

Focus Paper

The NASA Astrobiology Roadmap

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Abstract

The NASA Astrobiology Roadmap provides guidance for research and technology development across the NASA enterprises that encompass the space, Earth, and biological sciences. The ongoing development of astrobiology roadmaps embodies the contributions of diverse scientists and technologists from government, universities, and private institutions. The Roadmap addresses three basic questions: how does life begin and evolve, does life exist elsewhere in the universe, and what is the future of life on Earth and beyond? Seven Science Goals outline the following key domains of investigation: understanding the nature and distribution of habitable environments in the universe, exploring for habitable environments and life in our own Solar System, understanding the emergence of life, determining how early life on Earth interacted and evolved with its changing environment, understanding the evolutionary mechanisms and environmental limits of life, determining the principles that will shape life in the future, and recognizing signatures of life on other worlds and on early Earth. For each of these goals, Science Objectives outline more specific high priority efforts for the next three to five years. These eighteen objectives are being integrated with NASA strategic planning. *Astrobiology* 8, xxx–xxx.

Introduction

ASTROBIOLOGY ADDRESSES THREE BASIC QUESTIONS that have been asked in various ways for generations: how does life begin and evolve, does life exist elsewhere in the universe, and what is the future of life on Earth and beyond? Accordingly, the discipline of astrobiology embraces the search for potentially inhabited planets beyond our Solar System, the exploration of Mars and the outer planets, laboratory and field investigations of the origins and early evolution of life, and studies of the potential of life to adapt to future challenges, both on Earth and in space. Interdisciplinary research is required that combines molecular biology, ecology, planetary science, astronomy, information science,

space exploration technologies, and related disciplines. The broad interdisciplinary character of astrobiology compels us to strive to achieve the most comprehensive and inclusive understanding of biological, planetary, and cosmic phenomena.

The NASA Astrobiology Roadmap provides guidance for research and technology development across the NASA Enterprises that encompass the space, Earth, and biological sciences. The Roadmap is formulated in terms of seven Science Goals that outline key domains of investigation. These domains of investigation will probably require decades of effort to consummate. For each of these goals, Science Objectives outline more specific high priority efforts for the next three to five years. These eighteen objectives are being inte-

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grated with NASA strategic planning. The Roadmap also includes Example Investigations, which offer examples of specific research tasks that are both important and timely for their corresponding Science Objective. It is important to emphasize that these investigations are intended principally to be illustrative of relevant tasks, and that additional equally important example investigations can be envisioned.

The following four basic principles are fundamental to the implementation of NASA's astrobiology program:

- (1) Astrobiology is multidisciplinary in its content and interdisciplinary in its execution. Its success depends critically upon the close coordination of diverse scientific disciplines and programs, including space missions.
- (2) Astrobiology encourages planetary stewardship through an emphasis on protection against forward and back biological contamination and recognition of ethical issues associated with exploration.
- (3) Astrobiology recognizes a broad societal interest in its endeavors, especially in areas such as achieving a deeper understanding of life, searching for extraterrestrial biospheres, assessing the societal implications of discovering other examples of life, and envisioning the future of life on Earth and in space.
- (4) The intrinsic public interest in astrobiology offers a crucial opportunity to educate and inspire the next generation of scientists, technologists, and informed citizens; thus a strong emphasis upon education and public outreach is essential.

Goals and Objectives

Goal 1—Understand the nature and distribution of habitable environments in the universe. Determine the potential for habitable planets beyond the Solar System, and characterize those that are observable.

A planet or planetary satellite is habitable if it can sustain life that originates there or if it sustains life that is carried to the object. The Astrobiology program seeks to expand our understanding of the most fundamental environmental requirements for habitability. However, in the near term, we must proceed with our current concepts regarding the requirements for habitability. That is, habitable environments must provide extended regions of liquid water, conditions favorable for the assembly of complex organic molecules, and energy sources to sustain metabolism. Habitability is not necessarily associated with a single specific environment; it can embrace a suite of environments that communicate through exchange of materials. The processes by which crucial biologically useful chemicals are carried to a planet and change its level of habitability can be explored through the fields of prebiotic chemistry and chemical evolution. A major long-range goal for astrobiology is to recognize habitability beyond the Solar System, independent of the presence of life, or to recognize habitability by detecting the presence of life (see Goal 7: Biosignatures). This goal directly addresses the call for searches for Earth-like planets and for habitable environments around other stars that is included in the Vision for Space Exploration.

Background. Research in astrobiology supports NASA in its attempt to search for habitable or inhabited environments beyond the Solar System. Humans have pondered for millennia whether other inhabitable worlds exist. Now, for the first time, they have an opportunity to look and see. Of course it is not possible to examine the $\sim 10^{10}$ Earth-like planets that simple statistical models predict to exist in our galaxy, much less the $\sim 10^{21}$ such planets expected to be in the universe. Still, it should be possible to determine whether

terrestrial planets are indeed as common as predicted above, whether a substantial fraction of them show signs of habitability, and whether an appreciable fraction of these show biosignatures.

A key difference between the search for life in the Solar System and the search in external planetary systems is that, within the Solar System, interplanetary transfer of viable microbes seems a plausible process, and therefore the discovery of life elsewhere in the Solar System seems plausible. While this is indeed of extraordinary interest, it may not cast light on whether it is easy or difficult for life to begin. On the other hand, the fact that dispersion times between stars are $\sim 10^5$ to 10^6 times longer than for dispersion within the Solar System makes independent origination of life forms outside the Solar System more probable.

The research objectives under this goal address three key questions. First, do terrestrial planets and large satellites tend to form in a state where they are likely to become habitable, or do habitable environments emerge only after a sequence of less probable events? Second, how frequently do habitable environments arise on solid planets, including large satellites? Third, what are the specific signs of habitability and habitation, and how do such signs change with the circumstances of the planet (*e.g.*, mass, distance from its star, history and relative abundance of volatile compounds)? To address these questions effectively, we must investigate how habitable planetary systems form and evolve (Goals 1 and 2), and we must understand the ultimate environmental limits of life (Goal 5).

Much of this effort focuses upon the presence or absence of liquid water in bulk form. Water is made from the two most abundant chemically reactive elements in the universe, and it is the necessary ingredient for Earth's type of life. Liq-



FIG. 1. Artist's representation of a habitable planet orbiting another star. Courtesy of Cheryse Triano, Topspin Design Works.

uid water has played an intimate, if not fully understood, role in the origin and development of life on Earth. Water contributes to the dynamic properties of an Earth-sized planet, permitting convection within the planetary crust that might be essential to supporting Earth-like life by creating local chemical disequilibria that provide energy for life. Water maintains a strong polar-nonpolar dichotomy with certain organic substances. This dichotomy has allowed life on Earth to form independent stable cellular structures. Thus the primary focus of Goal 1 is concerned with planets having a liquid water boundary layer, although the focus may expand to include other planets or satellites as astrobiology matures as a discipline.

There is also a focus—though not exclusive—on molecular oxygen and ozone as biosignatures (see also Goal 7), and therefore on dealing with the interface between understanding the geological and biological aspects of oxygen, and determining the details of the spectral features that can be observed and interpreted remotely. Oxygen is a very common element that has provided Earth with its most distinctive biosignature. The chemical state of an Earth-like planet, as well as the geological activity that delivers reduced species to its surface environment, will cause virtually all of the molecular oxygen to be consumed unless it is produced rapidly (*e.g.*, by oxygen-producing photosynthesis). Also, the rela-

tively modest ultraviolet fluxes of many stars prevent rapid production of oxygen from photo-dissociation of water. These factors will help to minimize the possibility of false positive detections of oxygen biosignatures.

The challenge of remotely detecting life on a planet that has not developed a biogenic source of oxygen is fraught with unknowns. What chemical species and spectral signatures should be sought? What metabolic processes might be operating? How does one guard against a false positive detection? Research that is guided both by our knowledge of Earth's early biosphere (*i.e.*, before the rise of an oxygenated atmosphere) and by studies of alternative biological systems can help address these questions and provide guidance to astronomers seeking evidence of life elsewhere (Goal 7).

- *Objective 1.1—Formation and evolution of habitable planets.* Investigate how solid planets form, how they acquire liquid water and other volatile species and organic compounds, and how processes in planetary systems and galaxies affect their environments and their habitability. Use theoretical and observational studies of the formation and evolution of planetary systems and their habitable zones to predict where water-dependent life is likely to be found in such systems.

Example investigations

Understand how the processes and time scales of planet formation vary with the mass of the central star, for example, whether low mass M dwarf stars or very low metallicity stars are likely to host habitable planets or satellites.

Model the potential diversity of habitable planets that might emerge from the evolution of protoplanetary disks. For comparison, measure key time scales for planet-forming events in our own Solar System based on studies of isotopic chronometers in meteorites and samples returned from primitive Solar System bodies.

Investigate how the delivery of water and other volatiles to and their loss from terrestrial-like planets of various size and mass can affect climate, surface, and interior processes, and how these changes affect habitability.

Develop comprehensive models of the environments of terrestrial-like planets (including the recently discovered “Super Earths,” planets with masses in the range of ~1 to ~10 Earth-masses) to investigate the evolution of habitability.

- *Objective 1.2—Indirect and direct astronomical observations of extrasolar habitable planets.* Conduct astronomical, theoretical, and laboratory spectroscopic investigations to support planning for and interpretation of data from missions designed to detect and characterize extrasolar planets.

Example investigations

Use ground-based telescopes to detect “Super Earths” that may offer habitable environments around low mass, M dwarf stars.

Investigate novel methods for detecting and characterizing extrasolar planets, particularly those that might lead to an improved understanding of the frequency of habitable Earth-like planets.

Use atmospheric models to understand the range of planetary conditions that can be determined from low resolution, full-disk spectra at visible, near-IR, and thermal wavelengths. Use data for Venus, Earth, and Mars to validate these models.

GOAL 2—Determine any past or present habitable environments, prebiotic chemistry, and signs of life elsewhere in our Solar System. Determine the history of any environments having liquid water, chemical ingredients, and energy sources that might have sustained living systems. Explore crustal materials and planetary atmospheres for any evidence of past and/or present life.

This goal seeks to understand the distribution of the basic requirements for life elsewhere in our Solar System and to understand how any habitable environments and life persisted over geological time. Although possible life elsewhere in the Solar System may have developed differently from life on Earth, our understanding of the nature of terrestrial life provides an important starting point to guide our exploration strategies. For example, studies of microorganisms in extreme environments, including the biota sustained by chemical energy in the deep subsurface, have revolutionized our assessment of the potential for life on Mars and the icy moons in the outer Solar System. Surface environments on those bodies are presently hostile to life as we know it; however, subsurface environments might be habitable. Ancient surface environments also might have been habitable, at least intermittently. By mapping the distribution of any past and present habitable environments, robotic missions will guide the selection of samples to be returned to state-of-the-art laboratories on Earth to conduct life detection experiments.

Background. During the past decade, dramatic progress has been made in our understanding of the potential for past and present habitable environments elsewhere in the Solar System. For example, the Mars Global Surveyor orbiter, Mars Exploration Rovers, and the Odyssey and Mars Reconnaissance orbiters revealed that, early in martian history, surface water environments were widespread over the surface and shallow subsurface and were sustained by both

atmospheric precipitation and outflows from aquifers. Theoretical models and surface geomorphology have indicated the potential for a global groundwater system capable of sustaining an extant subsurface biosphere. The recent discovery of atmospheric methane indicates that subsurface habitable environments might exist even today. The Galileo mission found strong evidence of subsurface brines on three of the four Galilean satellites of Jupiter (Europa, Ganymede, and Callisto), maintained by internal tidal heating. The Cassini-Huygens mission has confirmed the presence on Saturn’s moon, Titan, of an atmosphere and surface enriched in prebiotic organic compounds. Titan can be viewed as a natural laboratory where we might gain important new insights into the origins of life here on Earth. The existence of lakes of liquid hydrocarbons on Titan opens up the possibility for solvents and energy sources that are alternatives to those in our biosphere and that might support novel life forms altogether different from those on Earth. The Cassini spacecraft has imaged plumes of water vapor that erupt episodically from the subsurface of Enceladus, an icy moon of Saturn. This indicates the possibility that interior habitable zones with liquid water might exist on yet another body in the outer Solar System. Recent biological research has deepened our understanding of the nature, environmental limits, and evolutionary history of life on Earth. Such discoveries have contributed to strategic planning activities that broadly support NASA missions, including the specification of scientific goals, objectives and measurement re-

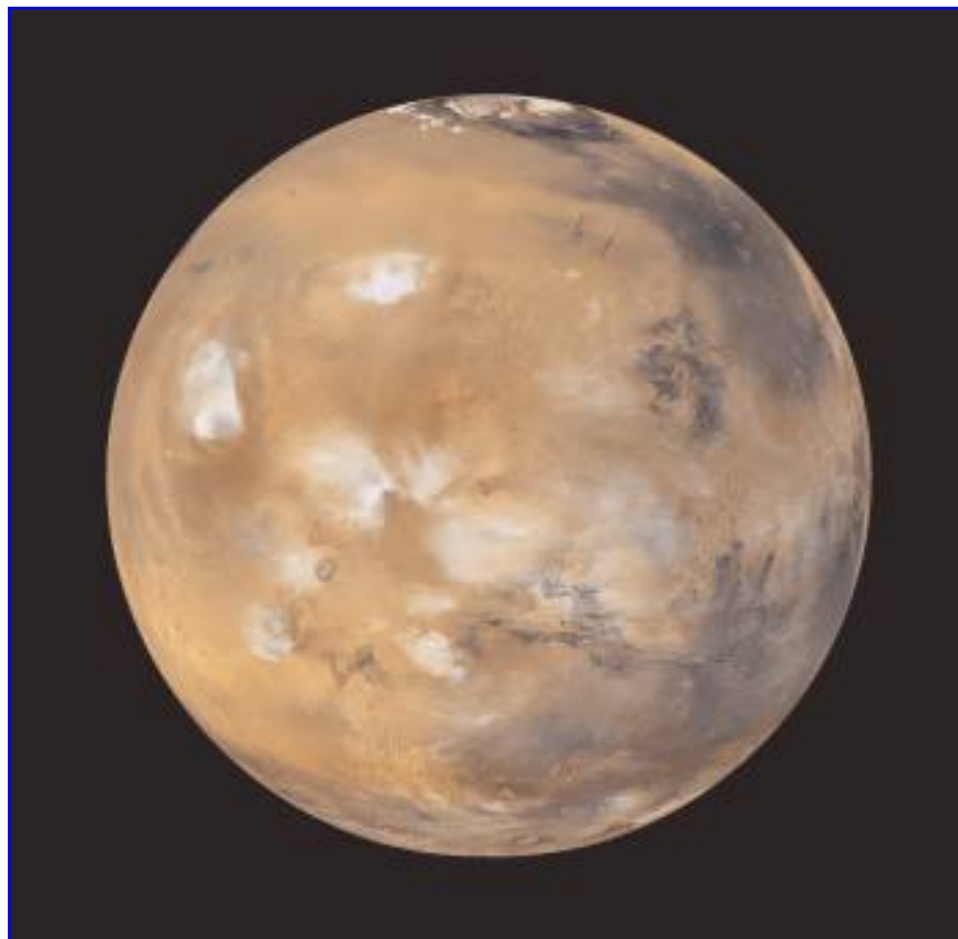


FIG. 2. Hemisphere of Mars showing (from left to lower right) Olympus Mons, Tharsis volcanos and Vallis Marineris. Courtesy of NASA.

quirements, new instrument designs, and integrated payload concepts.

Building upon such discoveries, logical next steps in the exploration for extraterrestrial life in the Solar System include the following: (1) continuing to refine our understanding of the nature and distribution of past and/or present habitable environments in the Solar System, (2) identifying the most favorable landing sites for future *in situ* life detection missions, (3) developing experiments for the unambiguous detection of extant and fossil biosignatures in surface/subsurface rocks, soils, and ices on other planetary bodies, like Mars and Europa, (4) developing robotic drilling systems capable of accessing subsurface environments on Mars and possibly on other bodies in the Solar System, (5) collecting and returning samples to Earth from high priority sites on Mars and possibly other bodies in the Solar System to explore for prebiotic chemistry and biosignatures utilizing the advanced capabilities of terrestrial laboratories. Key questions include the following: If life ever arose elsewhere, is it related to terrestrial life, or did other bodies in the Solar System sustain independent origins of life? If life never developed elsewhere in our Solar System, is there a prebiotic chemical record preserved in ancient rocks that might contain clues about how life began on Earth?

Renewed lunar exploration offers opportunities to explore the earliest history of habitable environments on Earth. The Moon might harbor an inventory of crustal materials that were delivered from Earth before, during, and after the interval of heavy bombardment. The discovery of terrestrial meteorites on the Moon could provide important new insights about the evolution of planetary habitability during the birth of our biosphere.

Sample return(s) from important astrobiology targets in the Solar System (*e.g.*, Mars, icy satellites, asteroids, and comets) will greatly expand opportunities to explore for prebiotic chemistry and life using the most sophisticated tools available in terrestrial laboratories. Logical steps toward planning future sample returns include the development of reliable robotic systems for the *in situ* targeting, collection, and storage of samples, the safe transport and delivery of samples to Earth, the construction of sample containment facilities on Earth for the safe handling and storage of extraterrestrial materials, and the distribution of samples to members of the scientific community for detailed laboratory analyses.

- *Objective 2.1—Mars exploration.* Through orbital and surface missions, explore for potentially habitable environments and evidence of life, as indicated by water, organic

matter, atmospheric gases, and/or minerals. Study martian meteorites to guide Mars exploration. To support both exploration at Mars and the first sample return mission, update astrobiology measurement requirements, support site selection studies, and develop/improve relevant technologies and analytical methods.

Example investigations

Target a well-instrumented robotic rover to a site of past aqueous activity and analyze rocks for their geochemistry, minerals formed in association with water (*e.g.*, sulfates, silica, phyllosilicates, etc.), organic chemistry, and fossil biosignatures (including organic biomarker compounds, stable isotopes, atmospheric gases, biosedimentary structures, and microtextures).

Develop flight instruments to characterize samples *in situ*, to select samples for return to Earth, and to analyze atmospheric composition from orbit.

Develop universal approaches for detecting evidence of extant life forms that can be applied over a broad range of surface environments to distinguish between forward contamination and *in situ* extraterrestrial life.

Analyze results from previous and current missions in the context of their significance for astrobiology.

- *Objective 2.2—Outer Solar System exploration.* Conduct basic research, develop instrumentation to support astrobiological exploration, and provide scientific guidance for outer Solar System missions. Model the potential for subsurface habitable environments on icy moons such as Europa, Titan, and Enceladus. Support the development of missions to explore the surface ices and thin atmospheres of these bodies for evidence of subsurface habitable environments, organic chemistry, and/or biosignatures.

Example investigations

Develop flight instrumentation that can survive the surface environments of Europa and Titan and that can determine the composition (including any organic compounds) of surface ices and atmospheres, and explore for cryo-preserved biosignatures.

Develop numerical models to constrain the nature of deep subsurface environments on Europa, Titan, and Enceladus (presence of life-sustaining solvents, biologically essential elements, and energy sources) that might sustain life.

Analyze results from the Cassini mission in the context of their significance for astrobiology.

GOAL 3—Understand how life emerges from cosmic and planetary precursors. Perform observational, experimental, and theoretical investigations to understand the general physical and chemical principles underlying the origins of life.

How life begins remains a fundamental unsolved mystery. The origin of life on Earth may well represent only one pathway among many along which life can emerge. This belief forms the intellectual foundations for observations and missions aimed at searching for extant or extinct life elsewhere in the universe. Thus the universal principles must be understood that underlie not only the origins of life on Earth, but also its possible origins elsewhere. The starting point for establishing these principles is to determine what raw materials of life can be produced by chemical evolution in space and on planets. Further, it should be understood how organic compounds are assembled into more complex molecular structures and how the functions of these biomolecular structures become coordinated to form complex evolving systems that accompany life's origins. Such systems must have the capabilities to perform and coordinate capture of energy and nutrients from the environment, catalyze the chemical reactions needed for maintenance and growth of these systems, and manufacture copies of key biomolecules. Clues from the biomolecular and fossil records, as well as from diverse microorganisms, should be explored in order to define better the fundamental properties of the living state.

Background. We must move beyond the circumstances of our own particular origins in order to develop a broader

discipline, "Universal Biology." Although this discipline will benefit from an understanding of the origins and limits of terrestrial life, it also requires that we define the environmental conditions and the chemical structures and processes that could support life on other habitable planets. Thus we need to exploit universal laws of physics and chemistry to understand polymer formation, self-organization processes, energy utilization, information transfer, and Darwinian evolution that might lead to the emergence of life in planetary environments other than Earth. Clearly an inventory of molecules must exist that is capable of gaining chemical, structural, and functional complexity and eventually assembling into living systems. This is strongly conditioned on temperature, solvent, energy sources, etc. Some conditions that support chemistry that is sufficiently rich to seed life might be detrimental to self-organization of biological structures. Conversely, conditions that promote the emergence of biological complexity might be unfavorable to organic chemistry. Thus an integrative, interdisciplinary approach is necessary to formulate the principles underlying universal biology. The perspectives gained from understanding these principles will markedly improve our ability to define habitability and recognize biosignatures. This, in turn, will guide missions and observational projects aimed at finding life in the Solar System and beyond.

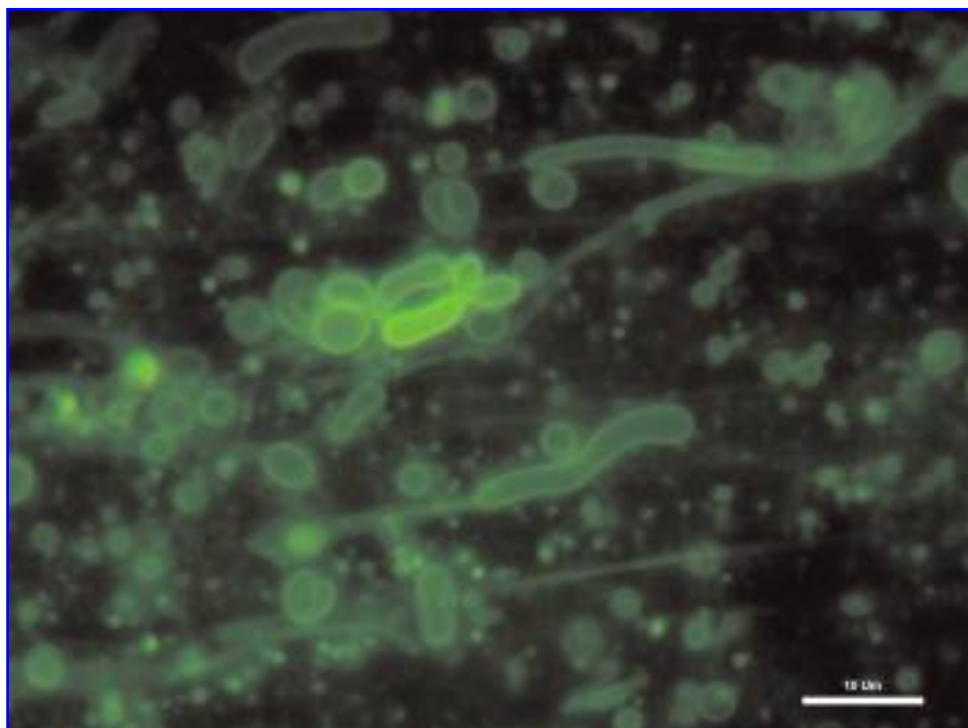


FIG. 3. Vesicles formed spontaneously from an aqueous solution of decanoic acid and decanol. Courtesy of D. Deamer, University of California, Santa Cruz.

Sources of organic compounds required for the origin of life. To understand how life can begin on a habitable planet such as Earth, it is essential to know what organic compounds were likely to have been available and how they interacted with the planetary environment. Chemical syntheses that occur within the solid crust, hydrosphere, and atmosphere are likely to be important sources of biogenic compounds. Interesting organic compounds are also present in interstellar clouds, the birthplace of planetary systems. Laboratory simulations of interstellar ices have recently demonstrated that key prebiotic molecules can also be synthesized under interstellar cloud conditions, and such materials are incorporated into nascent solar systems. More recent astronomical observations and analyses of extraterrestrial materials have shown that many compounds relevant to life processes are also present in meteorites, interplanetary dust particles, and comets. It is likely that substantial amounts of such organic material were delivered to Earth during late accretion, providing organic compounds that could serve as a feedstock for chemical evolution or that could be incorporated directly into early forms of life. An important research objective within this goal is to establish sources of prebiotic organic compounds and to understand their history in terms of universal processes that would take place on any newly formed planet. This will require an integrated program of pan-spectral astronomical observations, sample return missions, laboratory studies of extraterrestrial materials, and realistic laboratory simulations of inaccessible cosmic environments.

Origins and evolution of functional biomolecules. Life can be understood as a chemical system that links a common

property of organic molecules—the ability to undergo spontaneous chemical transformation—with the uncommon property of synthesizing a copy of that system. This process, unique to life, allows Darwinian-like selection and evolution to occur. At the core of the life process are polymers composed of monomeric species such as amino acids, carbohydrates, and nucleotides. The pathways by which monomers were first incorporated into primitive polymers on early Earth remain unknown, and physical properties of the products are largely unexplored. A primary goal of research on the origin of life must be to understand better the sources and properties of primitive polymers on early Earth, their initial evolution towards acquiring increased fidelity, efficiency, and diversity of functions, and the pathway by which polymerization reactions of peptides and oligonucleotides became genetically linked. As a parallel effort, the catalytic and informational potential of other polymers that can form in different planetary conditions should be explored. These specific lines of inquiry should be complemented with theoretical work, based on a “general principles” approach, to elucidate how the various protobiological properties of molecules and systems, including emergent behavior and information transfer, depend on and scale with complexity.

Origins of energy transduction. Life requires energy to yield, in a reproducible fashion, specific, very low probability outcomes, such as the generation and maintenance of locally ordered states of the biological system, the production of thermodynamically unfavorable species, and the synthesis of polymers having specific sequences from among large numbers of alternative sequence possibilities. Thus the emergence of complex life depends upon the development of re-

liable mechanisms for capturing energy from the surroundings and channeling it, in appropriate forms, into specific processes. Overarching areas for focus are the following: (i) Foundational—understanding the relationship between energy, information, and complexity; understanding what types of energy can be captured and utilized by biological systems; and understanding how threshold requirements for complexity and information processing place upper and lower bounds on the biological utilization of energy. (ii) Mechanistic—elucidating mechanisms by which the principal elements of energy transduction—capture of environmental energy, storage by membrane-based or molecular means, and coupling to key energy-requiring processes—may have functioned in primordial environments and combined into dedicated energy-transducing systems. (iii) Evolutionary—understanding how the systems for energy capture and utilization evolved from a complete lack of energy transduction, through a partially developed state, to fully elaborated and dedicated systems for collecting and directing energy, and examining how these systems co-evolved with the capabilities for functionality, information processing, and replication.

Origins of cellularity and protobiological systems. For life to begin in a natural setting such as a planetary surface, mechanisms must exist that concentrate and maintain interacting molecular species in a microenvironment. A bounded system of replicating and catalytic molecules capable of undergoing Darwinian evolution is by definition a cell. At some point life on Earth became cellular, either from its inception or soon thereafter. Boundary membranes divide complex molecular mixtures into large numbers of individual structures that can undergo selective processes required for biological evolution. They also have the capacity to develop substantial ion gradients that represent a central energy source for virtually all life today. A primary research objective is to understand self-organizing and evolutionary processes that can lead to the emergence of cellular structures and to test this understanding by creating laboratory models of primitive cells. These models are systems of interacting molecules within bounded environments capable of working in concert to capture energy and nutrients from the surroundings, transduce environmental signals, form metabolic networks that allow for growth through polymerization, and reproduce some of their polymeric components. Approaching this challenging problem will lead to a more refined definition of the living state and will clarify the hurdles faced by self-assembled systems of organic molecules as they evolved toward life.

- *Objective 3.1—Sources of prebiotic materials and catalysts.* Characterize the exogenous and endogenous sources of matter (organic and inorganic) for potentially habitable environments in the Solar System and in other planetary and protoplanetary systems.

Example investigations

Emphasizing important prebiotic species, trace the formation, chemical evolution, and processing of interstellar molecules and solids into more complex compounds. Analyze meteorites and returned samples to understand the

nature of extraterrestrial organic compounds. Conduct laboratory experiments and simulations to provide a framework for interpreting observations of meteorites, samples returned from comets and asteroids, and spectra of interstellar clouds.

Identify the organic compounds and complexes produced under primordial planetary conditions through laboratory simulation experiments.

- *Objective 3.2—Origins and evolution of functional biomolecules.* Identify plausible pathways for the synthesis of prebiotic monomers and their condensation into polymers. Identify the potential for creating catalytic and genetic functions, investigate their protobiological evolution, and explore primitive mechanisms for linking these two functions.

Example investigations

Investigate polymers other than nucleic acids that have the potential to have been precursor molecules capable of containing genetic information.

Conduct laboratory experiments and computational studies on the emergence of functional proteins. Investigate mechanisms by which primordial proteins evolved towards increased efficiency and selectivity, and acquired new structures and functions.

Investigate ancestral translation mechanisms and the emergence of the genetic code using laboratory experiments and clues from structural biology and bioinformatics.

- *Objective 3.3—Origins of energy transduction.* Investigate, conceptually and quantitatively, the relationship between energy, complexity, and information as applied to the origin of biological systems. Understand how the evolution of molecules, metabolic cycles, linked systems, and organisms is enabled and constrained by the development of energy transduction. Identify prebiotic mechanisms by which energy can be captured, stored, and coupled to energy-requiring processes.

Example investigations

Quantify the theoretical amount of energy required to specify the sequence of amino or nucleic acid polymers as a function of chain length; compare to the actual energy input required based on known biological mechanisms.

Identify the classes of reactions available for prebiotic synthesis under a range of plausible Solar System environmental conditions, based on single-random inputs of energy or no inputs of energy.

Investigate mechanisms by which the energy available in ion gradients across boundary membranes could couple to the synthesis of high-energy compounds such as pyrophosphate.

- *Objective 3.4—Origins of cellularity and protobiological systems.* Investigate both the origins of membranous boundaries on early Earth and the associated properties of energy transduction, transport of nutrients, growth, and division. Investigate the origins and early coordination of key cellular processes such as metabolism, energy transduction, translation, and transcription. Without regard to

how life actually emerged on Earth, create in the laboratory and study artificial chemical systems that undergo mutation and natural selection.

Example investigations

Determine how ionic and polar nutrients could permeate membrane boundaries to supply monomers and energy for intracellular metabolism and biosynthesis.

Investigate polymerase reactions that can take place in membrane-bounded microenvironments using external sources of monomers and chemical energy, and determine self-replication capabilities of such simple systems. Considering clues from prebiotic chemistry and contemporary biochemistry, investigate the organization of chemical reactions into a primitive cellular metabolism and establish properties of the emerging metabolic networks.

GOAL 4—Understand how life on Earth and its planetary environment have co-evolved through geological time. Investigate the evolving relationships between Earth and its biota by integrating evidence from the geosciences and biosciences that shows how life evolved, responded to environmental change, and modified environmental conditions on a planetary scale.

Understand how extraterrestrial processes and the planetary environment have influenced the evolution of life and how biological processes have transformed conditions on local to planetary scales. An improved knowledge of how life operated under diverse and extreme conditions will improve our ability to define, detect, and interpret biosignatures of living and extinct organisms, here and elsewhere. Studies of

key steps in the development of life will enable a deeper understanding of the pathways leading to biological complexity and thus inform the search for living systems on distant worlds.

Background. As in other areas of astrobiology, integration of knowledge from many fields of science is needed to



FIG. 4. Banded chert, more than 3.4 billion years old, near Marble Bar, Western Australia. Ancient cherts continue to reveal key insights about Earth's early biosphere, thus they underscore the importance of recently discovered silica-rich deposits on Mars. Photograph by D. Des Marais, NASA Ames Research Center.

understand the evolution of life in a planetary context. Earth system models that relate processes operating on vastly different temporal and spatial scales, from the core of Earth to the atmosphere and beyond, are an integral part of this endeavor. Comparative genomic studies, often based on environmental samples, including those from subsurface habitats, will provide a fuller understanding of microbial biodiversity within communities that control biogeochemical cycles, such as those involving the use of carbon, sulfur, iron, and nitrogen compounds. Studies of the metabolic requirements for life, the geochemical effects of those metabolic activities in the form of proxy records, and the preserved biomolecular signatures of ancient organisms will provide a deep time dimension to the evolution of life in a global context and show how Earth's planetary profile, as observed remotely, has changed throughout time. Investigations that explore the response of life to environmental perturbations on ecological to geological time scales will enhance our understanding of planetary habitability and contribute to the search for life beyond the Solar System. And research based on the fossil record of life and its activities, coupled with knowledge gained from living organisms, will enable key steps in the pathways to biological complexity to serve as guideposts in the search for life beyond the Solar System.

Using these tools and methods, astrobiologists can study the reciprocal interactions between organisms and their planetary environment and address the following questions: What microbial metabolisms existed at the time of the oldest sedimentary rocks, and what were their environmental effects? What might we learn about the earlier history of life on Earth if sedimentary samples that are even older can be found on the Moon? What can we learn from the early history of life on Earth that will inform the search for biosignatures on ancient Mars? How was the evolution of Earth's atmosphere and oceans during the first half of Earth history related to the development of life? How have life's course and Earth's habitability been changed by major environmental perturbations such as those resulting from extraterrestrial impacts, the eruption of large igneous complexes, the oxygenation of the atmosphere, global glaciations, and significant biological innovations? How does biological complexity arise, and what are its effects on planetary-scale environments? Is there a predictable series of biological innovations that will inform searches for life on planets orbiting other stars? These and other questions are tied to this goal that seeks to understand the historical interconnections between Earth and its biota to help guide our search for life elsewhere. All of this research requires a deeper understanding of evolutionary mechanisms at the levels of molecules, cells, organisms, and ecosystems (Goal 5). The results contribute directly to the identification of biosignatures (Goal 7).

- *Objective 4.1*—Earth's early biosphere. Investigate the development of key biological processes and their environmental consequences during the early history of Earth through biogeochemical, paleobiological, geological, and genomic studies.

Example investigations

Use information obtained from microbial genomes to understand the early evolution of key microbial processes (e.g., methanogenesis, sulfate reduction, aerobic metabolism, etc.).

Develop timelines for the evolution of different microbial processes by linking observations of biogeochemical proxies to detailed, high-resolution geochronological measurements of ancient rocks.

Develop complex numerical models for the performance of biogeochemical cycles under conditions that existed on early Earth and apply such knowledge to the interpretation of early Mars.

- *Objective 4.2*—Production of complex life. Investigate the pathways and mechanisms that increased the complexity of life from microbial communities through successive levels of multicellularity.

Example investigations

Study detailed records of biogeochemical proxies to determine if global environmental events were driven by biological innovation.

Use comparative genomics in conjunction with the fossil and biomolecular fossil records to better understand key steps in the evolution of eukaryotes and sources of their genomes.

Apply knowledge gained from studies of the evolution of development to understand the sudden evolution of complex animals during the Neoproterozoic and early Cambrian.

- *Objective 4.3*—Effects of extraterrestrial events upon the biosphere. Study the short- and long-term effects of extraterrestrial phenomena such as secular changes in the magnitude and quality of solar and cosmic radiation, the evolution of the Earth-Moon system, nearby supernovae, and infalling comets and asteroids on life and the environments in which it exists.

Example investigations

Use data obtained from the geological record to determine any effects of extraterrestrial environmental perturbations upon the sustainability and/or diversity of life.

Investigate the mechanisms that enable small changes in the amount and quality of solar radiation received by Earth to influence global climate and biological productivity.

GOAL 5—Understand the evolutionary mechanisms and environmental limits of life. Determine the molecular, genetic, and biochemical mechanisms that control and limit evolution, metabolic diversity, and acclimatization of life.

The diversity of life on Earth today is a result of the dynamic interplay between genetic opportunity, metabolic capability, and environmental change. For most of their existence, Earth's habitable environments have been dominated by microorganisms and subjected to their metabolism and evolution. As a consequence of geological, climatologic, and microbial processes acting across geological time scales, the physical-chemical environments on Earth have been changing, thereby determining the path of evolution of subsequent life. For example, the release of molecular oxygen by cyanobacteria as a by-product of photosynthesis as well as the colonization of Earth's surface by metazoan life contributed to fundamental, global environmental changes. The altered environments, in turn, posed novel evolutionary opportunities to the organisms present, which ultimately led to the formation of our planet's major animal and plant species. Therefore, this "co-evolution" between organisms and their environment is an intrinsic feature of living systems.

Life survives and sometimes thrives under what seem to be harsh conditions on Earth. For example, some microbes thrive at temperatures of 113°C. Others exist only in highly acidic environments or survive exposures to intense radiation. While all organisms are composed of nearly identical macromolecules, evolution has enabled such microbes to

cope with a broad range of physical and chemical conditions. What are the features that enable some microbes to thrive under extreme conditions that are lethal to many others? An understanding of the tenacity and versatility of life on Earth, as well as an understanding of the molecular systems that some organisms utilize to survive such extremes, will provide a critical foundation for the search for life beyond Earth. These insights will help us understand the molecular adaptations that define the physical and chemical limits for life on Earth. They will provide a baseline for developing predictions and hypotheses about life on other worlds.

Background. The evolution of biogeochemical processes, genomes, and microbial communities has resulted in the complexity and robustness of the modern biosphere. However, we lack an understanding of how mutational events on the single gene level scale upward to altered macroscopic ecological performances of entire populations. We can examine the reciprocal interactions between biosphere and geosphere that can shape genes, genomes, organisms, and species interactions. Accordingly we will develop an understanding of the evolution of biochemical and metabolic machinery that drives the global cycles of the elements, as well as the potential of such evolution and its limits. Furthermore

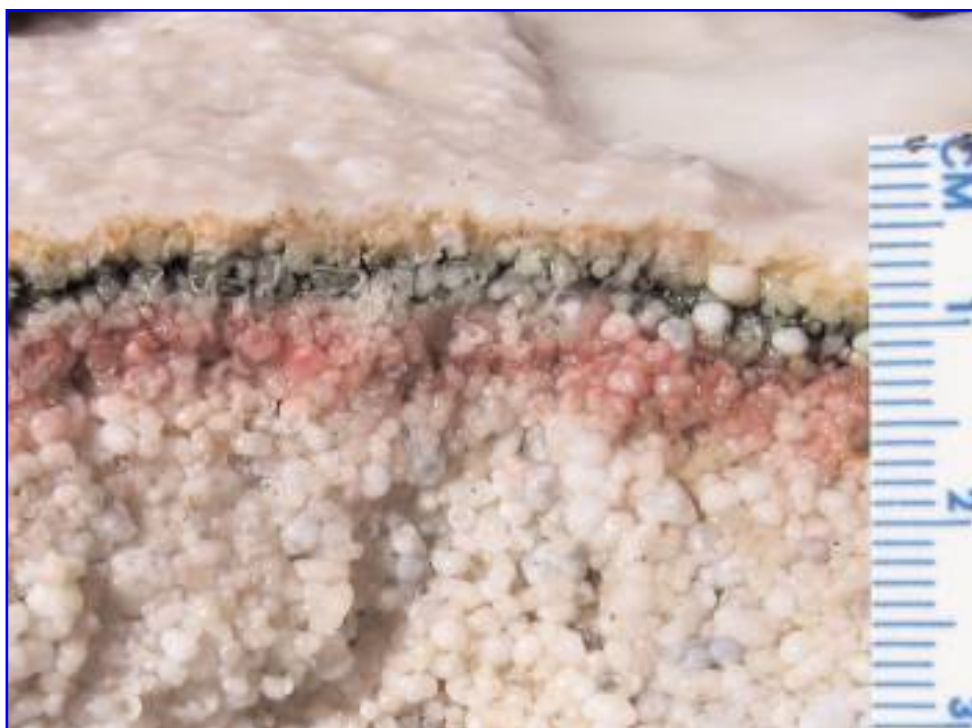


FIG. 5. Cyanobacteria and red phototrophic bacteria in a gypsum-hosted microbial community in a solar saltern, Exportadora de Sal, S. A., Guerrero Negro, Baja California Sur, Mexico. Photograph by D. Des Marais, NASA Ames Research Center.

we must observe their coordination into genetic circuitries and their integration into more complex biological entities such as whole cells and microbial communities.

While co-evolution of Earth's physical-chemical environment and its life is dynamic and proceeds at all organismic levels, microorganisms have played a critical role in shaping our planet. Microbes and viruses can serve as highly advanced experimental systems for biochemical, genetic, and genomic studies. More than 500 microbial genomes have been sequenced as of this writing. This unprecedented wealth of information, together with the experimental tools now available for single cell studies, provides a tremendous opportunity for experimental studies to be conducted on the evolution of microbial genes, genomes, microbial communities, and viruses. Such studies will uncover fundamental principles of molecular, cellular, and community level evolution with relevance to Earth and other planets. Of specific interest is observing or simulating the evolution of those molecular properties that facilitate the metabolic coupling of the oxidation/reduction cycles of elements and the adaptation to novel environments, especially extreme environments, created by simulated perturbations. Hypothesis-driven experimentation on microbial ecosystems using single species with known genome sequences can be employed to predict environmental changes and evolutionary solutions. Such studies can be extended to defined mixed communities to study the plasticity and adaptation of the "metagenome," which comprises the genomes of all members of a microbial community, when it is subjected to environmental changes and genetic flux. The evolved genotypes and phenotypes should be correlated to the specific changes they induce in the physical-chemical environment.

Our ongoing exploration of Earth has led to continued discoveries of life in environments that have been previously considered uninhabitable. For example, we find thriving communities in the boiling hot springs of Yellowstone, the frozen deserts of Antarctica, the concentrated sulfuric acid in acid-mine drainages, and the ionizing radiation fields in nuclear reactors. We find some microbes that grow only in brine and require saturated salts to live, and we find others that grow in the deepest parts of the oceans and require 500 to 1000 bars of hydrostatic pressure. Life has evolved strategies that allow it to survive even beyond the daunting physical and chemical limits to which it has adapted to grow. To survive, organisms can assume forms that enable them to withstand freezing, complete desiccation, starvation, high levels of radiation exposure, and other physical or chemical challenges. Furthermore, they can survive exposure to such conditions for weeks, months, years, or even centuries. We need to identify the limits for growth and survival and to understand the molecular mechanisms that define these limits. Biochemical studies will also reveal inherent features of biomolecules and biopolymers that define the physical-chemical limits of life under extreme conditions. Broadening our knowledge both of the range of environments on Earth that are inhabitable by microbes and of their adaptation to these habitats will be critical for understanding how life might have established itself and survived in habitats beyond Earth.

- *Objective 5.1—Environment-dependent, molecular evolution in microorganisms.* Experimentally investigate and observe

the evolution of genes, metabolic pathways, genomes, microbial species, and viruses. Experimentally investigate the forces and mechanisms that shape the structure, organization, and plasticity of microbial genomes. Examine how these forces control the genotype-to-phenotype relationship. Conduct environmental perturbation experiments on single microbial species to observe and quantify adaptive evolution to astrobiologically relevant environments.

Example investigations

Experimentally observe the expansion and contraction of microbial genomes within the context of different environments and selective forces.

Examine the molecular basis of the robustness and resilience of metabolic pathways in response to environmental changes.

Develop an understanding of the link between single gene evolution and the ecological consequences on the level of microbial populations.

- *Objective 5.2—Co-evolution of microbial communities.* Experimentally examine the metabolic and genetic interactions in microbial communities, including viruses, which have determined major geochemical processes and changes on Earth. Investigate how these interactions shape the evolution and maintenance of metabolic diversity in microbial communities. Investigate how novel microbial species establish and adapt into existing communities.

Example investigations

Investigate small molecule interactions and their role in coordinating energy flow in mixed phototrophic/chemotrophic microbial communities.

Examine the molecular basis of speciation, *e.g.*, the evolution of a generalist to a specialist, and, conversely, of a specialist to a generalist.

Examine the deterministic and stochastic processes leading to the resilience of established microbial communities.

- *Objective 5.3—Biochemical adaptation to extreme environments.* Document life that survives or thrives under the most extreme conditions on Earth. Characterize and elucidate the biochemical capabilities that define the limits for cellular life. Explore the biochemical and evolutionary strategies that push the physical-chemical limits of life by reinforcing, replacing, or repairing critical biomolecules (*e.g.*, spore formation, resting stages, protein replacement rates, or DNA repair). Characterize the structure and metabolic diversity of microbial communities in such extreme environments.

Example investigations

Investigate the physiological and molecular basis of the ability of microorganisms to persist at low water activity.

Biochemically characterize the diversity of DNA-repair mechanisms that allow microorganisms to recover from radiation damage.

Study microbial strategies that permit life in stationary phase.

GOAL 6—*Understand the principles that will shape the future of life, both on Earth and beyond. Elucidate the drivers and effects of microbial ecosystem change as a basis for forecasting future changes on time scales ranging from decades to millions of years, and explore the potential for microbial life to survive and evolve in environments beyond Earth, especially regarding aspects relevant to US Space Policy.*

Life on Earth depends upon networks of biogeochemical reactions that interact with the crust, oceans, and atmosphere to maintain a biosphere that has been remarkably resilient to environmental challenges. These reaction networks developed within self-organized microbial ecosystems that collectively responded to environmental conditions and changes. Evolutionary biologists are working to understand how such biological and environmental processes have shaped specific ecosystems in Earth's history. It is highly challenging yet critically important to employ such principles to formulate accurate predictions about the state of future ecosystems, especially when environments change faster than the tempo of biological evolution. Predictions of this nature will require improved models of the biogeochemical cycling of critical elements that links biological processes with the surrounding physical world.

Viewing Earth's ecosystems in the context of astrobiology challenges us to consider how "resilient" life really is on a planetary scale, to develop mathematical representations of

stabilizing feedbacks that permit the continuity of ecosystems in the face of rapidly changing physical conditions, and to understand the limits of these stabilizing feedbacks. Ideally this consideration will provide insight into the potential effects of environmental changes that are abrupt as well as those changes that unfold over time scales ranging from seasonal cycles to millions of years.

The ability of life to move beyond Earth will depend upon the potential for microorganisms to utilize resources and to adapt and evolve in extraterrestrial environments. Viable microorganisms *might* be transported by natural events such as impacts or by robotic spacecraft, but they most certainly *will* accompany human missions. Life forms will be challenged by extremes in temperature, pressure, radiation and the availability of nutrients. Studies of adaptation and survival will indicate not only whether microbial life can expand its evolutionary trajectories beyond Earth but also how it can play key supporting roles in human exploration.



FIG. 6. Earthrise over the Moon. Courtesy of NASA.

Background. Humans are increasingly perturbing Earth's biogeochemical cycles. In addition to impacting the carbon cycle, humans have doubled the natural global sulfur emissions to the atmosphere, doubled the global rate of nitrogen fixation, enhanced levels of phosphorus loading to the ocean, altered the silica cycle, and perhaps, most critically, altered the hydrological cycle. When compared to many natural perturbations, the effects of human activities have been extremely rapid. Understanding how these changes will affect planetary climate, ecosystem structure, and human habitats is an urgent research priority in which astrobiology can play an important role.

A conceptual continuum embraces the development of biogeochemical cycles, the evolution to the modern biosphere, and ongoing human effects. Studies of processes over long time scales (millennia to millions of years) offer an observational context that extends and strengthens the interpretation of shorter time scale (annual to century) phenomena. While longer-term changes in Earth's ecosystems are strongly affected by processes such as tectonics and evolution, the relatively rapid rates of recent change, influenced by anthropogenic forcing, may only have analogues in previous important events such as major extinctions.

A key objective for elucidating the sign of the feedbacks in biogeochemical cycles and for understanding how the cycles respond to perturbations is to develop quantitative models that incorporate the interactions between metabolic and geochemical processes. For example, how are the key biogeochemical cycles of the light elements (*e.g.*, C, N, O, S, P, etc.) related? What constrains these cycles on time scales of years to millions of years? How are these cycles altered by rapid changes in climate? Does functional redundancy, as indicated by a great diversity within microbial ecosystems, ensure ecosystem resilience? Are specific metabolic pathways more sensitive to perturbations than others? How have the biogeochemical cycles co-evolved with terrestrial environments on time scales of millions of years? Our vision of the future will be sharpened by a retrospective view offered by a biogeochemical model that is verified by preserved records. This effort is needed in order to expand the current focus on short-term changes and "what is happening" in order to perform more hypothesis testing and thus address "why is this happening."

Life forms that are transported beyond their planet of origin will probably experience conditions more extreme than those in the most extreme habitats on Earth. Such conditions will challenge their very existence in most, if not all, cases. Understanding survival and evolution beyond the planet of origin is essential for evaluating the potential for the interplanetary transfer of viable organisms and thus the potential that life elsewhere in the Solar System might share a common origin with life on Earth. Survivorship beyond Earth is an ultimate test of the resilience of terrestrial life and thus of its potential to diversify far beyond the limits of our current understanding. Microbes and other organisms are destined ultimately to play critical roles in life support during extended human missions. Their study should be an integral component of the expansion of mankind throughout the Solar System as NASA carries out US Space Policy over the next century.

- *Objective 6.1—Effects of environmental changes on microbial ecosystems.* Conduct remote sensing, laboratory, and field studies that relate the effects of present-day environmental changes to the biogeochemical cycling of key elements by microorganisms. Relate changes in elemental cycling to effects on the structure and functioning of microorganisms, their ecosystems, and the surrounding environment. Develop predictive models that integrate biogeochemical cycles with adaptation by microbial ecosystems and with environmental change (both those driven by anthropogenic and non-anthropogenic forces, including extraterrestrial events [see Objective 4.3]).

Example investigations

- Document the ecological impact of changes in climate, habitat complexity, and nutrient availability upon the structure and function of a selected ecosystem, as a guide to understanding changes that might occur over time scales ranging from abrupt events (a few years or less) to millions of years.
- Identify biosignatures associated with global change or microbial stress.
- Develop techniques for remote sensing of microbial biosignatures at a variety of scales.

- *Objective 6.2—Adaptation and evolution of life beyond Earth.* Explore the adaptation, survival and evolution of microbial and other organisms under environmental conditions that simulate conditions in space or on other potentially habitable planets. Identify survival strategies to evaluate the potential for interplanetary transfer of viable organisms and to establish requirements for effective planetary protection. Identify and validate roles that microorganisms might play in life support and resource acquisition during human missions envisioned by US Space Policy. Develop tools to track the function and adaptation of microbes and other organisms to extraterrestrial environments during mankind's exploration efforts.

Example investigations

- Document the effects of the space environment upon microbial ecosystems.
- Examine the survival, genomic alteration, and adaptation of microbial ecosystems in a wide range of simulated martian environments. Interpret the significance of these experiments regarding the potential for the forward biological contamination of Mars and for utilizing microorganisms to support the needs of human exploration.
- Examine the effects of the space environment upon the biosynthesis and utilization of biomolecules that play key roles in biogeochemical processes and also upon the viability of microbes that might be transferred between planets by natural processes (*e.g.*, impact ejection).
- Develop automated assay tools to monitor the adaptation of organisms in lunar and martian environments, especially those areas most likely to be visited by human explorers over the next century.

GOAL 7—Determine how to recognize signatures of life on other worlds and on early Earth. Identify biosignatures that can reveal and characterize past or present life in ancient samples from Earth, extraterrestrial samples measured *in situ* or returned to Earth, and remotely measured planetary atmospheres and surfaces. Identify biosignatures of distant technologies.

Our concepts of life and biosignatures are inextricably linked. To be useful for exploration, biosignatures must be defined in terms that can be measured and quantified. Measurable attributes of life include its complex physical and chemical structures and also its utilization of free energy and the production of biomass and wastes, phenomena that can be sustained through self-replication and evolution. Habitable planets might create nonbiological features that mimic biosignatures and therefore must be understood in order to clarify our interpretations. We must create a library of biosignatures and their nonbiological mimics of life as we know it. A strategy is needed for recognizing novel biosignatures. This strategy ultimately should accommodate a diversity of habitable conditions, biota, and technologies in the universe that probably exceeds the diversity observed on Earth.

Background. Astrobiological exploration is founded upon the premise that signatures of life (biosignatures) will be recognizable in the context of their environments. A biosignature is an object, substance and/or pattern whose origin specifically requires a biological agent. The usefulness of a biosignature is determined, not only by the probability of life creating it, but also by the improbability of nonbiological processes producing it. An example of such a biosignature might be complex organic molecules and/or structures whose formation is virtually unachievable in the absence of life. A potential biosignature is a feature that is consistent with biological processes and that, when it is encountered, challenges the researcher to attribute it either to inanimate or to biological processes. Such detection might compel investigators to gather more data before reaching a conclusion as to the presence or absence of life.

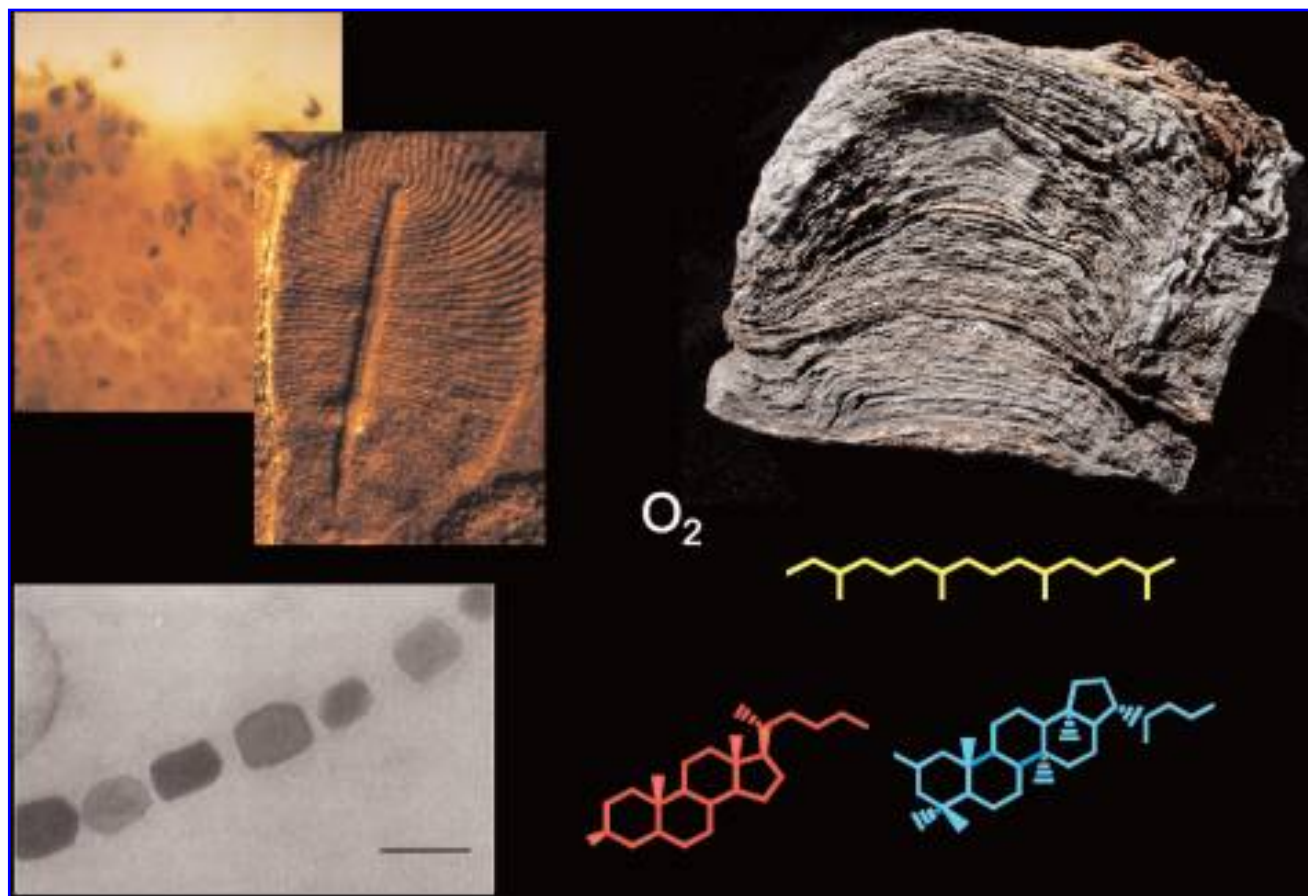


FIG. 7. Some examples of biosignatures. Images courtesy of A. Knoll, Harvard University (*Eoentophysalis* microfossil cells); B. Runnegar, U.C.L.A. (*Dickinsonia* Ediacara fossil); D. Des Marais, NASA Ames Research Center (stromatolite), D. Blake, NASA Ames Research Center (magnetite chain).

Suites of biosignatures must be identified that reflect fundamental and universal characteristics of life and thus are not restricted solely to those attributes that represent local solutions to the challenges of survival. For example, certain examples of our biosphere's specific molecular machinery, *e.g.*, DNA and proteins, might not necessarily be mimicked by other examples of life elsewhere in the cosmos. On the other hand, basic principles of biological evolution might indeed be universal.

However, not all of the universal attributes of life will be expressed in ancient planetary materials or detectable remotely (*e.g.*, by astronomical methods). For example, the processes of biological evolution are highly diagnostic for life, but evidence of biological evolution might not be readily detected as such in a sample returned from Mars. However, better-preserved evidence of life might include complex structures that are often retained in aquatic sediments or can be preserved in large quantities in the environment. Thus, for example, categories of biosignatures can include the following: cellular and extracellular morphologies, biogenic fabrics in rocks, bio-organic molecular structures, chirality, biogenic minerals, biogenic stable isotope patterns in minerals and organic compounds, atmospheric gases, remotely detectable features on planetary surfaces (photosynthetic pigments, etc.), and characteristic temporal changes in global planetary properties (*e.g.*, seasonally mediated respiration and biomass cycles). On Earth, biosignatures also include those key minerals, atmospheric gases, and crustal reservoirs of carbon, sulfur, and other elements that collectively have recorded the enduring global impact of the utilization of free energy and the production of biomass and wastes. Oxygen-producing photosynthesis has simultaneously created large reservoirs of atmospheric oxygen, marine sulfates, and sedimentary ferric iron and sulfates (its oxidized products), as well as large sedimentary reservoirs of biogenic organic matter and sulfides (its corresponding reduced products). Again, in order to qualify as biosignatures, such features must be sufficiently complex and/or abundant so that they retain a diagnostic expression of some of life's universal attributes. Also, their formation by nonbiological processes should be highly improbable.

All biosignatures are characteristic of the modification of a local or planetary environment by life. Human technology and its resultant products and outputs can therefore also be considered as a biosignature, with the added benefit that it might be detected remotely. Thus, although technology is probably much less common than life in the universe, its associated biosignatures perhaps enjoy much higher "signal-to-noise" ratios. Accordingly, current methods should be fur-

ther developed and novel methods should be identified for detecting electromagnetic radiation or other diagnostic artifacts that indicate remote technological civilizations.

- *Objective 7.1—Biosignatures to be sought in Solar System materials.* Learn how to recognize and interpret any biosignatures either in ancient rocks on Earth or in the crustal materials and atmospheres of other Solar System bodies in order to characterize any ancient and/or present-day life.

Example Investigations

Determine additional organic biomarkers that will help to chart the presence and development of photosynthetic microbiota in Precambrian rocks.

Determine the features of sedimentary laminated textures that uniquely require biological processes.

Identify examples of chemical, mineralogical and stable isotopic biosignatures that can indicate the presence of subsurface biota (*e.g.*, microbes living in water-saturated rocks) and that can be preserved in crustal materials.

Characterize any potential gaseous biosignatures in the martian atmosphere via orbiting spacecraft and/or ground-based observatories, and investigate their potential sources.

- *Objective 7.2—Biosignatures to be sought in nearby planetary systems.* Learn how to identify and measure biosignatures that can reveal the existence of life or technology through remote observations.

Example Investigations

Determine the nature and fate of reduced gases that are produced by specific microbial ecosystems in an anoxic ("pre-oxygenated") biosphere.

Carry out laboratory, observational and modeling studies to separate false from true biosignatures (*e.g.*, atmospheric O₂ in a range of planetary environments [see Objective 1.2]).

Develop novel approaches to detect evidence of distant technologies.

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