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# Astrobiology—Exploring the Living Universe

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**The new discipline of astrobiology, the study of life in the universe, addresses fundamental questions: Where did we come from? Are we alone in the universe? What is our future beyond the Earth? New capabilities in biotechnology, informatics, and space exploration provide the tools to address these questions. NASA has encouraged this new discipline by organizing workshops and technical meetings, establishing a NASA Astrobiology Institute, providing research funds to individual investigators, ensuring that astrobiology goals are incorporated in NASA flight missions, and initiating a program of public outreach and education. This paper describes the primary scientific goals of astrobiology at its inception, drawn from the NASA Astrobiology Roadmap.**

## Introduction

SINCE the beginning of history, people have speculated about the origin of life on Earth and the forms life might take on other worlds. Such questions grew in importance with the emerging realization that the Earth is only a minor planet circling a second-rate star in the outskirts of one galaxy among trillions. The so-called Copernican Principle hypothesizes that there is nothing unique about the Earth, and by implication there should be many other worlds like our own, populated by their own forms of life. Until recently, however, the plurality of inhabited worlds was essentially a philosophical construct, without much foundation in fact. It was relatively easy to believe in alien life forms in the abstract, as long as we had no way to contact these creatures or to verify their reality directly.

All of this changed when our civilization developed spacecraft that can land on Mars, telescopes that can detect planets circling other stars, and radio receivers sensitive enough to eavesdrop on microwave transmissions (if any exist) from nearby planetary systems. Astrobiology is the scientific discipline that brings these space-age technologies to bear on fundamental questions about life on Earth and in the universe. Because of the broad interest of our species on the nature of life, astrobiology can provide a unifying thread to tie together a variety of NASA programs and help focus public interest on space science and exploration.

As defined by NASA, astrobiology is the study of the origin, evolution, distribution, and destiny of life in the universe. It uses multiple scientific disciplines and space technologies to address some of the most profound questions facing humankind: How did life begin? Are there other planets like Earth? What is our future as terrestrial life expands beyond the home planet? For the first time in human history, advances in the biological sciences, space exploration, and space technology make it possible for us to progress toward answering these questions.

Astrobiology represents a synthesis of disciplines, from astronomy to zoology, from ecology to molecular biology, and from geology to genomics. Scientists from these disciplines are all working toward a common goal: discovering the thread of life in the universe. They will use cutting-edge research tools and facilities, such as the International Space Station, the Next Generation Space Telescope, and new robotic missions to Mars and Jupiter's moon Europa. In this context, investigating life can range from observing primitive microbes that flourish at deep hydrothermal vents to computer simulation of a proto-cell's metabolic processes, from searching for extraterrestrial planets to experimental testing of the adaptability of terrestrial life in space. It can include studying the natural processes that spread life beyond its planet of origin, such as meteorite transport, as well as the possibility of ecosynthesis to create new biospheres on other worlds.

A new field like astrobiology needs to establish its identity and define its goals. Several workshops in the middle 1990s addressed the main scientific themes for astrobiology. These themes were used as candidate research topics in the selection of the first 11 member institutions of the NASA Astrobiology Institute (NAI), which began operations in 1998. The NAI, which now has 15 member institutions in the United States and 3 foreign partners, coordinates and supports the research of more than 500 scientists, primarily in academic institutions. The NAI Director is Nobelist Baruch Blumberg. Many other scientists receive direct funding from NASA for astrobiology research, which is also supported by other agencies, such as the National Science Foundation through its Life in Extreme Environments and Biocomplexity Programs.

## Astrobiology Roadmap

In July 1998, about 150 members of the research community met at NASA Ames Research Center to produce a more formal roadmap for NASA astrobiology, defining the discipline primarily in terms of its scientific potential. The participants included NASA employees, academic scientists whose research is partially funded by NASA grants, and many members of the still wider community who have no formal association with NASA.

The Astrobiology Roadmap provides guidance for research and technology development across several NASA enterprises: Space Science, Earth Science, and the Human Exploration and Development of Space (or the more recently defined Biological and Physical Research Enterprise). The recommendations are formulated in terms of 10 science goals and 17 more specific science objectives, which will be translated into NASA programs and integrated with NASA strategic planning. The roadmap was formally accepted by NASA Headquarters in December 1998. It can be found on the Internet at URL: http://www.astrobiology.arc.nasa.gov.

The NASA roadmap is a snapshot of astrobiology near the time of its inception. It identifies broad goals and objectives, but not specific research plans or flight missions. In general, the roadmap suggests multiple paths that may prove fruitful in pursuing its science goals. Because astrobiology is a living science, it is not expected that these goals will remain constant in time. Research opportunities, national priorities, and available funding will all influence the directions in which astrobiology develops.

## Astrobiology Science Goals

This section describes the 10 long-term science goals that lie at the heart of the Astrobiology Roadmap. Although no timescale is associated with these goals, it is assumed that significant progress can be achieved within the next decade, by which time the roadmap will itself have undergone multiple revisions. The 10 goals are themselves

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loosely organized around the fundamental questions: Where did we come from? Are we alone? What is the future of life?

## Question: How Does Life Begin and Evolve?

### 1. Understand How Life Arose on the Earth

Perform historical, observational, and experimental investigations to understand the origin of life on our planet, including the possibility that it arrived from elsewhere.

Terrestrial life is the only form of life that we know, and it appears to have arisen from a common ancestor. How and where did this remarkable event occur? We can now perform historical, observational, and experimental investigations to understand the origin of life on our planet. We should determine the source of the raw materials of life, either produced on this planet or arriving from space. We seek to understand in what environments the components may have assembled and what forces led to the development of systems capable of deriving energy from their surroundings and manufacturing copies of themselves. We should also investigate the exchange of biological materials between planets to assess the possibility that life formed elsewhere and subsequently migrated to Earth. Understanding the interplanetary transportation and survivability of organisms is also relevant to issues surrounding possible contemporary exchange of biological material with Mars and, hence, the importance of quarantine of Mars samples returned to Earth.

For the prebiotic Earth, we seek to understand the origin and chemical nature of organic and inorganic compounds, plus the energy sources and microenvironments that created the context for the origin of life. Given a plausible primary source of organic components, alternative pathways by which such prebiotic compounds formed the ancient counterparts of proteins, nucleic acids, and lipid-like molecules can be investigated within plausible constraints. Scientists will also use the phylogenetic and geologic record to point to characteristics of our earliest ancestor.

### 2. Determine the General Principles Governing the Organization of Matter into Living Systems

Use laboratory and computational approaches to establish the general physical and chemical principles that lead to the emergence of living systems under different conditions in the universe.

Goal 2 is a generalization of goal 1, moving from the specific historical events that produced life on Earth to the general nature of life as it might form in any environment. The molecular machinery leading to the origin of life on other planets might well be substantially different from the one that formed on the early Earth, because the remarkable versatility of organic chemistry offers multiple solutions for the basic requirements of life. Life on Earth represents only one example of living systems. One genetic code, one set of amino acids of specific chirality, and one energy currency have survived from primitive Earth. We seek to establish the general physical and chemical principles that lead to the emergence of systems capable of converting molecules for energy and growth (catalysis), generating offspring (reproduction), and changing as conditions warrant (evolution). Having only one example of life today, we do not know which properties of life are general and necessary and which are the result of specific circumstances or historical accident. We seek these answers by pursuing laboratory experimental approaches and computational theoretical approaches. This work leads into issues of the definition of life and to interactions with the study of artificial life (AI).

### 3. Explore How Life Evolves on the Molecular, Organism, and Ecosystem Levels

Utilize modern genetic studies, the fossil record, and ecosystem analyses to understand the processes of evolution, with emphasis on the development of microbial communities.

Life is a dynamic process of changes in energy and composition that occurs at all levels, from individual molecules to ecosystem interactions. Much of traditional research on evolution has focused on organisms and their lineages as preserved in the fossil record. However, processes such as the exchange of genetic information between organisms and changes within DNA and RNA are key drivers of evolutionary innovation. Modern genetic analysis, using novel laboratory and computational methods, allows new insights into the diversity of life and evolution at all levels. Complementary to such studies are investigations of the evolution of ecosystems consisting of many interdependent species, especially microbial communities.

This goal anticipates that the powerful techniques of molecular biology and molecular phylogenetics will provide important insight into the diversity of life and the evolutionary relationships between organisms. Studies of RNA and other conserved gene sequences have revealed previously unknown kingdoms of organisms in unlikely (to us) habitats. We hope to understand how organisms affect each other and how ecosystems alter the environment through modulation of chemistry and the composition of the oceans and atmosphere. Our understanding of evolution will also be altered by considering catastrophic environmental changes of external origin, including asteroid and comet impacts and the consequences of nearby stellar explosions. This research is linked to studies of the coevolution of life and the planet (goal 4) and the search for biomarkers on distant planets (goal 7).

### 4. Determine How the Terrestrial Biosphere Has Coevolved with the Earth

Trace the coupled evolution of life and the planet by integrating evidence acquired from molecular biology, studies of present and historical environments, and research in ecology and organismal biology.

It is a truism that life evolves in response to changing environments. In addition, however, changing ecosystems alter the environment of Earth. Scientists can trace the coevolution of life and the planet by integrating evidence acquired from studies of current and historical molecular biology (genomics) with studies of present and historical environment. We seek to understand the diversity and distribution of our ancient ancestors by developing technology to read the record of life as captured in biomolecules and in rocks (fossils), to identify specific chemical interactions between the living components of the Earth (its biosphere) and other planetary subsystems, and to trace the history of the changing environment in response to biological modifications. The ultimate objective is to use the geologic record to attach dates and environmental context to evolutionary events, leading to a robust history of the biosphere, based on biomolecular, paleoenvironmental, and paleobiological evidence. Understanding these biochemical pathways will also create an inventory of bioindicators that may be sought in ancient rocks on Earth and on other planets (goal 7).

In this goal, as in many aspects of astrobiology, we concentrate on the microbial world. Macroscopic life has only emerged on Earth during the last 15% of its history, and even today microbes play a decisive role in the coupling between biology and geochemistry. There are more microbes in a bucket of dirt from your backyard than there are stars in our galaxy, and estimates indicate that 99% of the microbial species are still not recognized. The Earth is, in many ways, a microbial planet, and we anticipate the same as we consider life on other worlds, both within our solar system and in orbit around distant stars.

## Question: Does Life Exist Elsewhere in the Universe?

### 5. Establish Limits for Life in Environments That Provide Analogs for Conditions on Other Worlds

Investigate the adaptation of life to the full range of habitable environments on our own planet, past and present, and use these as analogs for conditions on other bodies in our solar system, such as Mars or Europa.

To understand the potential for life on other worlds, we begin by investigating the limits to life on our own planet. The tolerance for extreme conditions shown by terrestrial life is much broader than previously thought. Microbes can be remarkably versatile in their choice of lifestyles, with communities thriving in such extreme environments as nuclear reactors, perennially ice-covered Antarctic lakes, the interiors of rocks, hydrothermal springs, and deep subsurface aquifers. Some extreme environments, such as those near marine hydrothermal vents, have actually been suggested as possible sites for the origin of life on Earth. To understand the possible environments for life on other worlds, we must investigate the full range of habitable environments on our own planet, both today and in the past. We will investigate these extreme environments not only for what they can tell us about the adaptability of life on this planet, but also as analogs for conditions on other bodies in our solar system.

#### 6. Determine What Makes a Planet Habitable and How Common These Worlds Are in the Universe

Investigate how planets acquire and sustain liquid water, and use theoretical and observational studies of the processes of planet formation, as well as surveys of a representative sample of planetary systems, to locate possible abodes for life.

As far as we know, planets are the most likely (and perhaps the only) environments to support life. The discovery during the past few years of planets orbiting other stars is as important for astrobiology as it is for astronomy. However, the large planets in inner orbits that we can detect today are not likely abodes for life. We have not answered the question whether habitable planets are common, and it is the abundance of planets with habitable environments that is critical for understanding the role of life in the universe.

The formation of planets, and the resulting configuration of planetary systems, can be approached both empirically and theoretically. From our only known example of life, it appears that habitability depends on the long-term stability of liquid water in which nutrient and waste transport can occur and catalytic function and exchange of genetic material are possible. As a starting point, the habitable zone in any planetary system is most simply defined as the region where liquid water is stable on a planet's surface. The frequency of occurrence of planets in habitable regions around other stars must be answered empirically, by surveying a representative sample of planetary systems (including Earth-mass planets) and determining their configuration. The proposed Kepler Discovery mission would survey for terrestrial planets by detecting the small drop in brightness when a planet transits the disk of a star. Later (beyond the 10-year timeframe of the roadmap), we expect to have large instruments in orbit, such as the Terrestrial Planet Finder (TPF), to permit imaging of terrestrial-type planets around the nearest stars.

#### 7. Determine How to Recognize the Signature of Life on Other Worlds

Learn to recognize extraterrestrial biospheres, by identifying structural fossils or chemical traces of extinct life in returned samples and by investigating what biomarkers could be detected in the spectra of planets circling other stars.

Recent discoveries of extrasolar planets and of possible evidence for past life on Mars bring the question, "Are we alone?," to the forefront of scientific inquiry. We are poised on the brink of searching for evidence of life on a variety of worlds. This search, however, requires that we be able to recognize extraterrestrial biospheres and to detect the signatures of extraterrestrial life. Within our own solar system, we must be able to identify the fossils or other biomarkers of extinct life in returned samples. That the supposed microbial fossils in Martian meteorite ALH84001 remain controversial shows that we are not yet ready to reach definitive conclusions based on such evidence. It is also essential to learn to identify the chemical signatures of life on a distant world through remote sensing of its atmosphere or surface. On Earth, life has produced easily detectable biomarkers such as high concentrations of oxygen in the atmosphere and the presence of a distinctive spectral feature (due to chlorophyll) on the surface. However, these effects have been most pronounced only for the last billion years of Earth history. For the preceding several billion years during which Earth had life, the atmospheric and surface signatures are not fully understood. Such understanding will be required when we begin in the next decade to acquire spectral information on the atmospheres of planets circling other stars.

In this goal we might also consider the role of the Search for Extraterrestrial Intelligence (SETI) by looking for microwave transmissions from other planets. A signal from an extraterrestrial civilization would certainly constitute an unambiguous biomarker, and SETI programs are a logical part of an overall search for evidence of life beyond Earth. However, evidence of intelligent life is likely to be much rarer than atmospheric biomarkers such as chemical disequilibria resulting from biochemistry, which we might hope to find on a planet that is inhabited by microbes only, as was the case of Earth over most of its history.

#### 8. Determine Whether There Is (or Once Was) Life Elsewhere in Our Solar System, Particularly on Mars and Europa

Explore the solar system from a biological perspective, emphasizing the search for past or present life on Mars and Europa, the two places beyond Earth that we know once supported liquid water.

Astrobiology science has become the centerpiece of NASA's plans to explore the solar system, especially for missions to Mars and Europa. These two worlds are likely to have, or have had, liquid water, which seems to be a requirement for life as we know it. Both Mars and Europa probably have habitats today that could support terrestrial life, although we have no way of knowing whether life began there or survived to the present. These two worlds offer us the greatest opportunity to find the "holy grail" of astrobiology, an example of life that formed separately from that of our own planet (a "second Genesis" in the words of Chris McKay).

Mars is cold and dry today, but there is ample evidence for stable flowing water early in that planet's history. Sedimentary deposits from possible paleolakes could hold fossil evidence of life that might have existed during this early wet period. Enigmatic evidence of recent flows from the Mars Global Surveyor images suggest that intermittent water might appear at the surface even today. More compelling (but more difficult to access) are potential subsurface aquifers. Both in situ investigations and the analysis of returned samples will be necessary to understand the past climate of Mars and its potential for life. In both cases, the selection of promising landing sites and identification of samples of biological significance are key. The primary objective of sample return missions is to settle the question of fossils of past life, whereas deep drilling below the surface may ultimately be necessary to access potential contemporary habitats for life.

Europa almost certainly has a global ocean of liquid water, based on both surface images and subsurface magnetic sounding by the Galileo spacecraft. Europa is difficult to reach and orbits Jupiter in an intense radiation environment; even an initial orbiter mission is not likely to reach Europa within the current decade. On longer timescales, however, deep penetration of the ice layer could provide a direct sample of the Europan ocean and lead to remote submersible vehicles instrumented to search for evidence of marine life. Europa is especially fascinating to astrobiologists because it seems unlikely to have exchanged materials (including life) with the Earth. Mars and Earth might turn out to support life that began with the same common ancestor, whereas if Europa has life, it most likely formed and evolved in isolation from other biospheres.

## Question: What Is Life's Future on Earth and in Space?

#### 9. Determine How Ecosystems Respond to Environmental Change on Timescales Relevant to Human Life on Earth

Examine the habitability of our planet over time in the face of both natural and human-induced environmental changes, and assess the role of rapid changes to enable predictive models of environment–ecosystem interaction.

Astrobiology seeks to understand and predict how changes on Earth alter the adaptation and evolution of our biosphere on timescales measured in units from one million years to less than one year. These changes can be studied more directly than the longer-term coevolution of Earth and life discussed in goal 4. Rapid environmental changes on Earth associated with recent human activities include toxic contamination of oceans, freshwater and soil, deforestation and desertification, exotic species invasion, decline in ozone in the stratosphere, and increasing atmospheric greenhouse gases. Other changes are related to the response of the biosphere to the ice ages or other long-term climate changes. To help assure the habitability of a planet, we will need experimental methods to detect critical biophysical and geochemical components and their interactions during the formation of new ecosystems. We will develop new models to address indirect effects and nonlinear environmental interactions that could produce unexpected and counterintuitive impacts on the biosphere. This integrated research approach will seek ultimately to identify the consequences for habitability of Earth if environmental changes outpace the capacity for adaptation and evolution of natural ecosystem components. Ultimately, we desire to understand a range of conditions that applies to other planets as well as the Earth, including planets that are both young and old, as well as biologically more simple or more complex than present-day Earth. Biosphere-level research is needed to define the general habitability of a planet, and its mechanisms of bioprotection, mainly through the study of the interactions of Earth's ecosystems with its atmospheric chemistry and radiation balance.

**10. Understand the Response of Terrestrial Life to Conditions in Space or on Other Planets**

Study the adaptation and evolution of Earth life in other environments, including the space station and Mars, and investigate the possibility of bioengineering ecosystems for better adaptation to alien environments.

Whereas many people hope and expect that humans will eventually (and perhaps relatively soon) establish permanent habitation beyond the Earth, there are many unknowns facing these pioneers. In biology as well as engineering, we are not yet ready to move to the moon or Mars. That is not to say that well-trained, fit, highly motivated astronauts could not make trips of limited duration to other planets. However, we are not prepared to answer fundamental questions about long-term, multigenerational exposure of either humans or the complex biospheres required to support human life and health.

All life that we know evolved on Earth. Now, for the first time in human history, we have the capability to move life intentionally beyond our home planet. Organisms have been carried to other surfaces in our solar system and have survived; yet they have not proliferated there. Delineating the mechanisms that organisms use to adapt to environmental extremes on Earth or simulated environments for other planets will provide insights into the environmental envelope that allows life to exist. The critical near-term questions are whether (and what kinds of) organisms can live reproductively successful lives over multiple generations beyond Earth, and what genotype changes (changes in the genes or DNA sequence) and phenotypic changes (changes in appearance or physiology) will result. The International Space Station will provide a testbed for studying evolution and ecological interactions of organisms. These studies will determine whether simple organisms and their ecosystems evolve similarly in space and on Earth. Such data will allow development and management of ecosystems to assist life in evolving beyond Earth. Because life exists in ecologies, investigations should also focus on engineering extraterrestrial environments for evolutionary success. Understanding the evolution of terrestrial life beyond Earth requires establishing multiple generations, then permanent colonies of a wide range of species in all of the extraterrestrial environments that humans explore. Long-term occupation of extraterrestrial environments will require living off the land or augmenting consumables with resources generated beyond Earth.

The results from attempting to answer these astrobiological questions will determine whether life can expand its evolutionary trajectory beyond its place of origin.

## Societal Implications of Astrobiology

Astrobiology, more than most science disciplines, addresses issues of wide public interest and concern. The origin of life on this world, and the ancient question of whether we are alone in the universe, have deep philosophical and religious overtones. On a different plane, the potential of our terrestrial life to move into space, and for humans to become a multiplanet species, speaks directly to our hopes and aspirations for the future. All of these topics relate to our image of ourselves and of our place in the universe.

One of the first events that publicly recognized astrobiology was a White House symposium convened by Vice President Gore shortly after the initial claim of possible fossil microbes in Martian meteorite ALH84001. It is interesting that philosophers, educators, and theologians were invited, as well as scientists from a variety of disciplines.

Although most of the public appears to resonate with the subject matter of astrobiology, there are some aspects that could be threatening. The potential to make lifeforms in the laboratory, or to modify dramatically existing species through genetic engineering, are hot button issues. There is also concern about the potential cross-contamination of life from different worlds and, in particular, the possible hazard to terrestrial life associated with the return of unsterilized samples for study on Earth. Although few persons expect to find viable Martian organisms in surface rocks, NASA has already taken the position that returned samples from Mars will be treated as a potential biohazard until proven safe. Forward contamination is also an issue, with questions raised about the ethics of transporting terrestrial life to Mars or Europa, locations that might already support their own indigenous biospheres. The entire issue of the confrontation between the terrestrial ecosystem and that of another world is fraught with issues, both scientific and ethical.

These issues are discussed in the NASA Astrobiology Roadmap as part of four crosscutting operating principles or assumptions that lie at the foundation of this discipline:

**Multidisciplinary Science**

Astrobiology is a broad metascience, dealing with studies of life in the universe from a variety of perspectives. We seek to involve scientists and technologists from many disciplines in the Earth, life, and space sciences, including microbiology, ecology, molecular biology, paleontology, astronomy, planetary science, and chemistry. We believe that the goals of astrobiology are most likely to be achieved when scientists from different backgrounds and training collaborate to create a synthesis of knowledge that is greater than the sum of its individual parts.

**Planetary Stewardship**

The search for life beyond the Earth, and the eventual expansion of terrestrial life to Mars or other planets in our solar system, carry the responsibility of the protection of planetary ecosystems. Astrobiologists must ensure that these programs are carried out according to generally understood ethical and scientific principles. We will not endanger terrestrial life by the introduction of alien lifeforms. We will lead in the development of internationally agreed on protocols for planetary protection. We will consider the broad ethical and cultural implications before we undertake to change the climate and surface conditions to make another world more hospitable to terrestrial life.

**Societal Responsibility**

Astrobiology research has implications that make themselves felt far beyond the confines of the laboratory. To understand the consequences will require multidisciplinary consideration of areas such as economics, environment, health, theology, ethics, quality of life, the sociopolitical realm, and education. Together we will explore the ethical and philosophical questions related to the existence of life elsewhere, the potential for cross contamination between ecosystems on different worlds, and the implications of future long-term planetary habitation and engineering.

**Outreach and Education**

The study of life in the universe has a great appeal that extends far beyond the scientific community. Students of all ages, as well as the general public, can relate to questions of our origins or to the search for life elsewhere in the universe. The astrobiology program will be carried out in the public eye, with open communications of results and sharing of the excitement of research and discovery.

A number of universities have introduced undergraduate courses in astrobiology, in the expectation that this topic will attract student interest. There are also a few initiatives to create graduate degree programs in astrobiology (for example, at the University of Washington, Arizona State University, and University of Colorado), although no university has yet proposed a Department of Astrobiology. Because this field draws strength from its interdisciplinary roots, it is probably best for scientists working in this area to be solidly grounded in one of its core disciplines, represented by established academic departments and degrees. This is an evolving issue, and it will be interesting to see the place of astrobiology in academia a decade from now. Meanwhile, there are already two international professional journals in astrobiology (published by Cambridge University Press and by Mary Ann Liebert Publications) and several moves to establish a professional society of astrobiologists.

If astrobiology is successful in finding answers to fundamental questions, and especially if we discover life on another planet, this discipline will receive a great deal of media and public attention. There will be many opportunities to reach out and use these discoveries to illuminate the way scientific discovery works, as well as to shine light on our place in the universe. Astrobiologists should be prepared to discuss our work with the public and to ensure that it reaches a broad audience, especially among the students who will be the scientists, engineers, and taxpayers of the future.

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