PART I INTRODUCTION

The volume you hold in your hands is the result not of a workshop or a conference, but of a "Study Week" in astrobiology. The distinction is important, because the term connotes a definite period of time in which participants, literally cloistered in the Pontifical Academy of Sciences within the walled Vatican City, confronted each other's research and together gained new insights by studying the connections. The usual bustle of a scientific conference was absent, as was the distraction of a dramatically seductive natural wonder (beach, mountains, forest) that seems obligatory at scientific workshops. In their place was the classical serenity of the Casina Pio IV, the unobtrusive and continuous maintenance of food and comfort by our gracious Vatican hosts, and a rich interchange of ideas that flowed effortlessly among the participants, making the week seem almost tragically too short. (In the interests of full disclosure, there were memorable visits to the remarkable town of Assisi and to the Vatican Museum, hosted again by the Pontifical Academy). Under such wonderful conditions, we all learned volumes from each other, so that the chapters you are about to read will reflect, we hope, a broader vision than might have been expounded before the Study Week.

As for the subject matter of this book, it speaks for itself. The usual introduction to a book on astrobiology includes a section, sometimes lengthy, defining the field and explaining its scope, and assuring the reader that it is indeed worthy of their attention. We will eschew that approach here, and say simply that the Study Week explored issues related to one of the most profound questions humans can ask in science: Is there life beyond Earth? If that question provokes your interest, then read on. As editors, we have paired authors of differing disciplines or viewpoints and asked them to write their chapters in a seamless, collaborative style. By common assent, the authors have written chapters for a much broader audience than would normally read a volume of conference proceedings. We hope we have been successful, and readers with an active interest but perhaps a modest background in science will find this book an entrée to a vibrant, interdisciplinary field.

It is a pleasure to express our deepest gratitude to the Pontifical Academy of Sciences for organizing and hosting the Study Week on Astrobiology, and especially to His Excellency Msgr. Marcelo Sánchez Sorondo, its Chancellor. We are very grateful as well for the support and presence of His Eminence Giovanni Cardinal Lajolo, emeritus President of the Pontifical Commission for Vatican City State, whose beautiful words of welcome grace the opening pages of this book. Finally, we are grateful to our colleagues who took time away from their research to come together in Vatican City, to engage in the purest form of scientific exchange, and then to write the chapters comprising this book. For all their insights, we thank them.

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Inauguration of the Study Week on Astrobiology

CARDINAL GIOVANNI LAJOLO

It is with great pleasure that I welcome all the distinguished scientists convened here, at the invitation of the Pontifical Academy of Sciences, to discuss a theme that is as new as it is difficult and fascinating: Astrobiology. It is a field which requires a range of all but the most profound of scientific knowledge, as well as highly refined research techniques, and it means often proceeding on the basis of scarce evidence and formulating hypotheses requiring strict verification, which in turn can be diversely configured. It means resorting to results of research based on extreme aspects of the possibility of life on Earth, and to study how to verify its presence on other planets or exoplanets. It means – at its limit – studying if and how one could verify the existence of extraterrestrial forms of intelligence and how to enter in contact with them. This is a task that demands scientific integrity, not to be confused with science fiction.

In your study, which represents, I would say, an intense and indispensable case of vast multidisciplinary research, I don't doubt that you will find yourself accompanied and stimulated by that human atmosphere of collegiality and friendship offered by the Pontifical Academy of Sciences.

In research we should not fear the truth. Only the error, which lies in ambush, can cause us fear. But the scientist must also be allowed the possibility to walk paths which do not always lead to positive results, otherwise it would not be research. Nonetheless, even these types of errors are never useless, precisely because, being led by the scientific method, they help us test other paths. And it is thus that the sciences are able to progress, and just as they open humanity to new knowledge, they contribute to the fulfilment of man as man.

Illustrious ladies and gentlemen, at the beginning of your week of study, I am very glad to offer you all a cordial welcome, good wishes for a successful collaboration, and the Blessing of the Holy Father.

Unfortunately, I am not able to participate personally in your lectures and discussions as I would certainly like, not for any competence I have in the field but merely to open myself to new horizons of knowledge. However, to accompany you on behalf of the Vatican, will be our scientists from the Vatican Observatory guided by their Director Jesuit Father José Gabriel Funes.

We will see each other again in Assisi, as scheduled in the programme prepared by His Excellency Monsignor Sanchez Sorondo, Chancellor of the Pontifical Academy of the Sciences, whom I want to thank for his renowned and always cordial hospitality.

I hope you will remember these days as rich in intellectual gratification and benevolent friendship among your scientific colleagues. I wish you very fruitful work.

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Astrobiology – A New Synthesis

JOHN BAROSS AND CHRIS IMPEY

Introduction

It is easy to envision our earliest ancestors, hands under chins, staring out into starlit space, wondering about their existence and how they came to be. With infinite possibilities it is no wonder that a myriad of gods could show their face in the galaxies and set the stage for the birth of religions, their theology, a moral code of ethics, a special and exclusive position for humans, and eventually a method of inquiry that has led to modern science. Furthermore, the early history of thought about life elsewhere in the universe was linked to more of a theological perception of man's relationship to gods, and Earth as the exclusive domain of life – exemplified in the thirteenth-century Aristotelian–Thomistic synthesis of science and religion.

It is particularly interesting and germane to astrobiology today, that it was astronomers, and particularly those in the fifteenth to seventeenth centuries, that were the first to make quantitative observations that questioned the orthodox view of man's place in the universe. One looked to the heavens for answers to the most profound philosophical questions and in doing so helped establish the scientific method as another method of inquiry. Perhaps a lesson from this early philosophical-based history is that the drive to grow knowledge is a fundamental and perhaps evolutionary characteristic of humans. The implication is that our survival is likely to be dependent on our exploring all possibilities that help us to understand the how, why, and uniqueness of our existence. Perhaps, no topic inspires this need to explore more than the search for life elsewhere with its implications for the origin of life and the possibility of life forms unrelated to Earth life.

Frontiers of Astrobiology, ed. Chris Impey, Jonathan Lunine and José Funes.

There are obvious parallels between our explorations for evidence of life in the universe and Darwin's almost five-year voyage on the *HMS Beagle* that spawned his theory of evolution by natural selection. Like Darwin's *Beagle* voyage, the current astrobiology "voyage" in search for life throughout the universe promises to profoundly alter and expand our notions of life, its origin, and a test of Darwin's (1979) notion that "from so simple a beginning endless forms most beautiful and most wonderful have been, and are being evolved." Moreover, as in Darwin's time when there were broad social and philosophical implications to the theory of evolution, there would be even broader implications if extraterrestrial life were found to exist, a second origin of life were discovered, or life very different from Earth life were found that could exist outside the bounds for life on Earth – and, even more profound, extraterrestrial life that we can communicate with.

In *The Origin of Species*, Darwin (1979) opined about natural selection: "I can see no limit to this power, in slowly and beautifully adapting each form to the most complex relations of life." While most of the diversity of life and particularly microscopic life during Darwin's time was mostly unknown, today we are beginning to appreciate the full scope of Darwin's vision of natural selection in the almost limitless diversity of life forms. There are very few environments on Earth that are incapable of supporting life – only extremes in temperature and the availability of liquid water limit Earth life.

In the search for life on other planets and moons both in our Solar System and beyond, we not only look for evidence of "life" as we know it, we also explore the possible evolutionary adaptation of "life" to conditions outside the bounds of Earth environments that are known to exist on other planetary bodies – what has been described as the search for "weird life." Some of these environmental conditions that might support life on other planetary bodies include liquid organic solvents instead of water, temperatures considerably colder than freezing or hotter than boiling where water might remain liquid due to high salt concentrations, high pressure or presence of organic solvents, or the use of energy sources other than light or chemical – the two sources used by Earth life.

Thus, astrobiology questions some of the fundamental tenets of Earth life including their canonical characteristics: Do we fully understand the evolutionary possibilities of the only life we know, and its limits? Is Earth life the best of all possible life forms? Would Darwinian selection always result in life resembling Earth life? Are there multiple ways to make life, even life as we know it? Like the astronomers of the past, we (as astrobiologists) seek the answers to these and other questions through exploration of the universe.

History and goals

The earliest published use of the word astrobiology is ascribed to Lafleur (1941) who defined it as "the consideration of life in the universe elsewhere than

Earth" (reference and quote from Chyba and Hand 2005). In 1957, a symposium described as "the first American symposium in astrobiology" was held in Flagstaff, Arizona, interestingly, just months before the Soviet Union shocked the United States with its launch of Sputnik 1 (see Smith 2004 for more details). By 1958, the National Academy of Science created the Space Studies Board, and shortly afterwards the National Aeronautics and Space Administration (NASA) was also created. While much of the initial US response to the launch of Sputnik 1 was politically motivated, the potential for biological discoveries from space exploration was not lost on the science and lay communities. Smith (2004) quotes from the book, *Science in Space* (Berkner and Odishaw 1961): "Unquestionably, the possibility that some form of living matter exists on other planets is the most exciting prospect: the origin of life under radically different conditions of environment and ecology is a subject of unprecedented significance to fundamental biology."

Before the formation of the NASA Astrobiology Institute (NAI) in 2004, the word exobiology, ascribed to Joshua Lederberg (1960), was widely used by NASA and the science community to describe the scientific study of life beyond Earth's atmosphere. Exobiology is still in use but generally more focused on studies of the origin and evolution of life.

The motivation behind Lederberg's interest in exobiology was his concern about interstellar contamination, both forward contamination by Earth organisms and back contamination that might include a pathogen to which we had no immunity. Lederberg was one of the founding members on the Space Studies Board established in 1958 and was very influential in formulating the Space Studies Board recommendations that all spacecraft be sterilized before launch and that samples returned from other planets be quarantined until determined to be harmless. NASA maintains these recommendations, presently under the control of a Planetary Protection Officer.

The Viking mission to Mars in 1976 was the most ambitious and expensive NASA program to date. At the time, state-of-the-art experiments were designed to detect life in Martian surface samples. Because the mission was unsuccessful in finding evidence of life, interest in astrobiology seemed to wane for almost 20 years. NASA continued to fund laboratory research in exobiology and particularly in origin-of-life related studies. While somewhat dampened by the results of the Viking mission, there remained generally keen interest in the possibility of life on Mars. The issue became more focused on how and where to sample on Mars and what to look for.

Twenty years after the Viking mission, the question of what to look for, or what are definitive signs of life, became the central issue in the claim by McKay *et al.* (1996) of evidence of life including fossil microorganisms in the Martian meteorite ALH84001. The McKay paper stimulated much discussion and debate with the conclusions being scrutinized by the scientific community (see Jakosky *et al*. 2007 for a thorough discussion of ALH84001). However, the seed was sowed that would blossom into then President Clinton's proposed NASA budget that would fund a new initiative in the study of "Origins – of life, planetary systems, stars, galaxies, or the universe" (Smith 2004). Significant funding was available for missions to Mars, Europa, and for the establishment of a program in astrobiology. In 1997, the NASA Astrobiology Institute was established.

It is interesting that the Mars Global Surveyor Orbiter, launched three months after the publication of the McKay *et al*. (1996) paper, captured images that showed the strongest evidence that liquid water did exist on the surface of Mars. The most dramatic example was from the Nanedi Vallis in the Xanthe Terra region. The Mars Odyssey Orbiter, launched in 2001, obtained dramatic evidence from hydrogen spectral measurements that extensive areas of water ice still exist below the surface of Mars. More recently, the Mars Exploration Rovers obtained confirming evidence of extensive quantities of liquid water existing on the surface and in the subsurface of Mars in the past. Moreover, the Mars Rovers identified iron and magnesium silicates and serpentine, and other minerals that also implicate water–rock interactions (Ehlmann *et al*. 2009, Mustard *et al*. 2008). On Earth, these water and mineral interactions, known as serpentinization reactions, produce hydrogen, methane, hydrocarbons, and organic acids, and result in alkaline conditions that support a hydrogen-based microbial community involved in methane production and consumption (Kelley *et al*. 2005). The recent evidence that methane may be escaping into the atmosphere from the subsurface of Mars (Mumma *et al*. 2009), and may be formed by serpentinization reactions, adds to the intrigue that Mars has the potential to support subsurface microbial communities today, or at some time in the past.

Besides the significant results from the Mars Orbiters and Rovers, the time since 1996 has seen many breakthroughs in astrobiology related research. Observations from the Hubble Space Telescope identified protoplanetary disks around young stars that have been hypothesized to lead to planetary systems. Observations from the Galileo spacecraft suggest the presence of a liquid ocean below Europa's icy surface. Cassini/Huygens reveals that Titan has organic solvent lakes suggesting this moon of Saturn may be an exciting laboratory for understanding prebiotic biochemistry. Cassini also made close passes by Enceladus, another moon of Saturn, and found water-rich geysers spewing organic compounds.

The first extrasolar planet was also identified during this period and since then more than 700 extrasolar planets have been reported, plus several thousand candidates awaiting confirmation. NASA's Kepler mission, launched in 2009, has obtained data estimating more than 50 million planets in our Galaxy. Given the rapid advancements in our technology to detect extrasolar planets, and measure and model their atmospheres, it is quite likely that an Earth-like planet in a habitable zone will be discovered during this decade (Impey 2010).

Coupled with these discoveries are advances being made in the biological sciences. For example, the application of new molecular methods has unveiled a huge phylogenetically and physiologically diverse group of previously unknown microorganisms and viruses, referred to as "the unknown biosphere." We now estimate that there may be more than one billion species of microorganisms of which less than 10 000 have been characterized. The physiological diversity of these unknown microbes, and particularly those from extreme environments, may greatly expand the environmental limits of carbon-based life. Another application of molecular tools is to control evolution and construct organisms that have the potential to grow under environmental conditions not found on Earth but on other planetary bodies. This line of research could ascertain the actual environmental limits of carbon-based life; it is also a line of research fraught with ethical issues.

These scientific discoveries are part of the backdrop to the NASA Astrobiology Institute. The guiding principles of this new discipline involve questions and issues that are multidisciplinary and that require an interdisciplinary approach to address. Astrobiology is focused on three basic questions: "How does life begin and evolve? Does life exist elsewhere in the universe? What is the future of life on Earth and beyond?" (Des Marais *et al*. 2008). The astrobiology roadmap identifies seven goals that expand on these three basic questions with the life sciences being the driving theme. Thus, astrobiology will endeavor to make life a central component of future missions to planetary bodies in our Solar System, in our search for Earth-like exoplanets, and in theories and models of the origin of the universe. It will also foster research to better understand life on Earth: its history, evolution, diversity, and limits, with a goal of increasing our chances of detecting life elsewhere. We might discover that life is a natural and inevitable product of cosmic evolution.

Defining life – Is it necessary?

Astrobiology, broadly defined as "understanding the origins, evolution, and distribution of life in the universe," forces us to confront an essential question in science: What is life and how did it originate? The search for life elsewhere begs this question. Even the simple assumption that all life in the universe will resemble Earth life restricts our search for life to Earth-like planets. While we don't yet know how life arose, we assume that it originated some four billion years ago on the Hadean Earth rather than being delivered to Earth from elsewhere. What were the conditions of the Hadean Earth that were essential to the origin of life and how would we be able to determine if other planetary bodies went through Earth-like geophysical and geological transformations that could lead to an independent origin of life or if planets with a different history could spawn a different form of life?

Any definition of life would have to include any living entity even if it were radically different from Earth life. This implies that a definition of life is not a list of canonical characteristics possessed by Earth life, such as being carbon-based, self-replicating, and having the ability to undergo Darwinian evolution. A case can be made that the ability to replicate and undergo Darwinian evolution are essential characteristics of all life even if significantly different from Earth life. However, these requirements would not be part of a definition of life, but instead essential mechanisms to produce progeny and to create diversity and complexity (Baross 2007). What we don't know is how all of the components that make up a living entity become life – the "gestaltian" issue. Cleland and Chyba (2007) approach this dilemma by rightly pointing out that "to answer the question 'What is life?' we require not a definition but a general theory of the nature of living systems." This theory does not yet exist.

In the absence of a theory of the nature of all possible living systems, searching for evidence of past or present life on other planets relies on understanding the physical and chemical characteristics germane to life, and the properties of life itself. The presence of water, essential elements, and sources of carbon and energy define the Earth conditions that allow life to thrive. Living organisms also leave a signature of their existence, either as cellular remnants or as chemical indicators such as the fractionation of carbon, nitrogen, sulfur, and oxygen isotopes, and chemical elements out of normal equilibrium known in lifeless environments. Again, the assumption is that carbon-based life on an Earth-like planetary body will affect chemical transformations in a way analogous to Earth organisms. An example of this line of thinking is the principle of "follow the energy" (Hoehler *et al*. 2007), that posits that energy sources used by terrestrial life forms would be used by any life forms even if they are radically different biochemically.

While some in the scientific community debate whether or not a definition of life is possible, the astrobiology community has adopted the practical view of looking for life elsewhere that is recognizable as life because of its resemblance to Earth life; that is, it is carbon-based, requires water, and uses either chemical or light energy. Life having these characteristics will also leave some signature from its existence even if it is presently extinct. Astrobiology endeavors to better understand the full range of these biosignatures on Earth and elsewhere, from living organisms or their fossils to remotely measured disequilibrium in atmospheric gas chemistry of extrasolar planets. It is assumed that extraterrestrial life, no matter how different from Earth life, will leave its mark – we just need to be able to read the signs.