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Astrobiology Workshop

Final Report
Leadership in Astrobiology

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Introduction

Astrobiology is defined in the 1996 NASA Strategic Plan as "The study of the living universe." At NASA's Ames Research Center, this endeavor encompasses the use of space to understand life's origin, evolution, and destiny in the universe. Life's origin refers to understanding the origin of life in the context of the origin and diversity of planetary systems. Life's evolution refers to understanding how living systems have adapted to Earth's changing environment, to the all-pervasive force of gravity, and how they may adapt to environments beyond Earth. Life's destiny refers to making long-term human presence in space a reality, and laying the foundation for understanding and managing changes in Earth's environment.

The first Astrobiology Workshop was held at Ames on September 9-11, 1996, bringing together a diverse group of researchers to discuss the following general questions:

- Where and how are other habitable worlds formed?
- How does life originate?
- How have the Earth and its biosphere influenced each other over time?
- Can terrestrial life be sustained beyond our planet?
- How can we expand the human presence to Mars?

The objectives of the Workshop included: discussing the scope of astrobiology, strengthening existing efforts for the study of life in the universe, identifying new cross-disciplinary programs with the greatest potential for scientific return, and suggesting steps needed to bring this program to reality.

Ames has been assigned the lead role for astrobiology by NASA in recognition of its strong history of leadership in multidisciplinary research in the space, Earth, and life sciences and its pioneering work in studies of the living universe. This initial science workshop was established to lay the foundation for what is to become a national effort in astrobiology, with anticipated participation by the university community, other NASA centers, and other agencies.

This workshop (the first meeting of its kind ever held) involved life, Earth, and space scientists in a truly interdisciplinary sharing of ideas related to life in the universe, and by all accounts was a resounding success. It was broadly interdisciplinary in attendance, with the following breakdown of the invited participants: 23 astronomers and physicists, 37 Earth and planetary scientists, and 38 life scientists. Attendance was 250 on the first day. The smaller workshop held on the next two days was nominally restricted to about 100 invitees, but in fact it attracted an overflow crowd. Peak attendance was actually reached during the final afternoon. Numerous phone calls were received from the public wanting access to additional information. The news media called several times after the workshop to request updates on and access to the latest thinking, discussion, and speculation.

This report is a summary of the highlights of the workshop. The first section deals with the current state of knowledge in the fields that comprise astrobiology as presented by the invited speakers. This was widely considered to be one of the most significant aspects of the workshop, as participants were appraised of the latest thinking in fields outside their own. The next section identifies new cross-disciplinary research topics which resulted from new information exchanged among all of the relevant fields. These topics were developed during small group discussions organized around the 5 key questions noted above and occurred during two "working lunches." They were summarized and discussed during the final afternoon plenary session. The last section contains suggestions for follow-on activities which

were proposed by workshop participants during the final afternoon plenary session. The report concludes with appendices containing the workshop program, abstracts, and participant list.

There was no attempt made at the workshop to reach consensus on research priorities, recommendations, or funding requirements. Rather this workshop was intended to stimulate cross-discipline thinking and new ideas for productive research.

Current State of Knowledge in Key Areas of Astrobiology

Formation and Diversity of Planetary Systems

Fundamental to understanding the distribution of life in the cosmos is understanding the formation and diversity of planetary systems, which are the retinues of planets and satellites of different mass and composition orbiting stars of different luminosities. The conditions under which these systems form and evolve will determine the diversity of habitable environments in space and in time. Understanding planetary phenomena will rely on three key approaches: direct, multi-wavelength observations of planetary systems across the entire range of formative and mature stages; theoretical studies of the behavior of multiple, complex, and interacting processes under diverse conditions; and laboratory and astronomical measurements of primitive materials preserved since the formative stages of our own system.

A consensus theory of planetary formation is generally in hand: gradual accumulation of solids within a primarily gaseous, flattened circumstellar accretion disk, which itself is a byproduct of the formation of its parent star from a dense, rotating interstellar cloud of gas and dust. However, this theory has been studied in only a very narrow range of initial conditions, possibly important physics has been neglected, and it has little or no predictive capability. For example, recent discoveries of giant planets in circular orbits very close to solar-type stars were unexpected and are still not completely understood. There are, as of this writing, eight new giant planets known to orbit solar-like stars; at least one of these orbits within the "habitable zone" of its parent star. These new data provide not only a challenge to the current theoretical paradigms, but clear direction as to parts of parameter space in which both theoretical models and observations of extrasolar systems need more exercise. Furthermore, given the wide range of conceivable environments, we might ask "what makes a planet habitable?" (an associated question is "habitable for what kind of organism?").

Advances in technology are enabling not only new observations of these mature (if unanticipated) extrasolar planetary systems, but also of "protoplanetary nebulae" within which the planetary formation process is still ongoing. These observations are capable of telling us the extent, mass, gas and solid content, and thermal structure of the material from which planets form. In order to comprehend the new, surprising diversity of planetary systems, we must continue to study the early stages of planetary formation under a range of conditions, as well as to establish the full range of ultimate outcomes of the process.

In addition to observations of remote extrasolar planetary systems from ground and space, we are fortunate to have in hand, or accessible by spacecraft, actual material which survives from the days of the early accumulation of our own planets. So-called "primitive material" preserves clues as to the materials from which, and the processes by which, planets formed. To be found in these primitive materials are presolar grains which carry clues as to the variety and number of stellar precursors of our own system, complex organic material which might preserve the

signature of interstellar chemistry, once-molten silicate "chondrules" with composition, size, and mineralogy diagnostic of the pre-accretionary environment, and, in one recent case, suggestive evidence for past life on another planet.

Origin of Life

The occurrence of organic compounds in interstellar clouds, planets of the outer solar system, comets and meteorites suggests a chain of astrophysical processes which link the chemistry of interstellar clouds with the prebiotic evolution of organic matter in the solar system and on the early Earth. Although there is no record of the evolutionary pathway from this simple organic matter to present-day life on Earth, the main steps along this pathway can be deduced from basic physical and chemical principles, environmental conditions on the early Earth, and the cellular biology and phylogeny of contemporary organisms.

There is compelling evidence that cellular life existed on Earth 3.56 billion years ago. Recently, a persuasive argument was made that terrestrial life was already present toward the end of the period of heavy bombardment of the early Earth by asteroids and comets from 4.0 to 3.9 billion years ago. This implies that ancestors of contemporary life emerged rather quickly, on a geological time scale, and perhaps also survived the effects of large impacts. Such catastrophic events would have strongly favored survival of thermophilic organisms which thrive at high temperatures. This scenario is consistent with the phylogenetic record, which indicates that the last common ancestor was thermophilic. This record also supports the view that life might have arisen first near marine hydrothermal vents. The possibility remains, however, that the first common ancestor lived at moderate temperatures and only later adapted to thermophilic conditions, in which case ocean surfaces and near-shore shallow environments might have spawned life.

All present-day forms of life are cellular, with lipid bilayer membranes forming the primary barrier that separates the interior of a cell from the external environment. It has been proposed that similar, encapsulating structures (vesicles) made of simple membrane-forming material could have self-assembled in the protobiological environment. The presence of such membrane-forming material in carbonaceous meteorites is consistent with this idea. Furthermore, recent experiments showed that vesicular lipid bilayer structures can grow by spontaneous addition of membrane-forming material from the surrounding medium, and can encapsulate both ions and macromolecules. Besides separating intracellular components from the diluting effect of the environment, cell membranes also provide a barrier for separating charges, a fundamental process in bioenergetics. From phylogenetic data we infer that the earliest cells probably used chemical rather than photochemical energy sources. It has also been proposed that membranes helped stabilize the secondary structure of peptides (protein precursors) having appropriate sequences of polar and nonpolar amino acids. Some of these peptides may have been capable of performing basic protocellular functions, such as catalysis, signaling, and energy transduction, without requiring the existence of separate molecules capable of storing and transmitting genetic information (i.e., nucleic acids).

Alternatively, it has been postulated that there was a time in protobiological evolution when RNA played a dual role as both genetic material and a catalytic molecule ("the RNA world"). However, this appealing concept encounters significant difficulties. RNA is chemically fragile and difficult to synthesize abiotically. The known range of its catalytic activities is rather narrow, and the origin of an RNA synthetic apparatus is unclear. Therefore, it may be more likely that RNA and proteins co-evolved in protocells, rather than evolving independently. The co-evolutionary process leading to division of cellular functions between these molecules, however, is not at all clear.

Understanding the emergence of life requires studies that extend beyond the origin of biopolymers and cellular structures. All these components necessarily assembled into auto-catalytic, self-reproducing systems capable of evolution and selection. Based on theoretical arguments, it has been suggested that sets of mutually catalytic molecules can reproduce and evolve without templating, resulting in a primitive metabolism without a genome. However, only a limited number of experimental studies have been performed in this area.

The recent discovery of organic, possibly even biogenic, material in a martian meteorite (ALH84001) opens the exciting possibility of extending the search for the origin of life to places beyond the Earth. Although current findings on ALH84001 are inconclusive regarding possible life on Mars, future exploration might lead to fundamentally new insights into prebiotic chemistry and protobiological evolution, the record of which is lost on the Earth.

Interactions Between Earth and Its Biosphere

The history of life on Earth was directed, at least in part, by changes in the surface environment. Today we are experiencing rapid environmental changes of our own making, and our biosphere must adapt and, perhaps eventually, evolve to a different state. Environmental change surely has occurred in the past, but can studies of our past help to predict our future? Also, to the extent that rocky planets have followed similar evolutionary paths, at least during the early chapters of their history, can studies of our own biosphere assist us in our search for extraterrestrial life, past or present?

The processes which modified the environment vary widely both in their magnitude and time scales. For example, the increase in solar luminosity, the declining rates of comet and meteorite impacts, the exchange of volatile materials between Earth's mantle and crustal reservoirs, and the stabilization of continents have all exerted dominant controls on the surface environment. However, because these processes themselves evolved very slowly, they required 10^8 to 10^9 year time scales to cause global changes. The effects of plate tectonics, erosion, sedimentation, and glaciation acted more quickly, causing changes over 10^4 to 10^8 year time scales. Faster still have been the effects of ocean and climate dynamics and ocean-atmosphere-biosphere interactions, which can vary on 1 to 10^4 year time scales. Already, human activity has dramatically altered patterns of erosion, sedimentation, climate patterns, species biodiversity, primary productivity and ocean-atmosphere-biosphere exchange. These changes are happening over a few decades. In the earlier "natural" world, such changes would have required typically thousands to millions of years to occur. How will plants, animals and the microbial world respond to such rapid change?

Microorganisms are supremely adapted for coping with change. Should global conditions deteriorate, the small size of microbes allows them to "hide" in niches. Small cell size imparts a high surface/volume ratio, which allows rapid rates of chemical exchange with the cell's surroundings. Thus microbes can rapidly exploit favorable conditions. The diverse biochemistry of microbes permits them not only to survive, but even to prosper under environmental extremes. Already by 3.5 billion years ago, widespread microbial communities accommodated large meteorite impacts, UV irradiation, desiccation, wide excursions in temperature and salinity, and a long menu of chemical substrates as sources of energy and organic matter. For example, our early biosphere adapted to major changes in volcanism, coastal environments, atmospheric composition, and the oxidation state of the oceans and atmosphere. On the other hand, microorganisms can themselves contribute to environmental change by, for example, affecting rates of erosion and sedimentation or by influencing the

atmosphere's inventory of reactive gases. Microbes responsible for infectious diseases evolve to circumvent medical treatments, thereby continually challenging human populations.

In contrast with the bacteria, plants and animals are much larger, more complex and highly specialized. They typically depend upon a more limited suite of nutrients and a relatively narrow range of conditions for their survival. Accordingly, environmental change, human-induced or otherwise, can more easily trigger catastrophe within ecosystems which sustain these complex eukaryotic organisms. Modern challenges to the biosphere include rising atmospheric levels of CO_2, SO_2, CH_4, CO, and N_2O due to fossil fuel burning and agriculture (causing greenhouse climate effects as well as direct biospheric effects), declining ozone levels (leading to increased ultraviolet radiation), invasions of foreign species, and land use changes whose effects include the following: soil salinization, overgrazing, increased soil erosion, altered energy balance, loss of biodiversity, species extinctions, declines in food and fisheries, and chemical pollution.

While large meteorite impacts, such as the one which marks the Cretaceous/Tertiary boundary, were perhaps more severe than modern human-induced changes, impacts still serve as useful models for the effects of catastrophic change on the biosphere. For example, the severe "winter" which had been predicted to follow a large impact alerted us to the "nuclear winter" which might follow thermonuclear war. Also, impacts remind us that catastrophism probably does play at least a limited, but still important, role in the long-term evolution of our biosphere. The role of impacts in evolution was perhaps most pronounced during the earliest stages of Earth's history, when impact rates were much higher.

Sustaining Life in Space

Because life evolved and developed on the Earth, it is uniquely adapted to function on this planet. To sustain life beyond the Earth's biosphere for prolonged periods of time will require a better understanding of the processes underlying biological adaptation and the interactions among organisms and their environments. The relationships among the behavioral, structural, and genetic bases of survival remain to be elucidated. Adaptability in biological systems is a given, but the limits of adaptability and the issue of irreversibility of adaptive changes are major concerns. A concerted effort in enhancing our knowledge of biological adaptation, and developmental and evolutionary biology, will be needed if we are to sustain terrestrial life beyond the Earth's biosphere.

Electromagnetic radiation and gravity are two fundamental environmental variables that dramatically affect biological systems. On Earth, gravity is effectively constant in magnitude and direction, and the natural radiation environment has modest variability. These physical variables are difficult to control in space, and consequently can severely limit our ability to sustain life beyond the surface of the Earth.

How the radiation environment beyond the Earth affects biological systems is only partially understood. In space, galactic cosmic rays and particles from solar events can be lethal to terrestrial life forms. We have a very limited ability to predict solar events, and our understanding of shielding techniques to manage radiation risks is poor. Further, our ability to characterize the radio-biological effectiveness of various ionized and non-ionized particles, is limited. Space travelers beyond low Earth orbit must, therefore, monitor the Sun for solar storms as a matter of life or death.

Clearly, the effects of various forms of radiation on RNA and DNA are issues of major concern. Currently we are ignorant of the relationships among chromosomal damage,

chromosomal aberrations, and carcinogenesis. The direct effects of high energy particles on the nervous system are also poorly understood, as are biological mechanisms for the repair of radiation damage.

Gravity profoundly affects many biological systems, both directly and indirectly. The cardiovascular, musculoskeletal, and neurovestibular systems all undergo dramatic changes in space, where organisms are deprived of terrestrial gravity. For example, fluids shift from the lower limbs and lower torso to the upper torso and the head; blood volume is reduced; anti-gravity muscles in the lower limbs and torso tend to atrophy; bones that formerly supported the organism against gravity become less dense and more fragile; vestibular-ocular reflexes are altered, and the nervous system re-calibrates itself to function in the absence of gravity. Although these changes are generally benign for functioning in space, they can seriously compromise an organism's ability to function in a new gravitational environment and upon return to the Earth.

Humans currently use multiple countermeasures to minimize the effects of non-terrestrial environments on physiological systems for periods of more than one year. These countermeasures, which include training procedures, protective garments, physical exercise, conditioning devices, and various pharmacological agents, may be of only limited value to sustain life beyond the Earth's biosphere for prolonged periods of time that ultimately will include multiple generations. Artificial gravity, provided by continuous or intermittent centrifugation, lower-body negative pressure exercise chambers, or other techniques, may be necessary. Our experience with artificial gravity for humans in space is limited to a single, brief, Gemini flight experiment, and our current knowledge base is inadequate to assess the need for artificial gravity to sustain life beyond the Earth's biosphere.

Critical psychological variables in small group interactions during prolonged isolation in a perpetually hostile environment away from the home society are not well understood. The interactions of gravity, radiation, and isolation in non-terrestrial environments have never been studied systematically. Thus, many fundamental questions in the life sciences will need to be answered before we can assure that terrestrial life forms can be sustained beyond the Earth's biosphere for prolonged periods.

With current technology, we are able to maintain terrestrial life beyond the Earth for periods in excess of one year. To sustain terrestrial life beyond the Earth for longer periods, it is necessary to create a micro-environment that is similar to that on Earth, at least initially. This environment must provide an atmosphere with appropriate partial pressures of O_2 and allow for gas exchanges to support metabolism; it must provide adequate liquid water, appropriate microorganisms, adequate gravity, food, thermal protection, and radiation protection; it must allow for the partial recycling of nutrients and waste-products; finally, it must be stable and reliably sustainable for an indefinite period of time.

Human Exploration of Mars

As described in the section above, we still lack much of the fundamental knowledge necessary to send humans on extended space journeys beyond the protection of the Earth's biosphere (including its magnetic field). Only modest progress is being made towards actually carrying out the life science experiments and technology tests needed to ensure that a crew arriving at Mars will be at a sufficient fitness level (albeit that fitness level needs definition) to assure their well being and the success of their mission. Thus, fully effective countermeasures to deal with long duration exposure to microgravity have not yet been demonstrated, and the appropriate shielding requirements to deal with extended exposure to heavy galactic cosmic rays have not been fully

defined. However, these issues appear tractable if appropriate experiments are conducted on the International Space Station and if appropriate particle accelerator experiments are carried out.

A program to extend human presence to Mars will inevitably have both exploration and what we may term habitability goals. If evidence that life once evolved on Mars is discovered, human explorers will provide much of the scientific capability needed (beyond robotic capabilities projected for the next several decades) to investigate how the pre-biotic seeds of microbial life evolved and subsequently prospered or perished.

Theory, laboratory experimentation, subterranean terrestrial sampling and meteoritic evidence suggest that microbial life could have evolved on early Mars. Our present lack of direct knowledge about subterranean martian environments should make us cautious, therefore, about concluding (as seems common) that any such early life would inevitably have become extinct on a planet where present surface conditions are indeed extremely hostile. To answer questions about possible extant life we need to explore the subsurface below the cryosphere, which extends to kilometer depths, and into the warmer martian hydrosphere. Although a thorough exploration of the martian subsurface by robots alone is feasible in principle, the combined effects of great communication distances and intrinsically limited machine intelligence might well require postponement of such exploration for many generations. Therefore, some astrobiologists are considering whether human exploration of Mars may be legitimately identified as a real scientific priority as the only efficient and timely way in which we will be able to study, at first hand, a second sample of life (all terrestrial life being linked to a common ancestor).

The consequences of the discovery of life, past or present, on Mars in the coming decades will have profound implications beyond just the intense interest of molecular biologists. (Likewise, although it will be much harder to disprove the case, the determination that Mars never evolved life would also have profound implications.) Scientists and non-scientists alike will immediately appreciate the improbability that humans are "alone" in our galaxy. The discovery of life on Mars will surely add priority to the search for life elsewhere in our solar system (e.g. in the subterranean oceans of Europa), to the search for Earth-like planets orbiting other stars in our galaxy, and to the search for extraterrestrial intelligence. More generally, the stimulation of such a discovery of martian life is also likely to lead us to a recognition that, having the technological means at hand, we can be on the verge of becoming a multi-planet civilization, with Mars as our second abode.

New Cross-Disciplinary Research Programs

Formation and Diversity of Planetary Systems

It was recommended that part of NASA's vision should be to understand the planetary formation process in enough depth to be able to predict, or at least constrain, the diversity of habitable planetary systems. Within this vision, primary science goals might include: What are the fundamental processes and conditions that lead to planetary formation? What kinds of planets form, around what kinds of stars, and at what distances from their parent stars? What defines and determines "habitability"?

There are several well-posed problems that are ready for accelerated study by astronomical observations. Recent indirect radial velocity observations of extrasolar planets, and millimeter-wave, infrared, and HST observations of circumstellar gas and particle disks, are outstanding examples of the tip of this iceberg. Certainly, observations of mature planetary systems around a large variety of stellar types of various ages will be needed to determine what kinds of planets

form around what kinds of stars. Direct or indirect detection of planets in "mature" systems is the focus of NASA's planning efforts to date. However, there remain critical gaps in our understanding of the earlier "protoplanetary" stage; these include the actual absolute (not assumed relative) abundances of gas and solids, the nebula radial extent under different initial conditions, its radial and vertical temperature structure, the particle-to-planet accumulation time scale, the role and distribution of angular momentum of in-falling material, the properties of stellar winds, and the role of magnetic fields. We are completely ignorant of whether any of these properties vary with stellar type and/or with star formation environment (i.e., solitary or densely clustered), and there are hints in current data that protoplanetary systems in the two different star forming regions in Taurus and Ophiuchus have rather different properties.

The observations need to be conducted over a wide range of wavelengths between the short microwave (millimeter) and near-infrared spectral regions to penetrate the thick nebular dust envelopes and sample the mid-plane where planet formation is occurring. Infrared (Keck and follow-on) and millimeter-wave interferometers are needed to resolve protoplanetary disk structure at 1 AU resolution. NASA's planned "Origins" program proposes a series of space-based infrared telescopes and interferometers; other approaches were mentioned which are less connected technologically but are also worthy of consideration (photometric detection, balloon missions, HST upgrades, far-IR [100 micron] interferometer, microlensing, etc.). Several key theoretical questions are ripe for interdisciplinary attack. These include the properties of a densely clustered protostellar environment, the role of ionization, grain charging, and electromagnetic forces, the role of global wave modes and/or energetic infall itself in nebula evolution, the presence, extent, duration, and energetics of nebula turbulence, the possibly wide-ranging migration of protoplanets (and solid material in general) within the nebula and even relative to the nebula gas. It was noted that the Sun-Earth Connections theme of the Space Science Enterprise might be tapped to a larger extent for its expertise in electrodynamics and stability or instability of weakly ionized media, properties of stellar and solar winds, and of dusty plasmas.

It was generally felt that augmentation of the numbers of primitive meteorites returned, catalogued, and analyzed from the Antarctic would yield commensurate rewards. Much of the nation's analytic resources are Apollo-era and worthy of considerable upgrading. Of particular interest might be the sort of ultra-high resolution analytic equipment capable of studying the internal structure of putative nano-fossils (such as found in ALH84001) or of obtaining accurate age dates and/or isotope data on small mineral samples. Exploration of this sort of "inner space" is probably just as demanding of technology and expertise, and as rewarding in terms of understanding of the planetary formation process, as comparable efforts devoted to exploring "outer space."

Concerning the issue of habitability, there are many unknowns (even in the case of our own planet). For instance, what stellar and/or planetary conditions are most important for the origin of life, or for its evolution and increasing complexity? Are stellar photons of extreme energies and charged particle fluxes positive or negative factors? What is the role of internal planetary activity (tectonics) in truncating or prolonging the habitable era? Water is generally agreed to be the *sine qua non* of life, but how is water distributed across growing planets or reintroduced on mature planets that lost it or never had it at all? Does chaotic planetesimal dynamics spray icy objects from the outer solar system onto mostly formed inner planets? What is the composition of the "primitive" objects that even today impact the terrestrial planets? What is the mass and extent of the Kuiper belt of primitive planetesimals? Are terrestrial-sized satellites of close-in giant planets orbiting M dwarf stars habitable? Are they dynamically stable? Studies of the "habitable zone" using planetary scale climate evolution models might profit from more association with the sophisticated modeling supported in the Earth science community (such as to treat cloud feedback effects).

Origin of Life

The origin of protobiological self-organization and complexity.

The main thrust in this area should be to establish the principles of organization and complexity that led a collection of organic molecules to assemble into the earliest ancestors of contemporary cells. With these principles as a basis, attempts should be made to create laboratory versions of cellular, self-reproducing and evolving systems starting from material that might have existed under prebiotic conditions. Even though enough knowledge appears to exist to make fundamental progress in this direction, this research area remains severely under-represented in the current exobiology program. The expertise of cellular and molecular/structural biologists and bio-organic and physical chemists will be required, guided by collaboration between experimentalists and theorists. The goals of this interdisciplinary effort are to establish protobiological versions of basic cellular functions such as energy capture, chemical catalysis, and transport of solutes across membrane boundaries. These processes must be accomplished by simple molecules that self-assemble to form auto-catalytic, self-reproducing systems that evolve in response to environmental pressures. The laboratory experiments must be guided by theoretical work aimed at discovering general principles of organization and complexity from simulations that include realistic descriptions of intermolecular interactions, energetics and chemical kinetics.

Conditions on the Earth between 4.6 and 3.8 billion years ago.

Based on current evidence that life on Earth originated earlier than 3.8 Gyrs ago, it becomes especially important to establish plausible conditions on the Earth during the prebiotic period. This would be a truly interdisciplinary effort involving astronomers, geologists, chemists, and planetary and atmospheric scientists. Among the main unanswered questions are:
(a) How did the temperature and the chemical composition of the atmosphere, crust and the oceans evolve over this time? (b) What were the global environmental effects of impacts of varying degrees of severity on the origin and survival of life? (c) What was the inventory of organic material on the prebiotic Earth, and what were the relative contributions of terrestrial and extraterrestrial sources? (d) Could life have been transported between Earth and Mars? From the biological side, it would also be important to determine what can be learned about the early evolution of life and its environment by phylogenetic characterization of the last common ancestor.

Origin of life elsewhere in the solar system.

An unambiguous answer to the question about extant or extinct life on Mars will likely come only from direct exploration. Nevertheless, there is a considerable body of research that should be done prior to or in parallel with missions to Mars in order to interpret results of analyses of martian samples. Perhaps the most urgent task is to broaden and extend the study of the ALH84001 meteorite and Earth analogs with the goal of better understanding the morphological, chemical and isotopic characteristics attributable to micro-organisms. Collecting and analyzing more Mars meteorites is also a key task. Developing reliable criteria for distinguishing between biogenic and abiotic structures in the Mars meteorite is critical. Besides the rock record, information about prebiotic chemistry and possible life on Mars may be gained by comparing conditions on the early Mars and early Earth.

Since liquid water is required to support life, other, possibly transient, sub-surface micro-environments in the outer solar system and large asteroids could have been conducive to the origins of life, a prime example being Europa. These environments should be considered in

future missions and their prebiotic and biological potential should be assessed by model studies.

Organic chemistry in astrophysical and planetary environments.

The occurrence of organic matter in interstellar clouds, star-forming regions, comets and carbonaceous meteorites point to a chain of processes linking interstellar material to solar system formation and perhaps even to prebiotic evolution on Earth and Mars. The complexity of molecular structure that can be achieved in astrophysical environments remains, however, to be fully explored. In particular, little is known about what survives molecular cloud collapse to become incorporated in planetary materials. Are there amino acids, nucleic acid bases or sugars in interstellar dust and comets? Now that optically active amino acids have been found in Murchison meteorite, what evidence can be found for astrophysical mechanisms capable of such stereoselectivity? These questions can be addressed by astronomical observations and further laboratory and theoretical studies of primitive materials.

Interactions between Earth and its Biosphere

The concept that the evolution of the biosphere and its environment are inextricably related should be investigated in detail. Far beyond simply demonstrating that such a relationship exists, such an investigation offers many conceptual and practical benefits. Understanding the extent to which biological evolution has been a product of environmental change will reveal the mechanisms of the evolutionary process. The consequences of human-induced environmental change will therefore be easier to forecast. The search for life beyond the earth will be improved by a firmer understanding of how planetary environments influence the survival of biospheres.

Studies of ancient ecosystems could explore the relationship between the microenvironment and the diversity of microbiota and how these changed over time. Comparative studies of modern and ancient ecosystems could identify those aspects of the microenvironment which are crucial to microbial diversity and evolution and how they changed over geologic time. Microbial communities in hydrothermal systems (including hot spring deposits) and in groundwater are especially important analogs both for understanding the very early fossil record on Earth and for guiding the search for evidence of past life on Mars. Also, the changes in morphology and chemistry which accompany fossilization should be examined.

Regarding Earth's "macroenvironment," we should identify those mechanisms which directed the long-term increase in atmospheric O_2 and the decline in atmospheric CO_2 levels. To accommodate these changes, microbes modified their pathways of CO_2 uptake, invented protocols for detoxifying oxidants, devised new O_2-requiring biosynthetic pathways, and so forth. What were the nature and timing of these innovations? What were the composition and abundance of trace biogenic gases in the ancient atmosphere, particularly before significant levels of O_2 were attained? What were/are the significant feedback effects involving biota, trace gases and climate? How did oxygen-utilizing eukaryotes evolve in response to these changes? Given anticipated land-use changes today, what role will trace gases play in future climate change?

How does an entire ecosystem, including its microbes, respond to abrupt environmental perturbations? The natural microbial world is a rich source of information about the mechanisms which could permanently change those ecosystems which sustain plants and animals. Can these microbial effects be detected before permanent change occurs? Ecosystem-level studies could monitor the effects of change. For example, such studies could explore the

following: (a) the ecology of microbial communities which are still relatively unaltered by human activity, (b) the sensitivity of ecosystems to changes in specific parameters, singly or in combination (e.g., CO_2 levels, UV irradiation, soil acidity, reductions in biodiversity, etc.), and (c) the relationships between the biota, climate, geography and hydrology.

Studies also could be pursued for plants and animals, specifically in the following areas: a) the influence of extraterrestrial phenomena such as impacts upon evolution, b) the physical and biological drivers of mass extinctions, and (c) ecosystem, hydrologic and climate changes which impact the natural ecosystem and also public health.

Extrasolar planets will eventually be examined to search for other biospheres. Life should ultimately be detectable through spectroscopic analyses of a planet's atmospheric composition. Under what conditions does the presence of abundant atmospheric O_2 definitely indicate life? Aside from abundant O_2 levels, what other atmospheric compositions are definitive indicators of a biosphere? Is the early history of our own atmosphere actually representative of other evolving, habitable planets?

Obviously an effective research and exploration program requires that new cross-disciplinary technologies be developed to exploit novel approaches for getting answers. These involve, for example, the development of new microsensors for probing the dynamics of microbial ecosystems, field sensors to monitor gas exchange between ecosystems and the atmosphere, new approaches in remote sensing and so forth. An effective technology program is one which is closely integrated with the research program and responds effectively to new needs as they arise.

Integrated quantitative models should be constructed which help to develop a deeper understanding between physiology, ecology, and the environment. Such models could account for changes over various time scales, and ultimately they should be able to predict community responses to perturbations. We also should model other planets which might still be habitable but which are different from Earth. How would different planetary sizes, solar insolation or volatile inventories affect the evolution of the planet and its biosphere? Such insights would greatly enrich our understanding of Mars as well as those extrasolar rocky planets which we are destined to discover.

Sustaining Life in Space

Perspectives from the early evolution and development of life on Earth can provide perspectives for developmental biology in space. The same mechanisms that allowed terrestrial life forms to adapt to the earthly environment will probably be at work in allowing terrestrial life forms to adapt to non-terrestrial environments. Similarly, experimental studies investigating gravitational and radio-biological influences on genetic material and developmental processes can provide perspectives for an understanding of the evolution of life on Earth. The new field of astrobiology provides a framework in which this integration can take place.

To sustain terrestrial life beyond the Earth's biosphere for prolonged periods of time will require new fundamental knowledge and an integration of that knowledge in many disciplines. Further, we need a more profound understanding of closed or semi-closed ecological systems. Interdisciplinary studies involving radiation physics, gravitational biology, genetics, neurobiology, and developmental biology are required to provide the critical understanding.

The International Space Station is an essential evolutionary test bed for research on the effects of the space environment in biological development and evolution, as well as the only place

where the effects of gravity on living systems can be investigated systematically. For example, we do not fully understand the role of gravity in development. Are there thresholds and critical periods for the effects of gravity; how are phenotypes and genotypes affected by gravity at the cellular, system, and organism level?

Improved models for definition and prediction of solar events, the development of advanced radiation shielding techniques, and enhanced understanding of genetic biological radiation repair mechanisms are of particular importance. Other interdisciplinary studies involving gravitational physics and life sciences are also needed. Just as importantly, we need a new interdisciplinary perspective to integrate the information that will assure the long term survival of terrestrial species beyond the Earth's biosphere.

A regenerative life support system (i.e. one which can be fully restored/replenished), will ultimately be needed to sustain terrestrial life beyond the Earth. Thus, a biodome will be required. Unfortunately, we cannot fully specify all the necessary characteristics of the required micro-environment at this time because we do not understand all the control mechanisms that function to maintain closed or nearly-closed ecological systems. A research biodome is an important tool that will be needed to help us examine these relationships. The transition from constant re-supplying to the use of *in situ* resources will eventually be necessary to sustain terrestrial life beyond the Earth's biosphere.

Cross-disciplinary studies continue to provide insights into the Earth's complex ecosystem, and these can ultimately be applied to developing artificial life support systems. This remains a promising area for future cross-disciplinary efforts, for the better we can characterize those events that alter the Earth's biosphere, the more adequately we will be able to specify what is needed to provide stable and sustainable life support systems in space.

Human Exploration of Mars

Progress in understanding the origin and evolution of life includes further efforts to explore the subterranean portion of the Earth's biosphere. The development of improved technologies to do so should include equipment that could later be used on Mars; e.g., light-weight, semi-automated drill rigs. Moreover, techniques should be evolved from current procedures to ensure that as samples are acquired from new subsurface environments, those samples are protected from contamination -- all the way from their source to their detailed examination within a well-equipped Mars base laboratory. Such aseptic protection of the samples must be carried out in a way to ensure that the samples are effectively quarantined until adequately determined to be free of pathogenic properties. If and when samples of extant martian life are indeed discovered, we must be prepared to proceed with their fundamental characterization and to have clear procedures established to determine if and when such samples should be returned to Earth. The importance of this issue will surely influence astronaut selection and training requirements which will likely include participation in the exploration of the extremes of our own planet's biosphere, e.g. desert (including Antarctica) and subterranean environments.

If Mars does have an extant subterranean biosphere, then our exploration of that biosphere raises the serious environmental and ethical questions that we face on our own world where species are endangered and lost sometimes even before we have discovered and characterized them. The need to avoid contaminating and changing a presently unknown biologic environment was raised at the workshop and acknowledged to be not only a potential scientific catastrophe but also a real policy issue, as yet without an assigned advocate.

Further, even if it should turn out that Mars is now a sterile planet, environmental issues will confront us -- issues relating to the control of the pollution and waste associated with an expanding human base. In the much longer term our technology may provide us with the ability to seriously consider "terraforming" regions of Mars (or even the entire planet). Today terraforming another planet amounts to little more than a thought experiment, but human history demonstrates that such conjectures can indeed become reality, usually with severe unintended consequences.

In the absence of any other organization likely to grapple with the ethical dilemmas involved in the future expansion of humans beyond the Earth, the astrobiology component of NASA's space research program appears to be the natural home for analysis of exploration ethics.

Additional Activities

1. New Programs

   a. A number of the promising new research directions fit within existing NASA programs. In these cases, it is recommended that solicitations be included within existing NRAs to recruit research offerings in these areas. Because of the multidisciplinary nature of these proposals, it is also recommended that existing peer review panels be supplemented with reviewers possessing relevant skills. High quality research would be funded by the sponsoring program.

   b. Several important new research directions have been proposed which cross traditional NASA discipline and programmatic boundaries. For these, a funding commitment to support new research is recommended. This program should be designed to support an average grant interval of approximately three years (the length of time usually needed for a graduate thesis). It is recommended that astrobiology research proposals be solicited using a NASA Research Announcement and peer reviewed by a multidisciplinary panel organized by the Chief Scientist's office at NASA Headquarters (HQ) or "hosted" by each of the participating HQ Offices in turn: Space Science, Life and Microgravity Science, and Mission to Planet Earth.

   c. Based on the high level of interest expressed by the Workshop participants, a funding commitment from Ames Research Center is recommended to sponsor one focused conference (nano-fossils was proposed as a topic to follow-on to the ALH84001 results) per year to follow up on the high priority research topics that require further refinement and one general conference every 3 years to present the latest results of research important to astrobiology. The results will be made available to HQ and its advisory committees for consideration and programmatic action as appropriate.

2. Cross-agency and Cross-disciplinary Collaboration.

   a. In many areas of research summarized earlier, it was felt that an increased level of NASA-NSF collaboration would yield great rewards. Several powerful observational tools currently on the drawing boards are ground-based facilities (Keck interferometer, mm Array, etc.) and lie in a grey area between NASA (which traditionally emphasizes flight missions) and NSF (which emphasizes ground-based facilities). In the area of primitive materials, NSF and NASA already share the load in collecting and analyzing meteorites. Much theoretical modeling is highly computer intensive, yet both NASA and NSF are rethinking and/or downsizing their dedicated computational facilities. An increased level of

interagency cooperation in all of these areas, and perhaps others, might be both appropriate and desirable.

b. While fostering cross-agency cooperation, and with the likely support of Congress and the public, the workshop participants recommended that NASA also rededicate an appropriate fraction of its R&A to "interdisciplinary" research. Teaming across discipline boundaries is not always efficient at the beginning, but can be a critical step towards creative insights as each team member assimilates the knowledge of other disciplines while remaining an expert in their own right. Providing tangible incentives for working scientists to move in this direction is perhaps the most obvious tack. Policy-level adjustments to the R&A program priorities or practices might be appropriate; short "learning" sabbaticals might be encouraged to a greater extent under the grants programs; NAS-NRC associateships in interdisciplinary "new direction" research might be endowed.

3. Outreach and Communication Activities.

There was widespread public as well as scientific interest in the Astrobiology Workshop and its results. Beyond its deep fundamental scientific value, it was felt that a driving force for astrobiology is unquestionably the enormous public interest it excites. Hopefully, this interest will not flag at any point along the long path which now lies ahead. Opportunities should be built in from the start to engage the public and to provide them with new results and information appropriate to their level of public investment. A more problem- or theme-focused approach perhaps provides more appeal to the public and to Congress than a traditional method- or discipline-oriented approach.

Workshop participants urged more multidisciplinary discussions and interactions. Some Workshop participants are interested in teaching courses in astrobiology. Workshop participants also urged that a special effort be made to ensure that scientists interested in astrobiology have easy access to the latest findings, including access to the results of new research efforts described above. Four mechanisms are proposed to respond to this interest.

a. In addition to future astrobiology workshops and conferences, astrobiology may be a topic or session at other scientific conferences such as the American Society of Gravitational and Space Biology, COSPAR, the International Society for the Study of the Origin of Life, the Gordon Conference, and others.

b. A Web page will be established that will not only present formal work but will also allow discussion and interaction via chat rooms and dialog groups. Part of this Web page may be an "electronic textbook" accessible to the public to support education efforts in this area. Interdisciplinary communication can be furthered by using web-based connections to allow motivated discipline experts better insight into other communities.

c. A lay person's summary of the results of the current Astrobiology Workshop will be developed for presentation in a publicly accessible medium such as *The Planetary Report, Discover Magazine, Scientific American,* etc.

d. Special workshops will be convened for educators and students.

Appendices

Astrobiology Workshop

September 9-11, 1996

Program

Astrobiology is defined in the 1996 NASA Strategic Plan as "The study of the living universe. This field provides a scientific foundation for a multidisciplinary study of (1) the origin and distribution of life in the universe, (2) an understanding of the role of gravity in living systems, and (3) the study of the Earth's atmosphere and ecosystems." Ames Research Center has been assigned the lead role for astrobiology within the agency.

In a response to the challenge from the NASA Administrator to develop new cross-disciplinary programs and strengthen existing efforts for the study of life in the universe, Ames will host a scientific workshop, organized around several major questions in astrobiology:

- How does life originate?
- Where and how are other habitable worlds formed?
- How have the Earth and its biosphere influenced each other over time?
- Can terrestrial life be sustained beyond our planet?
- How can we expand the human presence to Mars?

Session 1 (Monday morning, Conference Center Ballroom)

0800 Registration

0900	Harry McDonald	Welcome and introductions
0930	Carl Pilcher	Astrobiology and space science
0955	Arnauld Nicogossian	Astrobiology and life science
1020	William Townsend	Astrobiology and earth science 4
1045	Frank Martin	Astrobiology and exploration
1110	David Morrison	Key questions in astrobiology 7
1130	*Lunch break*	

Session 2 (Monday afternoon, Conference Center Ballroom)

Co-chairs: MRC Greenwood & David Morrison

1300	Stuart Kauffman	Chemical and physical pathways to complexity
1340	Geoff Marcy	Detection of planets orbiting Sun-like stars 9
1420	James Kasting	Habitability of planets 10
1500	Chris McKay	The search for life on Mars 12
1540	William Sprigg	Near-term evolution of Earth's climate 13
1620	Emily Holton	Gravity and biology 14
1730	*Reception*	

Session 3 (Tuesday morning, Space Science Auditorium)

Co-chairs: Warren Gore & Kevin Zahnle

Session 4 (Tuesday afternoon, Space Science Auditorium)

Co-chairs: Nancy Daunton & Charles Fuller

Co-chairs: Alan Hargens & Sam Pool

Session 5 (Wednesday morning, Space Science Auditorium)

Co-chairs: Jeffrey Bada, Robert Pepin, Frank Shu, & Don DeVincenzi

Session 6 (Wednesday afternoon, Space Science Auditorium)