held in Germany; uneven coverage and levels.

Gargaud, M., Barbier, B., Martin, H. and Reisse, J. (eds.) (2005, 2006). *Lectures in Astrobiology* (Vols. I and II). Berlin: Springer. Mammoth volumes of technical chapters (by individual authors) mostly on the early Earth, the origin of life, and other possible habitats for life; based on lectures in1999 and 2001 at French summer schools.

Ehrenfreund, P., Irvine, W. M., Owen, T., *et al.* (eds.) (2004). *Astrobiology: Future Perspectives*. Dordrecht: Kluwer. Technical chapters, mostly covering the context of life chemically (on Earth and in space) and geologically; based on a 2003 workshop in Switzerland.

Seckbach, J. (ed.) (2004). *Origins: Genesis, Evolution and Diversity of Life*. Dordrecht: Kluwer. Technical chapters covering a broad range of astrobiology, especially the origin of life.

Journals

Astrobiology (2001–). Mary Ann Liebert, Inc.

International Journal of Astrobiology (2002–). Cambridge University Press.

Other

Mix, L. (chief ed.) (2006). The Astrobiology Primer: an Outline of General Knowledge. *Astrobiology*, **6**, 735–813. Graduate students and postdocs in astrobiology have written short sections on the basics of each subfield of astrobiology (e.g., four pages on "life's basic components"); very nice resource to accompany the present volume.

Chyba, C. F. and Hand, K. (2005). Astrobiology: The study of the living Universe. *Ann. Rev. Astron. Astrophys*. **43**, 31–74. Best current review article.

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Prologue

A new synthesis: the Biological Universe

A remarkable shift in our scientific world picture is taking place, potentially as fundamental in its consequences as the new views put forth by Copernicus in the sixteenth century, or by Darwin in the nineteenth. Although astronomers have long been involved with the prospects for extraterrestrial life, their fundamental task since Newton has been to apply physics to a lifeless Universe. On the other hand, biologists have pursued their studies for centuries in cosmic isolation, meaning that biology considered life on Earth, with no attention paid to its cosmic context. Today, however, both camps are recognizing fruitful and exciting avenues of research created by a new synthesis. Biology is vastly enriched when attention is paid to a broader context for life as we know it, as well as the possibilities for other origins of life. And astronomy is coming to realize that the themes of cosmic, galactic, stellar, and planetary evolution, which have become central over the past century, must now also incorporate biological origin(s) and evolution(s).[1] Historian of science Steven Dick (1996) has hailed this new synthesis as the *Biological Universe*.[2][2] Although astronomy and biology are its two primary poles, many other disciplines are also vital components, in particular Earth and planetary sciences.

Astrobiology has become the rubric for this new synthesis, but it has also been called *bioastronomy*, *cosmobiology*, *biocosmology*, etc.[2] It has received a tremendous boost over the past decade because empirical science can for the first time powerfully address three questions that have always been fundamental to humans.

Fundamental questions

What is life?

What types of life differing from our own are possible? Our understanding of molecular genetics has allowed new insights into the mechanics of how life works, and results from studies on the origin of life have begun to elucidate the question of what separates a system of chemical reactions from a living entity.

What is the course of life?

How did life come to be? When and where did life first arise on Earth? How does life evolve? What are the limits of Earth life? What are the possibilities for future life? How might the answers to these questions change for other, extraterrestrial, locations? Is biology an inevitable stage of cosmology? Are the origins and evolutions of the physical Universe and of life part of a larger whole?

Are we alone?

This experimental aspect of astrobiology has become possible only with the technology of the past fifty years. New types of telescopes, as well as robotic visits to other planets, have meant that, guided by studies of Earth life, we can now actively search other worlds for evidences of extant life, of fossils, or of technology indicative of intelligence.

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[1] Note that the astronomer's usage of the term *evolution* refers to the change with time of an entity (such as a star), analogous to the ageing of an individual organism. On the other hand, the biologist's meaning for *evolution* is in the context of a specific theory of how life as a whole changes over time. Yet it is interesting how the two concepts are today melding, both within biology ("Evo Devo"; see Chapter 10) and in terms of the Biological Universe.

[2] In this Prologue superscript numerals in square brackets refer to chapter numbers that deal with the indicated topics.

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These three questions in turn inform the root question:

Who are we?

This question of course has many aspects beyond science, but our yearning for an answer drives much of today's astrobiology. Where did we come from? Are we here by chance or necessity? Where are we heading?

The public is also deeply interested in these questions, which can be a two-edged sword. Modern science is happy to have political and financial support (sometimes for billions) and educators find astrobiology a compelling lure to attract students to science. On the other hand, the beliefs of many of the public regarding extraterrestrial life, especially intelligent life, have less to do with science and more to do with wishful fantasies and Hollywood tales. This is often embarrassing to the astrobiologist. Historian Karl Guthke (1990) has rightly called extraterrestrial intelligent life society's modern myth, in the sense of a widespread quasi-religious belief satisfying deep needs.

Recent discoveries

Specific scientific developments over the past decade have helped create a sense of legitimacy for astrobiology, as has strong institutional support from the NASA Astrobiology Institute, founded in 1997.[2] The discovery of planets circling other stars, now numbering over 200 and since 1995 climbing ever higher, has made our own solar planetary system just one of a myriad.[21] The announcement in 1996 of evidence for fossil life from Mars in the meteorite ALH 84001 ironically is now thought to have been premature, but on the other hand the next claim could be right: subsequent studies have shown that microbial life could indeed travel and survive between planets on a rock rocket.[18] At about the same time, the NASA Galileo mission to Jupiter discovered strong evidence for a huge ocean of liquid water beneath the icy crust of the moon Europa – a bizarre potential habitat for life that has revolutionized our thinking about niches for life.[19] On Mars, the case for liquid water in the past has grown ever stronger over the past decade, culminating with the Mars Rovers (2004–) returning stunning geological evidence of extensive flowing water on the surface at Meridiani Planum.[18] The ESA/NASA Cassini/Huygens mission to Saturn (2005 and ongoing) has revealed unprecedented details of the amazing world of Titan, where today methane cycles through phases not unlike water's hydrological cycle on Earth, and the rich organic chemistry may teach us much about the prebiotic Earth.[20] And most recently, on the very day the manuscript for this book was sent off to the publishers, evidence was announced of organic compounds and geyser action on Saturn's small moon Enceladus, with possible liquid water just below the ice-covered surface (*Science*, 10 March 2006).

On the biological side, it has become increasingly appreciated how robust microorganisms can be in their adaptations right here and now on Earth, engendering further optimism that the extreme conditions of other planets and moons may be less of a deterrent than we had thought.[14,15] Moreover, new molecular and culturing techniques are being applied to decipher the physiologies of the "unknown majority" of microorganisms sampled in most Earth environments, about which we had been ignorant since they had no analogues among the characterized organisms in culture. For example, recent sleuthing of this kind has revealed novel photosynthesizing microorganisms, unique metabolic pathways for using carbon dioxide and methane as carbon sources, the importance of hydrogen as an energy source in many extreme environments, and unusual strategies for growth and survival in extremely nutrient-deprived environments such as the deep sea and deep marine sediments. It is likely that new organisms will be discovered that will expand our current view about the physiological versatility of organisms to grow and survive under environmental conditions not found on Earth. In addition, ever more powerful genetic and mathematical techniques now allow insights into the evolutionary history of life that, when combined with the geological record, reveal the complex manner in which new species and new adaptations arose.[10–13]

A science of optimism

Astrobiology is the scientific discipline of optimism – optimism that the grand questions are not only fundamental, but tractable; optimism that life has a good chance to exist elsewhere; and optimism that such life can be detected. Astrobiology tends to attract scientists who enjoy discussing radical ideas about science and are excited about the search for life elsewhere despite great difficulties and probably many decades at best before success.[28] Carl Sagan deserves special mention in this regard (Fig. 2.7). From 1960 onwards he was the consummate astrobiologist and an eloquent popularizer of science, often receiving great criticism for taking on each of these vital roles. We profit today from his lifelong belief in the field and his battle for its respectability. It is a shame that he did not live long enough to

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witness today's efflorescence of astrobiology. We commend his many excellent and inspiring books to younger scientists who no longer have the opportunity to experience the man directly.

There is a considerable scientific, philosophical and theological literature proclaiming the uniqueness of life (particularly human-like life) and its likely restriction to Earth among the billions of planets. The arguments expressed follow three primary lines: (1) the origin of life is so complex that it is not likely to occur more than once in the history of the Universe; (2) we and our Earth are too "special" to have evolved more than once (the Rare Earth hypothesis);[1,3] and (3) if intelligent life exists elsewhere, why have we not been notified (the Fermi Paradox)?[26] We cannot accept these arguments and the resulting a posteriori conclusion that we are lonely hunters trying to find meaning in a Universe of chance. The question of whether or not other intelligent life exists or has existed in the Universe may never be answered, but knowing the answer is not necessary in our search for life's meaning. How could we be lonely when we are intimately enmeshed in a Cosmos that inspires us in our search to understand how intelligent life arose on Earth from the same elements and physical principles that spawned the entire Universe? Should there be any doubt that at least in this sense we are not alone in the Universe?

Contingency or natural outcome?

Contingency has been billed as one of the most important arguments for our uniqueness as an intelligent species and our planet's uniqueness in supporting intelligence. The late paleontologist Stephan Jay Gould expressed this idea in *Wonderful Life* (1989) by positing that a "rewinding and replaying of the tape of life" to life's origin would result in a completely different outcome after 4 Gyr of evolution, and very likely not including the likes of us. An example of his views:

> Since dinosaurs were not moving toward markedly larger brains, and since such a prospect may lie outside the capabilities of reptilian design, we must assume that consciousness would not have evolved on our planet if a cosmic catastrophe had not claimed the dinosaurs as victims. In an entirely literal sense, we owe our existence, as large and reasoning mammals, to our lucky stars. Gould (1989)

Gould misses the point that catastrophic events, including killer impacts and other events that cause radical changes in atmospheric chemistry and temperature,[3,4,17] are features of the environment, natural outcomes of physical laws. These events occur and cause long-term effects frequently enough that evolution has selected traits that allow organisms to survive these events and in most instances take advantage of new habitats thus created. Moreover, we do not know if intelligent mammals or some other animal lineage would have evolved alongside the dinosaurs – why does intelligent life have to look like us? Catastrophic extinction events are as natural as tides changing or temperatures shifting. There would be no life-supporting planets without impact events.[3]

While Gould was only concerned with our own emergence on Earth, similar arguments have been made about the improbability of a second instance of life. But how can we confidently make this assertion when we do not even know how life originated on Earth or if there are many different ways to make life?[6–9] Indeed, we cannot even agree on a definition of life.[5] What we do not *yet* understand, however, should not be considered as *never* scientifically understandable. These conundrums and others illustrate how biology is in many ways hamstrung by having only one example of its primary phenomenon, a problem that astrobiology modestly aims to solve. The history of science has shown that the acquisition of a second data point, $n = 2$, or at least a great extension of $n = 1$ to previously untapped realms, often leads to a more general theory and profound breakthroughs. Witness the extension of Newtonian gravity to general relativity, the discovery of viruses in the early twentieth century ($n = 1.5$?), the realization over the past decades that dark matter and dark energy dominate over "normal" matter in the Universe, and, as mentioned, the new extrasolar planetary systems, most of which are nothing like our familiar Solar System.[21]

The origin of life is very likely a solvable problem and one that could possibly become much easier if we found life elsewhere, whether that life form were identical to Earth life or quite different. Conversely, the more we understand about the origin of life on *this* planet, the better our chances to recognize and detect elsewhere biochemical precursors to life or early stages in the evolution of the cell. Understanding the conditions here that favored the origin of life and its evolution will also greatly aid in identifying candidate planets and moons that now have or have had the potential to generate life.[18–22]

An astrobiological optimist believes that the origin and evolution of life has less to do with chance and more to do with principles of nature, including many

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we do not yet fully understand. In response to Gould, fellow paleontologist Conway Morris (1998) expresses the view that there may be limits to the number of evolutionary possibilities. For example, the emerging science of Evolution/Development ("Evo Devo") has altered our perception of convergent evolution (separate evolution of similar traits) by showing that groups of regulating genes, ubiquitous in all animal lineages, control the evolution of animal form and organ development (Carroll, 2005).[10] Evo Devo also offers plausible mechanisms for explaining the onset of the Cambrian explosion. The incredibly diverse body forms that appeared very quickly among the newly emerged animals [16] are believed to be a consequence of the evolutionary appearance of these key regulating genes.

Moreover, even at the level of organic chemistry, there appear to be rules that allow prediction of the kinds of complex organic compounds that can be formed and the conditions that favor their formation. These rules should inform the definitions of biosignatures that we will employ in our search for evidence of life elsewhere.[22,23] It is interesting that life also restricts the number of possible biochemical structures.[6,7] For example, cholesterol theoretically has 256 possible stereoisomer structures, yet life only synthesizes one. There are also rules in biochemistry restricting the number of possibilities for how macromolecules become synthesized and then fold and twist into complex three-dimensional structures.[3] It is likely that some of the early chemical steps that can lead to the development of life are very common in the Universe and, depending on the environmental conditions of the planet and its evolution, sometimes (commonly?) lead to complex biochemical structures and living cells. The key is the degree of habitability of the planet – whether or not conditions evolve that favor the development of ever-greater complexity, from organic compounds to organisms.

The bio-friendly Universe

Further extending the notion that life is a natural, perhaps inevitable, product of cosmic evolution, we come to the *Anthropic Principle*, the "weak" form of which, a self-selection principle, says that the Universe must be bio-friendly (to use cosmologist Paul Davies's felicitous term), since we sentient beings have succeeded in arising within its confines and insist on writing books about it (Barrow and Tipler, 1986). Further investigation reveals a remarkable panoply of physical constants (such as the gravitational constant G) and cosmological properties (such as the size of fluctuations in the cosmic background) whose values seem *very* "finely tuned," i.e., slightly different values would yield a Universe where life (especially intelligent life) as we know it *could not* exist. For example, the very existence of long-lasting stars rests on a delicate balance that can be thrown off by adjusting any one of many physical values. As with the biochemistry discussed above, it appears that the Universe *must* be like it is in its various physical details, or we would not be viewing it! This brand of thinking, called the Strong Anthropic Principle, is pre-Copernican, in that we revert to a Cosmos all set up for our benefit – a scientist of the early twenty-first century finds it unsettling (Falk, 2004). As the physicist Freeman Dyson (1979) says:

> The more I examine the Universe and study the details of its architecture, the more evidence I find that the Universe in some sense must have known that we were coming.

A recent theory that explains the bio-friendliness of the Universe in a post-Copernican manner has been developed by James Gardner (2003). Inspired by work of several leading cosmologists over the past decade, Gardner has developed a scheme whereby an entire universe evolves along with its intelligent life. This intelligence eventually develops (over huge times compared to the present age of the Universe) the ability to fabricate new universes that are designed to be even better at producing intelligent life. The physical laws and constants of any universe are its blueprint or "DNA," as established by its "parent," so they are necessarily designed to optimize life and intelligence. This is heady stuff, to be sure, but astrobiology fosters debates over concepts like this – for example, is there a way to test this theory? Is such thinking the best of scientific creativity, or does it dangerously border on religion and just-so stories? In either case, we see the intimate links, today as throughout the past, between cosmology and astrobiology.

Analogies to Earth and its life

The one model of a living planet that we have, Earth, provides us with a set of key characteristics that have affected and continue to shape the diversity and

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[3] A recent study indicates that even the origin of the genetic code might have little to do with contingency and more to do with rules of chemistry (Copley *et al.*, 2005).

complexity of life. Earth as a tectonically active, aquatic planet produces volatile gases such as carbon dioxide, methane, hydrogen, and hydrogen sulfide, which in the early stages of its history resulted in a greenhouse atmosphere.[4] This atmosphere helped maintain a liquid water ocean and otherwise contributed to the chemical events that led to the origin of life and later provided the chemical energy sources for Earth's fledging life forms.[9,11] The continuing interactions between organisms and their environments resulted in complex biogeochemical cycles and periods of relatively stable atmospheric and ocean geochemical conditions. The evolution of photosynthesis and the accumulation of oxygen in the atmosphere are thought to have been the key to the evolution of complex animals.[4,12] Imposed on this were catastrophic events including impacts by giant bolides, volcanoes, magma plumes and possibly "snowball Earth" periods which resulted in major extinction events and changes in habitat conditions that led to selection of different communities of organisms.[16,17]

Earth may, however, be just one of many possible models for planets that can evolve complex life.[27] We know only one kind of life:[27] (a) it is carbon-based, (b) it requires liquid water, and (c) it has evolved in a Darwinian sense under particular environmental conditions into complex organisms that ask questions, experience love and hate, and commune with gods. But we do not know how wise it is to assume that planets outside of our perception of a habitable zone[3] could not harbor life, particularly life as we *don't* know it. Our practical search for extraterrestrial life is focused on aquatic planets and moons because of the possibility that they can support Earth-like life. Of course, this does not prevent the astrobiology community from thinking about ways in which carbon-based life could thrive in non-aqueous solvents such as exist on Titan[20] or in the hot, sulfuric acid atmospheric of Venus. Even more radical is the possibility of "weird life" on extremely hot, cold, or gas giant planets (Feinberg and Shapiro, 1980; Schulze-Makuch and Irwin, 2004).

Astrobiology rests on a Great Analogy, that between the one known case of a life-bearing planet and other potential extraterrestrial loci for life.[1,2] To a philosopher an argument by analogy is inductive and can never logically prove anything. It can only be relatively strong or weak depending on the number and quality of properties listed to be analogous/similar versus those that are contra-analogous/dissimilar (and of course all properties must be deemed relevant). But in most realistic cases there are numerous properties to consider, and the sticky issue is how to *weigh* the competing arguments. The philosopher John Stuart Mill in his *System of Logic* (1843) discussed arguments by analogy in general and then gave as an example none other than the question of whether the Moon or planets were inhabited. Mill concluded that, despite many positive attributes of the Moon, its apparent lack of water trumped all other properties and it therefore was not likely inhabited. For the planets, however, he came to a different conclusion that is well for us to note. He opined that there was so little information on, say, Mars that we should not come to *any* conclusion based on analogy.

So is the Great Analogy an unsound foundation for astrobiology? Not at all, says Mill, for analogical reasoning suggests scientific experiments that can provide further insight (Crowe, 1986: 231–2). This in fact is what we do in astrobiology as we make our analogies and argue about the relative weights to apply, then recast the analogies based on new knowledge of Earth life, then generate new working hypotheses and consider new extraterrestrial sites as analogues, and so on. Astrobiology rekindles the relationship between philosophy and science in this and many other ways.[1,2,5]

The promising future

Ultimately, analogies do not satisfy. Astrobiologists, arch empiricists, therefore go out and explore. This is what makes the field so exciting, for new technologies mean that, if public support continues, by 2025 we will have returned samples of rocks from Mars, carefully chosen to optimize the chances for finding evidence of past or extant life.[18,22] We will have landed on Europa, perhaps even have drilled through its ice.[19] We will have searched several million Sun-like stars for extraterrestrial radio signals of intelligent origin (SETI).[26] We will have detected Earth-sized planets of moderate temperatures around many stars, and in some cases determined the composition of their atmospheres.[21] We will have made significant progress in understanding the history of life on Earth, and perhaps as well the origin of life.

We will have made great strides in discovering the physiological versatility of the microbial world and how evolution has experimented with more possibilities then can now be imagined. The microbial communities in sub-seafloor crust will have been found to have an ancient origin and the capacity to thrive in the absence of chemical nutrients derived from sunlight-driven photosynthesis. Through studies of viruses associated with organisms that live in the most extreme environments,

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we will have made significant advances in understanding the origin of viruses and their pivotal roles in the origin of life, as well as in biocomplexity and diversity. We will likely have been able to create carbon-based life forms that grow in environments beyond the bounds of Earth environments, allowing us to better understand the ultimate limits for carbon-based life. Finally, it will have been recognized that evolution is an essential feature of *all* life, on Earth or elsewhere.

While this volume only touches on the broader philosophical questions that astrobiology engenders,[5,24,25] inherent in many chapters is a sense of the profound implications if life, particularly intelligent life, were discovered elsewhere in the Universe.[26] Will we have found strong evidence for extraterrestrial life within the lifetime of our younger readers? This of course is not knowable, but a positive answer will certainly thrust us into a new philosophical framework. And a negative answer, if the past be any guide, will still have yielded a great deal of ancillary information about life on Earth and how to better define the search.

Successful or not in finding extraterrestrial life, astrobiology will make important contributions to helping us answer that root question: *who are we?*

> We have found a strange footprint on the shores of the unknown. We have devised profound theories, one after another, to account for its origins. At last, we have succeeded in reconstructing the creature that made the footprint. And lo! It is our own.
>
> Arthur Eddington (*Space, Time and Gravitation*, 1920)

> We shall not cease from exploration
> And the end of all our exploring
> Will be to arrive where we started
> And know the place for the first time.
>
> T. S. Eliot (*Four Quartets*, No. 4, 1942)

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