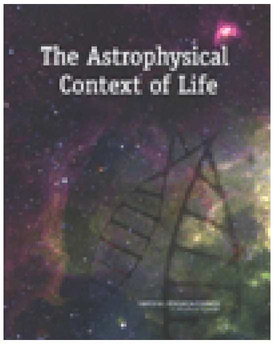
The Astrophysical Context of Life



Committee on the Origins and Evolution of Life, National Research Council

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THE NATIONAL ACADEMIES
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The Astrophysical Context of Life

Committee on the Origins and Evolution of Life

Space Studies Board
Division on Engineering and Physical Sciences

Board on Life Sciences
Division on Earth and Life Studies

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BOARD ON LIFE SCIENCES

To astronomers, biologists, chemists, and geologists
who have caught the astrobiology bug

Preface

This study addresses issues raised in the recent assessment of astrobiology programs at the National Aeronautics and Space Administration (NASA)—*Life in the Universe: An Assessment of U.S. and International Programs in Astrobiology*.[1] The authors of that report found that research in certain key areas of astrophysics relevant to understanding the astronomical environment in which life arose on Earth (and, potentially, elsewhere in the universe) was not well represented within the broad range of issues being addressed by NASA's astrobiology program. This report is intended to highlight the contributions astronomers can make to the field of astrobiology.

Life on Earth originated more than 3.5 billion years ago and has since then evolved in a complex and highly variable astronomical environment. Earth was assembled from interstellar gas already enriched in prebiotic molecules that were themselves the product of generations of stellar nucleosynthesis and chemical evolution in interstellar matter. Asteroid and comet impacts, some perhaps triggered by the random passage of another star, have evidently altered the course of evolution. Long-lived radioactive elements from stellar explosions have contributed heat to Earth's molten core, helping to drive plate tectonics.

Life on or near the surface of Earth is strongly affected by the evolving output of radiation from the Sun, interrupted by solar flares. The flux of cosmic rays that can induce mutations and perhaps affect climate has probably varied significantly over geological time. Earth is estimated to have been exposed to perhaps thousands of jolts of potentially biologically significant radiation from supernovas, and more exotic events such as gamma-ray bursts have been considered.

Other solar system bodies and extrasolar planets that might harbor life have similar histories, but the effects of these events will be varied in import and detail. Thus, there are compelling reasons to argue that a full and complete picture of the origin and evolution of life must take into account its astrophysical context.

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[1] National Research Council. 2003. *Life in the Universe: An Assessment of U.S. and International Programs in Astrobiology*. Space Studies Board and Board on Life Sciences. The National Academies Press, Washington, D.C.

One of the goals of the burgeoning intellectual field of astrobiology is to integrate the core sciences of biology, biochemistry, chemistry, physics, and geology into the broadest appropriate context of astronomy. Conversely, relevant aspects of astronomy should inform the biology, chemistry, and geology in order to facilitate intellectual exchange between those fields and to maximize the synergism within this innately multidisciplinary field.

An example of the mutual interchange among these fields arises when we attempt to define "habitable zones." Classic habitable zones are planetary environments where radiation from a host star results in surface temperatures commensurate with the existence of liquid water. Even hyperthermophilic microorganisms require a temperature and pressure realm where liquid water persists. On a broader scale, there have been attempts to define the locations and temporal stability of habitable zones within galaxies. The issues here include the abundance of heavy elements required to support the growth of terrestrial planets and the degree to which the galactic setting remains sufficiently stable to permit the emergence and continuance of life.

In response to these opportunities, the Space Studies Board (SSB) charged the Committee on the Origins and Evolution of Life, one of its standing committees, with investigating ways to expand and integrate astronomy and astrophysics into astrobiology—in particular, into NASA's astrobiology program and into relevant programs in other federal agencies.

The goals of this study are as follows:

- Identify areas where there can be especially fruitful collaboration between astrophysicists, biologists, biochemists, chemists, and planetary geologists.
- Define areas where astrophysics, biology, chemistry, and geology are ripe for mutually beneficial interchanges and define areas that are likely to remain independent for the near future.
- Suggest areas where current activities of the National Science Foundation (NSF) and other federal agencies might augment NASA programs.

Although some preliminary work on this study was undertaken during the committee meeting in October 2002, the study was not formally initiated until the committee met at the National Academies' Keck Center in Washington, D.C., in March 2003. Work continued at meetings held at the Desert Research Institute in Reno, Nevada, and at the National Academies' Beckman Center in Irvine, California, in July and October 2003, respectively. An initial draft of the report was assembled in December 2003 and extensively revised during a meeting of the committee held at the University of Arizona, in Tucson, in January 2004. A new draft was created in February 2004 and circulated to the committee. It was revised in March and sent out for external review in April.

The committee's work in drafting this report was made easier thanks to the input provided by many individuals, including the following: Ariel Anbar (University of Rochester), David Archer (University of Chicago), Charles Beichman (Jet Propulsion Laboratory), Alan Boss (Carnegie Institution of Washington), William Boynton (University of Arizona), Roger Buick (University of Washington), Philippe Crane (NASA Headquarters), Pascale Ehrenfreund (Leiden Observatory), Guillermo Gonzalez (Iowa State University), Andrew Gould (Ohio State University), Rosalind Grymes (NASA Astrobiology Institute), Frank Kyte (University of California, Los Angeles), Jonathan Lunine (University of Arizona), Michael Meyer (NASA Headquarters), Michael New (NASA Headquarters), Carl Pilcher (NASA Headquarters), Stefan Rahmstorf (Potsdam Institute for Climate Impact Research), Lynn Rothschild (NASA Ames Research Center), Bruce Runnegar (University of California, Los Angeles), Nir Shaviv (Hebrew University), and Bruce Wielicki (NASA-Langley Research Center).

Acknowledgment of Reviewers

This report has been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the NRC in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The contents of the review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

David W. Deamer, University of California, Santa Cruz,
James P. Ferris, Rensselaer Polytechnic Institute,
Donald Ingber, Children's Hospital/Harvard Medical School,
Victoria S. Meadows, Jet Propulsion Laboratory,
Simon Conway Morris, University of Cambridge, England,
Sara P. Seager, Carnegie Institution of Washington,
Norman H. Sleep, Stanford University,
Virginia Trimble, University of California, Irvine, and
Nicolle E.B. Zellner, Lawrence Livermore National Laboratory.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Leslie Orgel, Salk Institute for Biological Studies. Appointed by the NRC, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring task group and the institution.

Contents

APPENDIXES

Executive Summary

BACKGROUND

The National Aeronautics and Space Administration (NASA) Astrobiology Roadmap summarizes astrobiology in the following way:[1] "Astrobiology is the study of the origins, evolution, distribution, and future of life in the universe." Astrobiology thus addresses three fundamental questions:

- How does life begin and evolve?
- Does life exist elsewhere in the universe?
- What is the future of life on Earth and beyond?

The Committee on the Origins and Evolution of Life was charged with investigating ways to augment and integrate the contributions of astronomy and astrophysics in astrobiology—in particular, in NASA's astrobiology program and in relevant programs in other federal agencies.

The goals set for this study were as follows:

- Identify areas where there can be especially fruitful collaborations between astrophysicists, biologists, biochemists, chemists, and planetary geologists.
- Define areas where astrophysics, biology, chemistry, and geology are ripe for mutually beneficial interchanges and define areas that are likely to remain independent for the near future.
- Suggest areas where current activities of the National Science Foundation (NSF) and other agencies might augment NASA programs.

In considering how to achieve these general goals, the committee focused on the key words in the statement of task (Appendix A): "to study the means to augment and integrate the activity of astronomy

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[1] Available online at <http://astrobiology.arc.nasa.gov/roadmap/>.

and astrophysics in the intellectual enterprise of astrobiology," in particular on the words "augment" and "integrate." It understood "augment" as an instruction to find issues in astronomical/astrobiological research where fruitful work could be done that is not now being done. The integration of interdisciplinary research topics is relevant to all the areas of astrobiology research, not just with respect to astronomy. The topic stimulated broad interest on the part of all the committee members and led to some generic—but, the committee believes, important—recommendations designed to facilitate interdisciplinary research.

The discussions about the charge led to the committee's specific approach to the study and to the structure of the report. Seven tasks were identified:

1. Outline current astronomical research relevant to astrobiology.
2. Define important areas that are relatively understudied and hence in need of more attention and support.
3. Address the means to integrate astrophysical research into the astrobiology enterprise.
4. Identify areas where there can be especially fruitful collaboration among astrophysicists, biologists, chemists, biochemists, planetary geologists, and planetary scientists that will serve the goals of astrobiological research.
5. Identify areas of astronomy that are likely to remain remote from the astrobiological enterprise.
6. Suggest areas where ongoing research sponsored by NSF, the Department of Energy (DOE), and the National Institutes of Health (NIH) can augment NASA support of astrobiological research and education in a manner that complements the astronomical interconnection with other disciplines.
7. Where applicable, point out the relevance to NASA missions.

PRINCIPAL CONCLUSIONS

Astrophysical research is a vital part of astrobiology today, especially with the addition of the NASA Astrobiology Institute (NAI) nodes that are primarily focused on astrophysics. This report identifies still more areas where astrophysical research can contribute to astrobiology, including the galactic environment, cosmic irradiation in its myriad forms, bolide impacts, interstellar and circumstellar chemistry, prebiotic chemistry, and photosynthesis and molecular evolution in an astronomical context.

Astronomy brings two important perspectives to the study of astrobiology. One is to encourage thinking in a nonterracentric way. The opportunities are vast for different conditions to produce different outcomes for life, even within the standard paradigm of carbon-based life with a nucleotide-based coding system. The ambient conditions could be different—hotter, colder, more radiation or less—and the coding system could be different. It will be a challenge to discern the most important convergent processes when the details of overwhelmingly complex life are different. The other perspective that astronomy brings to astrobiology is that the astronomical environment—from the host star, to the ambient interstellar gas through which a planetary system passes in its galactic journey, to cosmic explosions—is intrinsically variable. The dominant driver of this variability is probably the host star, which is likely to be susceptible to violent chromospheric activity and nearly continuous flares when it is young or if its mass is less than that of the Sun, the most likely situation. Life in an intrinsically variable environment raises deep and interesting issues of fluctuating mutation rates, genetic variation processes, and the evolution of complexity—and even of evolvability itself. Some of these issues overlap with topics being pursued in biomedical research.

This study attempts to identify areas where astrophysical research can fruitfully interact with research in the other disciplines of astrobiology: biology, geology, and chemistry. It also identifies some broad issues involved in integrating astronomy within astrobiology. First, there is a need to recognize when astronomical research is relevant to astrobiology and when it is not. The consensus is that to be relevant to astrobiology, astronomical research should be "life-oriented." This is a broad and dynamic filter through which not all astronomical research will pass. Second, there is the need to integrate astrophysical research in the astrobiology effort. Here the report urges the NAI teams to develop metrics for determining when truly integrated interdisciplinary work involving astrophysics is being done and to actively promote that integration.

The third broad issue is that of integrating work in an intrinsically interdisciplinary field. While integrating astrophysics research is the focus, the problem transcends astronomy alone. To this end, the report recommends a series of educational and training initiatives conceived with the astronomy component of astrobiology in mind, but that could be applied to the whole enterprise. Among these initiatives are NAI's institutionalization of education and training, the establishment of an astrobiology graduate student fellowship program and of exchange programs for graduate students and sabbatical visitors, and sponsorship of a distinguished speaker series in astrobiology.

The astrophysics component of astrobiology has a rich and vibrant future in one of the great intellectual enterprises of humankind, understanding the origin and evolution of life.

FINDINGS AND RECOMMENDATIONS

The following is a summary of the committee's detailed findings and recommendations.

NASA Efforts in Astrophysics for Astrobiology

Funding for astrobiology is limited, and the boundaries of the field are unclear; there is a risk that some funds might go to research topics that cannot be justifiably classified as "astrobiology." The committee recommends that in funding decisions, NASA and other funding agencies should regard astronomical research as astrobiology if it is life-focused in plausible ways.

Review of current astronomically oriented research shows that it is concentrated in relatively few areas, especially in the Exobiology program. The committee recommends that NASA continue to ensure that an appropriate diversity of topics is included within the astrophysics component of astrobiology and that its support be coordinated with funding through other relevant programs. NASA also should develop metrics to evaluate the degree to which truly interdisciplinary work involving astronomy and astrophysics is being done in the current NAI nodes.

Areas That Could Benefit from Augmentation and Integration

Some broad areas are relatively understudied and would be especially amenable to focused effort in the near future: the galactic environment, the radiation/particle environment, bolide bombardment, interstellar molecules and their role in prebiotic chemistry, photochemistry and its relation to photosynthesis, and molecular evolution in an astronomical context. Specific areas needing attention by the research community and by funding agencies include the following:

- Galactic habitability, including correlating stellar heavy-element abundance with the existence of planets; characterizing the interaction among stellar winds, the interstellar medium ram pressure, and the resulting cosmic ray flux; and determining which regions of the Galaxy could give rise to and sustain life.

- Characterization of the ultraviolet (UV), ionizing radiation, and particle flux incident on evolving, potentially life-hosting planets and moons.
- The variability of damaging UV and ionizing radiation over the course of life on Earth and how such conditions might be manifested on other life-hosting bodies.
- Planetary geology models to better understand the presence and nature of volcanism and tectonics on other planets as a function of the age of formation of the planet, the initial concentration of long-lived radioactive species, the accretion history, and the mass of the planet.
- Geological field work and models to characterize the rates of damage and mutation due to background radioactivities on evolving Earth and other potentially life-hosting bodies and to compare them with the rates due to other endogenous and exogenous radioactivities.
- Searches for cosmogenic material and other live radioactive elements in ice cores and ocean sediments.
- Research in the chemistry of the circumstellar accretion disks that evolve from molecular clouds, considering both gas- and solid-state phases and the delivery of chemical compounds to planet surfaces for an appropriate range of planets and planetary environments.
- Research to complete the interstellar and circumstellar molecular inventory and to test reaction pathways.
- Geological and geochemical work to identify ejecta material in the rock record surrounding large impact basins—in particular, to study existing evidence and search for additional signs of impact at the Permian/Triassic boundary and to document various anomalies in noble gas isotopic signatures and rare earth and other metal abundances that can be clearly linked to extraterrestrial impactors.
- Return to the Moon to acquire more lunar samples to help determine when the “impact frustration” of life’s origin ended by sampling more sites—particularly sites that are older than the six sites sampled by the Apollo astronauts and the three sites sampled by the Soviet robotic sample-return missions and, especially, the oldest and largest impact basin on the Moon, the South Pole-Aitken Basin.
- Research on how carbon, nitrogen, and sulfur cycles might work on a prebiotic planet with an ocean and an incident flux of photons and particles, and how these cycles might couple with primitive life forms to provide feedstocks for their formation and energy for their metabolism.
- Coordinated theoretical, laboratory, and observational studies of interstellar chemistry, accretion, condensation, and transport processes to determine the inventory of compounds that was delivered to a young planet, when they were available, where they were available, and in what quantities.
- Studies of abiotic photochemistry in concert with astronomical sources of trace elements and energy to determine whether trace elements play a role in photochemical sources of organic compounds and/or high-energy activated compounds.
- Studies of the extent to which the astrophysical environment could have fostered symmetry breaking in prebiotic organic pools.
- Studies to understand the evolution of earthlike organisms and organisms with other coding mechanisms that are subjected to the fluctuating thermal and radiation environments expected for planetary systems with various impact histories and planets orbiting stars of various masses and ages in different parts of the Galaxy.
- In vitro and in silico studies to learn how the stochastic variability of the environment, including the mutational environment, affects the evolution of life, especially by promoting complexity and the evolution of evolvability.

Integrating Astronomy with the Other Disciplines of Astrobiology

The committee identified three factors that currently limit the integration of astronomy and astrophysics with astrobiology and, indeed, limit robust interdisciplinary research of any kind: (1) a lack of common goals and interests, (2) lack of a common language, and (3) insufficient background in allied fields to allow experts to do useful interdisciplinary work.

The committee recommends to NASA, other funding agencies, and the research community the following approaches to overcoming communication barriers:

- Continue and expand cross-disciplinary discussions on the origin and evolution of life on Earth and elsewhere, as are already being promoted by the NAI.
- Continue intellectual exchange through interdisciplinary meetings, focus groups, a speaker program, and workshops, all targeted at augmenting and integrating astronomy and astrophysics with other astrobiology subdisciplines.
- Promote a professional society (and cross-disciplinary branches within existing societies) that will cover the full range of disciplines that make up astrobiology, from astronomy to geosciences to biology. The International Society for the Study of the Origins of Life, which holds triennial meetings, may provide an appropriate basis for this. The BioAstronomy conferences sponsored by the International Astronomical Union,[2] the astrobiology conferences held at NASA Ames Research Center, and the Gordon Research Conferences on the Origin of Life are useful but do not fulfill the needed roles of a professional society.
- Undertake missions to asteroids, comets, moons such as Titan, and, possibly, Saturn's rings to sample and analyze the surface organic chemistry.
- Broaden the definition of outreach activities within the NAI beyond general public awareness and K-12 education to achieve the greater degree of cross-fertilization that is needed among NAI senior researchers, postdoctoral fellows, and students.
- Reach out to university faculty in general, not just to NAI members and affiliates. This is essential for astrobiology to be embraced as a discipline and for extending and perpetuating support beyond NAI/NASA, which is otherwise unlikely to happen.

Education at all levels is a central issue. The committee recommends multiple approaches that invest both in training the next generation and in giving the larger scientific community opportunities for interdisciplinary training and collaboration.

- NASA should encourage NAI nodes to institutionalize education in astrobiology. In particular, the committee recommends that the next competition for NAI nodes encourage the creation of academic programs for interdisciplinary undergraduate and graduate training in astrobiology.
- In order to provide opportunities for graduate training within and outside the NAI nodes, NASA should establish an astrobiology graduate student fellowship program similar to existing programs in space and Earth science. These fellowships should be open to students enrolled in any accredited graduate program within the United States.
- NASA should encourage the NAI to foster cross- and interdisciplinary training opportunities for graduate students and faculty, as already exist for postdoctoral fellows. In particular, the committee

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[2] See <http://www.ifa.hawaii.edu/~meech/iau/>.

recommends that exchange programs be created to allow students to matriculate in programs outside their home field and that resources be made available for a sabbatical program for the interdisciplinary training of established scientists.

- NASA should encourage the NAI nodes and the NASA Specialized Center of Research and Training (NSCORT) nodes to engage in a self-study as part of their reporting processes to assess the progress of graduate and postdoctoral programs in training truly interdisciplinary scientists who actively engage in interdisciplinary research.
- The NAI should sponsor a distinguished speaker series in astrobiology. It would identify accomplished speakers and provide travel support for them to present their interdisciplinary research at universities and colleges. Speakers should be selected on the basis of both disciplinary and demographic diversity. The institutions hosting the speakers would be required to involve multiple academic departments or programs.

1

Introduction

THE ASTRONOMICAL PERSPECTIVE

The National Aeronautics and Space Administration (NASA) Astrobiology Roadmap summarizes astrobiology in the following way:[1]

> Astrobiology is the study of the origins, evolution, distribution, and future of life in the universe. It requires fundamental concepts of life and habitable environments that will help us to recognize biospheres that might be quite different from our own. 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 needed 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 for the most comprehensive and inclusive understanding of biological, planetary and cosmic phenomena. . .

Astrobiology thus addresses three fundamental questions:

- How does life begin and evolve?
- Does life exist elsewhere in the universe?
- What is the future of life on Earth and beyond?

Astrophysics provides the fundamental underpinnings for life: space and time. Astronomy has taught us that our universe is mostly space—lots of it. This space is filled with a vast number of galaxies, each with billions of stars and, accordingly, possible sites for the origin and evolution of life. Merely making a census of the possible sites for life in the vast space of our galaxy is a challenging task, rife with important unanswered questions: What sorts of environments are needed to seed life? What sorts

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[1] Available at <http://astrobiology.arc.nasa.gov/roadmap/>. Last accessed April 27, 2005.

are needed to promote its success and its increasing complexity? Astronomy has also shown that our universe has time—lots of it here, too. Life has had a very large, but not infinite, time in which to become established, to grow, and to develop. The time kept by the clocks of orbiting planets marches smoothly onward, but the time marked by living organisms is roiled by turmoil and occasionally punctuated by catastrophic astronomical events. How does the enormous span of time, punctuated by drastic events, affect the origin and evolution of life?

Scientists also know from astrophysical study that the galactic environment has provided crucial ingredients for life. The big bang provided hydrogen for the eventual formation of water, in addition to helium and a smattering of light elements, such as lithium, that are of little consequence for life. All the elements needed for life as we know it—oxygen to complete the water molecule, indispensable carbon, phosphorus for nucleic acids and key metabolites, metal ions and transition elements to serve as catalysts in the chemistry of life and more—came from generations of stars that formed from the dilute interstellar gas. These stars evolved and forged heavier elements from the primordial hydrogen and helium and then expelled these critical elements back into space, sometimes with a gentle push and other times with a catastrophic explosion, to form the next generation of stars and planets, which were becoming ever more hospitable to the origin and evolution of life. In addition to playing a crucial role in the chemistry of life, the elements forged in stars provided natural radioactivity, which is, in part, responsible for the tectonic activity that shapes the Earth and which is one unavoidable source of mutation, the driving force of genetic evolution.

The galaxy that hosts all these processes has its own structure and composition, which will affect the conditions for the development and flourishing of life on a planet. It has denser regions near the center that tend to have more supernova explosions and greater concentrations of life-giving heavy elements. In the vicinity of the Sun, the Galaxy winds spiral arms that are the site of ongoing star formation. Far from the galactic center the abundance of heavy elements may be too dilute to support the growth of planets. The explosions of stars and other processes push around the interstellar gas, creating pockets of dense gas where new stars can form, along with large volumes of more dilute gas. The shock waves from supernova explosions create the bath of cosmic ray particles that suffuses the Galaxy.

Life may have formed in a warm tidal pool or in the seas of Hadean Earth, when massive bolide impacts were the rule. Astronomy has taught us, however, that complex molecules had already formed in the interstellar medium. Scientists know that complex chemistry transpires in interstellar space: some through gas-phase chemistry, some through catalysis on the surface of grains of various composition, some in quiescent environments, and some in environments ablaze with the intense ultraviolet light of clusters of massive stars. The limits of that complex interstellar chemistry are not yet known. Nor do we know the relevance of these interstellar processes to the chemical environment on the surface of a planet or to the origin of life.

Astronomy has yielded a rapidly expanding knowledge of bodies that are possible hosts for life—not only the planets and moons of our solar system but also, possibly, further afield, as extrasolar planets are discovered orbiting other stars. How do all these planets come to be as they are? What is their geology, what are their tectonic regimes? The full range of environments that might harbor at least microbial life is yet to be explored.

The astronomical context of life includes a bath of photons of electromagnetic radiation and energetic particles that affect life. Optical photons are an important source of energy. The radiation from Earth's central star provides the bulk of the free energy necessary for the maintenance of its biosphere, through the intricate mechanisms of photosynthesis. Ultraviolet (UV) and visible light are likely to have played a role on prebiotic Earth through photochemical reactions. The total luminosity from host stars defines the classic habitable zone, the region around a star where a planet will be at the right surface temperature to support liquid water. The light from host stars may be predominantly steady, but it is not always so, and variability in the form of flares is the norm for lower mass stars, which are in a constant state of flaring. The Sun was highly variable in the past and is sporadically so even now. This variability may play a role in how we think about the habitable zone, especially in the case of lower mass stars, where the energy of frequent flares may exceed the luminosity of the stellar photosphere. UV radiation affects biomolecular structure by, for instance, forming dimers that interfere with the ability of DNA to replicate. Ionizing radiation—x rays and gamma rays—produces free radicals that interfere with the biochemical processes in cells. The energetic particles generated by the Sun and those arriving as cosmic rays induce additional ionizations that interfere in these ways in exposed cells.

The particle and electromagnetic radiation environments may also set bounds on where in the Galaxy life is feasible. As outlined above, the Galaxy is not an intrinsically quiescent environment; rather, it presents a fundamentally disturbed ecology for the stars and planets it hosts. Novas and supernovas, winds and radiation from massive stars, and even occasional catastrophic gamma-ray bursts are all part of the natural astronomical environment in the Galaxy. Along with explosive events come cosmic rays that alter atmospheric chemistry, may affect cloud cover, and provide an additional source of mutation. The flux of cosmic rays inevitably fluctuates significantly since the sources are stochastic, and screening by the heliopause will be modulated as the Sun moves through a range of interstellar gas and attendant ram pressures. The same will be true of any star hosting planets and moons that might cradle life.

Scientists look to astronomy to find other hosts for life. The search for extrasolar planets has been a resounding success, but the search for terrestrial planets is in its earliest planning phases. Developing missions like NASA's Terrestrial Planet Finder and the European Space Agency's Darwin will open new vistas in this quest. There is a great surge of interest in defining and understanding biomarkers that might reveal nascent life on another planet.

One of the principal benefits of bringing an astronomical perspective to the study of astrobiology is the effect on the conceptual framework in which astrobiological research is pursued. Of course we know Earth best, and it is the only site for life that we know. An astronomical perspective encourages us to keep the bigger picture in mind. Common questions for all astrobiologists should be these: How would this apply on another planet? How would this be different? How would it be the same? The differences might be vast, or they might be tiny, but they will surely exist, and by keeping that in mind we will more aggressively push the frontiers of our knowledge and thinking.

Another conceptual area is characterized by the question, What level of disturbance is good for the formation and evolution of life? Too much disturbance is surely inimical to the creation of life, its survival, and its evolution. Equally true, it seems, is that life would evolve more slowly to greater complexity in a relatively quiescent environment driven only by unrepaired replication errors. On the macroscopic scale, there is evidence that life would evolve more rapidly to greater complexity in a varied environment. So, a key conceptual issue, driven at least in part by the recognition that the Galaxy does present an unavoidably disturbed ecology, is the level of disturbance that is good for evolution.

In this study, the committee attempts to address some of these issues for the benefit of the astrobiological community and for the funding agencies—NASA, the National Science Foundation (NSF), the Department of Energy (DOE), and the National Institutes of Health (NIH)—that are relevant to this enterprise. The purpose is to foster the interaction of other disciplines with astronomy and vice versa, and to aid planning, research, and funding. The committee attempts to identify what gaps there might yet be in the study of the astrophysical context of life after the funding of the latest round of NASA Astrobiology Institute (NAI) teams. It comments on relevant space missions where appropriate and attempts to identify topics, especially in areas that are not now receiving much attention and that are therefore ripe for interdisciplinary work, with astronomy as a key component.

GOALS OF THE CURRENT STUDY

Life on Earth exists in an astronomical environment. Because astrophysical research and perspectives play an important role in astrobiological research, the Committee on the Origins and Evolution of Life was charged with investigating how to augment and integrate the activity of astronomy and astrophysics in the intellectual enterprise of astrobiology, in NASA's astrobiology program, and in relevant programs in other federal agencies.

The specific tasks of this study were as follows:

1. Outline current astronomical research relevant to astrobiology.
2. Define important areas that are relatively understudied and hence in need of more attention and support.
3. Address the means to integrate astrophysical research into the astrobiology enterprise.
4. Identify areas where there can be especially fruitful collaboration among astrophysicists, biologists, chemists, biochemists, planetary geologists, and planetary scientists that will serve the goals of astrobiological research.
5. Identify areas of astronomy that are likely to remain remote from the astrobiological enterprise.
6. Suggest areas where ongoing research sponsored by NSF, DOE, and NIH can augment NASA support of astrobiological research and education in a manner that specifically complements the astronomical interconnection with other disciplines.
7. Where applicable, point out relevance to NASA missions.

To further these goals, the committee summarizes current astrophysical research within the overall astrobiological enterprise (Chapters 2 and 3) and identifies areas that it thinks are understudied and deserving of greater effort (Chapter 4).

2

Related Efforts

NATIONAL RESEARCH COUNCIL'S *LIFE IN THE UNIVERSE* REPORT

In response to the NASA Authorization Act of 2000 and a subsequent request from Edward J. Weiler, NASA's associate administrator for the Office of Space Science, the Committee on the Origins and Evolution of Life was given the task of assessing the state of the NASA astrobiology program. The resulting report, *Life in the Universe,*[1] found that while efforts in astrobiology were dominated at that time by the biological and geological sciences, "the long-term success of astrobiology in addressing its objectives [would] depend on a deeper and more extensive exchange of ideas with the traditional space sciences." The report recommended that NASA foster more links between its astrobiology program and its Origins program. The current study is being undertaken in part to follow up on this perspective and this particular recommendation of *Life in the Universe*. More details of the report *Life in the Universe* are given in Appendix A.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Origins Roadmap

As part of the NASA strategic planning process, the Origins theme in the Office of Space Science's Astronomy and Physics Division recently revised its roadmap.[2] Topics that overlap with the enterprise of astrobiology are woven throughout the document. Among the high-level questions to be addressed are these: Where did we come from? Are we alone? More specifically, the Origins program looks at issues such as the formation of stars, galaxies, and the heavy elements that are arguably relevant to the

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[1] National Research Council. 2003. *Life in the Universe: An Assessment of U.S. and International Programs in Astrobiology*. Space Studies Board and Board on Life Sciences. The National Academies Press, Washington, D.C.

[2] Available at <http://origins.jpl.nasa.gov/library/roadmap03/>. Last accessed April 27, 2005.

broader astrobiological context, along with issues such as the origin and evolution of planets, the search for life beyond our solar system, and the physical and chemical conditions necessary for life to originate. These issues are indistinguishable from some of the central issues of astrobiology. More details of the Origins Roadmap and the NASA Astrobiology Roadmap[3] are given in Appendix A. The committee returns to the overlap between NASA's Origins theme and the general astrobiology mission in Chapter 3.

Cosmochemistry

NASA's Cosmochemistry program[4] supports investigations of extraterrestrial materials such as meteorites, cosmic dust, and lunar samples. These investigations study the geochemistry of our solar system bodies—planets; satellites, including the Moon; and small solar system bodies—with the goal of understanding the origin of our solar system and the processes by which its planets and small bodies have evolved to their present states. The Cosmochemistry program supports sample-focused research projects that promote exploration of our solar system or that develop techniques for such further exploration. The projects include measurements of mineral compositions, major and trace element chemistry, isotopic compositions, radiometric ages, magnetism, and radiation exposure effects; petrologic studies of extraterrestrial materials and laboratory studies of phase stability, chemical partitioning, and other processes necessary to interpret planetary data; and the synthesis of previously obtained geochemical data. The program sometimes supports research on terrestrial analog samples that addresses key geochemical processes in early planetary evolution, terrestrial history in terms of general solar system processes, and reasons for the different ways the various planetary bodies—including Earth, the Moon, and parent bodies of meteorites—evolved.

Space Radiation and Human Health

The Biomedical Research and Countermeasures (BR&C) program[5] is a research program to identify and characterize health, environmental, and other operational human biomedical risks associated with living in space and the strategies, tools, or technologies to eliminate or mitigate those risks. The National Space Biomedical Research Institute consortium was instituted in 1997 to pursue the knowledge and technologies required for long-duration spaceflight, including specific countermeasures. Studies exploring the effects of the space-radiation environment on human health, especially its propensity to cause cancer and to damage the central nervous system, are being carried out by investigators affiliated with the National Space Biomedical Research Institute. In particular, studies on the effects of protons and heavy ions are under way at Loma Linda University and Brookhaven National Laboratory, respectively. Although the purpose of this program is biomedical, the fundamental basis for it is the ubiquity of astronomical irradiation.

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[3] Available at <http://astrobiology.arc.nasa.gov/roadmap>.

[4] Available at <http://research.hq.nasa.gov/code_s/nra/current/NNh04ZSS001n/appendB_2.html>. Last accessed April 27, 2005.

[5] Available at <http://spaceresearch.nasa.gov/research_projects/biomedical.html>. Last accessed April 27, 2005.

OTHER AGENCIES

National Science Foundation

Life in Extreme Environments

The Life in Extreme Environments (LExEn) program was a successful interdisciplinary program run from 1997 to 1999 by the Directorates for Biological Sciences, Engineering, Geosciences, and Mathematical and Physical Sciences and the Office of Polar Programs of the National Science Foundation (NSF). This program placed heavy demands on both the financial resources and, especially, the personnel of the NSF, since neither new funds nor new personnel to manage the complex cross-disciplinary effort were made available. The success of the program was a credit to the dedicated NSF staff who worked so hard on it. (See Appendix B for additional information.)

RIDGE 2000

The Ridge Interdisciplinary Global Experiments (RIDGE) program[6] is designed to support research aimed at understanding the geological, chemical, biological, and physical oceanographic interactions between the oceans and hydrothermal circulation of seawater through the ocean crust. The RIDGE program supports a substantial amount of work that is related to the astrobiological topics of the origin of life and extremophiles.

Polar Programs

The NSF Office of Polar Programs—in particular, the U.S. Antarctic Program (USAP[7])—support research that can be done exclusively in Antarctica or that can be done best from Antarctica. The NSF is currently participating in NASA's review of the Astrobiology Science and Technology for Exploring Planets (ASTEP) proposals, which support research aimed at detailed, collaborative analysis of Earth's extreme environments in order to better understand analogous systems elsewhere. The Antarctic is one of those environments. Successful ASTEP Antarctic proposals will require the logistical support of the Office of Polar Programs.

Assembling the Tree of Life

The overall goal of NSF's Assembling the Tree of Life activity[8] is the construction of a framework phylogeny for all 1.7 million described species on Earth. Phylogeny, the genealogical map for all lineages of life on Earth, provides an overall framework for facilitating information retrieval and biological prediction. The aim of the Tree of Life activity is to resolve phylogenetic relationships for large groups of organisms on the Tree of Life and to improve understanding of the evolutionary processes that have operated to shape the history of life on Earth. The Tree of Life activity will be carried out by large teams working across institutions and disciplines.

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[6] Available at <http://www.ridge2000.bio.psu.edu/>. Last accessed April 27, 2005.
[7] Available at <http://www.nsf.gov/div/index.jps?div=ANT>. Last accessed April 27, 2005.
[8] Available at <http://www.nsf.gov/pubs/2005/nsf05523/nsf05523.htm>. Last accessed April 27, 2005.

Department of Energy

The Genomics:GTL program (formerly the Genomes to Life[9] program) of the U.S. Department of Energy is intended to use the new genomic data and high-throughput technologies for studying the proteins encoded by the genome to explore the amazingly diverse natural capabilities of microbes. Progress in these areas is also likely to be important for the astrobiological goals of understanding the origin and evolution of life. (Additional details can be found in Appendix B.)

Astrobiology in Europe

The European Astrobiology Network Association (EANA)[10] was created in 2001 to coordinate the different national research centers and to promote research in astrobiology in Europe. EANA is affiliated with the NASA Astrobiology Institute. Collaborative research areas in Europe's astrobiology network include cosmochemistry, star and planetary formation, the chemistry of the origin of life, terrestrial life as a reference, and the search for habitats and signatures of life beyond Earth. (Additional information about astrobiology research in Europe can be found in Appendix B.)

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[9] Available at <http://doegenomestolife.org>. Last accessed April 27, 2005.

[10] Available at <http://www.graz-astrobiology.oeaw.ac.at/eana.html>. Last accessed April 27, 2005.

3

NASA Efforts in Astrophysics for Astrobiology

WHAT IS ASTRONOMY? WHAT IS ASTROBIOLOGY?

One issue that has been faced historically by NASA's Exobiology program, and is now being faced by various astrobiology programs, is where to draw the line between astrobiology and other areas of astronomy and astrophysics. This question has no obvious, unambiguous answer. The presence of life in the universe depends on many different factors, especially the existence of the biogenic elements (including, but not limited to, carbon, hydrogen, oxygen, nitrogen, sulfur, phosphorus, and iron) and of planets where these elements can combine in a warm, sufficiently stable environment to form life. The existence of warm planets requires the coexistence of stars and star-forming nebulas. The existence of these objects requires the existence of galaxies, until ultimately the existence of everything depends on the occurrence of the big bang, some 14 billion years ago. Thus, if one wishes to take a broad view of astrobiology, such fields as star formation and cosmology should be included.

There is an obvious danger in trying to be this inclusive. NASA's astrobiology program is supported by substantial, but finite, amounts of funding. If one defines astrobiology too broadly, then this funding will be spread over such a wide range of disciplines that its impact on the core issues surrounding the topic of life in the universe will be hopelessly diluted. In exobiology, this issue came to a head more than a decade ago, when the program started receiving large numbers of proposals from observational astrochemists who were studying the distribution of carbon in the universe. Carbon is a key element for biochemistry, it was argued, so it is important to understand where and in what chemical forms it is found. Indeed, the discovery of organic molecules in interstellar clouds by radio astronomers in the 1960s was of indisputable significance for astrobiology. It is certainly conceivable that some or all of the key compounds required for the origin of life were formed in low-temperature gas-phase reactions or by ultraviolet-driven chemistry occurring in the icy mantles of interstellar dust grains. It is also true that much of the carbon in interstellar space consists of poorly characterized, polycyclic aromatic hydrocarbons that are important absorbers of stellar radiation at certain wavelengths but that probably have little or nothing to do with the origin of life.

How does one define the boundary between astrobiology and astrochemistry in these examples? In the Exobiology program, it was decided that the proposals needed to make a clear connection between the carbon in interstellar space and its delivery to Earth in the form of cometary or meteoritic material. More generally, the parts of astronomy that are most relevant to astrobiology are those that might directly influence either the origin or later evolution of life. They include many different subjects and should be viewed not as being narrow but rather as being life-focused. By applying this principle in a reasonable manner, it should be possible to define the parts of astronomy that ought to be included in astrobiological research at the critical step when funding decisions are made. Intellectually, the sweep should be broader in order to encompass areas that, with work and insight, can be brought directly into the astrobiological enterprise.

Finding. Funding for astrobiology is limited, and the boundaries of the field are unclear; there is a risk that not all funds will go toward research topics that are justifiably "astrobiology."

Recommendation. In funding decisions, NASA and other funding agencies should regard astronomical research as astrobiology if it is life-focused in plausible ways.

With these points of view in mind, the committee summarizes currently funded astronomical research at the NASA Astrobiology Institute (NAI) and in other NASA-funded astrobiology programs.

ASTROPHYSICAL RESEARCH AT NASA

NASA Astrobiology Institute

There is significant astronomical content in the research proposed or being done by the present NAI nodes; however, there is some potential redundancy since many subjects are treated or studied at multiple centers. The committee identified seven specific subject areas that are the focus of more than one NAI node:

- *Planet formation.* Planetary formation is being investigated at seven NAI nodes: NASA Goddard Space Flight Center (GSFC), Penn State Astrobiology Research Center (PSARC), Carnegie Institution of Washington (CIW), the University of Colorado at Boulder (CU-Boulder), the University of Washington (UW), the University of Arizona (UA), and NASA Ames Research Center (ARC). PSARC is investigating how stellar metallicity (elements with atomic weight greater than that of helium) affects planet formation and the possibility of planets around white dwarfs. CIW is modeling planetary formation and works on the detection of extrasolar planets. CU-Boulder is proposing to study the evolution of protoplanetary disks into planets. UA will study planetary formation through observations of circumstellar disks, while ARC is studying planetary formation in the context of planet habitability. GSFC will simulate interstellar clouds and protoplanetary chemistry.
- *Biomarkers.* The Virtual Planetary Laboratory (VPL) at NAI is exploring the possibility of detecting biomarkers (especially ozone) on planets around F, G, K, and M stars. The astronomical environment and the spectral characteristics and variability of the host star are important for this work. ARC will assess the prospects of survival of biospheres and the strategies to detect them. The Search for Extraterrestrial Intelligence Institute (SETI) looks for novel biosignatures—namely, signs of extraterrestrial technology.

- *Planetary habitability.* Astronomical influence on planetary habitability is one of the most widely studied topics at the NAI. The University of California at Los Angeles (UCLA) is studying the links between orbital dynamics, impact histories, and geological evolution and the effect of these links on planetary habitability. ARC is estimating how the delivery of volatiles, impacts, and orbital eccentricities may affect habitability. VPL is using planetary models and time-dependent stellar spectra to investigate surface-incident ultraviolet flux and planetary habitability for different parent star/planetary atmosphere combinations. SETI is using observational data and analyses to define the habitability of Europa and planets orbiting cool M stars. UW and PSARC also have a research component in this area. UA will investigate giant planet atmospheres.
- *Planet detection.* Extrasolar planetary detection has already been studied at both UCLA and CIW. They propose to continue this effort. UCLA will include planetary detection in nearby clusters of young stars.
- *Bombardment.* Life-related consequences of impacts are a focus of research by several nodes. UA proposes to connect giant impacts through circumstellar dust disk evolution. UCLA proposes a geological exploration of the Bellingshausen Sea, the only known site of an asteroid impact into a deep-ocean basin, to understand the processes and environmental effects of an oceanic event of this scale. UW investigates conditions for habitability and notes that periodic catastrophic events, including bolide impacts, may be necessary to create and maintain the high variability of habitable conditions that results in increased biodiversity and biocomplexity. Impacts were the topic of a workshop and are the subject of the Impact Focus Group.
- *Water.* The exogenous delivery of water to earthlike planets is being investigated by five NAI nodes: GSFC, CIW, the University of Hawaii (UH), ARC, and the University of California at Berkeley (UCB). CIW proposes research on the water in martian meteorites and its deuterium/hydrogen ratio. UH will observe the abundance and distribution of matter in the interstellar medium, circumstellar disks, and icy outer-solar-system bodies. GSFC will investigate the role of icy planetesimals in the delivery of water. ARC will consider delivery of water and the conditions to preserve it. UCB will explore the history of water on Mars.
- *Mars.* UCB will undertake studies that directly inform the selection of optimal sites for future Mars exploration and will design strategies for remote geomicrobiological investigation. ARC will try to define biosignatures for a martian biosphere. For example, the signature of methane has been detected by ground-based telescopes.[1]

Of the nodes that propose work on astronomy, ARC, CIW, GSFC, SETI, and UA propose work that connects astronomy and some other discipline. UCLA, CU-Boulder, UH, and UW propose astronomical research (primarily planet formation) in which the astrophysics is substantially independent of the other components of the proposed work. The work being done by PSARC and VPL is beginning to make the connection with the astronomical environment an explicit part of the proposed work. It is not clear that UCB does so. Four nodes focus on nonastronomical aspects of astrobiology: Indiana University, the Marine Biological Laboratory at Woods Hole, Michigan State University, and the NASA Jet Propulsion Laboratory.

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[1] M.J. Mumma, R.E. Novak, M.A. DiSanti, B. Bonev, and N. Dello Russo. 2004. "Detection and Mapping of Methane and Water on Mars: Evidence for Local Enhancements in Methane." *Bulletin of the American Astronomical Society* 36(4): Abstract No. 26.02.

Other NASA Programs

NASA has also supported astronomy research relevant to the astrobiology program under other programs:

- Exobiology
- Origins
- Cosmochemistry
- NASA Specialized Center of Research and Training (NSCORT)
- Terrestrial Planet Finder

The Exobiology program is a long-standing one that now serves as the major source of funding for single-principal-investigator (PI) astrobiology research associated with the broader astrobiological program, including grants to members of NAI teams. Within the Exobiology program, the committee identified 27 proposals funded since 1999 that deal with astronomical topics. Most of these focus on chemistry. Interstellar chemistry (organic and inorganic), atmospheric chemistry, and impact chemistry were represented. Delivery of material to planets and extrasolar planets was a minor focus (2 of 27 proposals).

Within the Origins program, the intent of which was to fund astronomical research, the committee identified 54 proposals funded in the last year with relevance to astrobiology. In addition, this program funded two meetings on topics relevant to astrobiology. The main funded topics included (1) meteorite chemistry/organics, (2) observation and detection of extrasolar planets, (3) dynamics and modeling of extrasolar planets, and (4) spectroscopy and modeling of planetary atmospheres. One study of impact and bombardment is being undertaken.

Origins was a program entirely separate from the NAI and the Exobiology programs in terms of management and funding. The goals of the 2003 Origins Roadmap overlapped considerably with those of the Astrobiology Roadmap. The issue of communicating work in the Origins program to the core astrobiology program was raised in the *Life in the Universe* report. With the new NASA vision for space exploration, the issue of which research comes within the rubric of the vision takes on new import and will probably have an impact on budgets. A draft of the present report noted that the old administrative themes (Origins, Structure and Evolution of the Universe, Solar System Exploration, Mars Exploration, and the Sun-Earth Connection) might no longer serve the current missions of NASA and suggested that the theme structure, and the role of astrobiology within it, be reconsidered to achieve greater clarity of mission, programs, and budget priorities. In June 2004, the theme structure was abolished. At this writing, it is not clear what structure will replace it within the new Science Mission Directorate or how the funding and administration of astrobiology programs will be handled. The committee urges NASA to ensure that research and training in astrobiology play an integral role in the new structure.

In the last round of selections by the Cosmochemistry program, in 2002, 60 proposals were selected. The majority of these were relevant to astrobiology. Among the topics proposed were meteorite mineralogy, lunar and martian rock studies, interplanetary dust, presolar grain inclusions, and issues of planetary differentiation. Few of the studies seem to be placed in a broader astronomical context.

The NSCORT program was reviewed in *Life in the Universe*. The program has been in existence for some time, but only two centers are now relevant to astrobiology, the University of California at San Diego (UCSD) and Rensselaer Polytechnic Institute (RPI). They host consortia where the collaborators are, typically, colocated and focus on graduate education. The UCSD effort in exobiology has as its research themes plausible chemistry under plausible prebiotic conditions, Earth-based synthesis and inputs from space, the nature of the first genetic material, and RNA/DNA/protein evolution under laboratory conditions. The second of these topics is manifestly related to astronomy. The New York Center for Studies on the Origin of Life, at RPI, has in its purview the astrophysical topics of interstellar chemistry, chemistry and physics in the solar nebula, and planetary habitability, as well as topics in biology, chemistry, and Earth science. In the current structure, NSCORTs focus on graduate training, but in a rather restricted range of areas. Graduate training does occur within the context of many of the NAI teams, but most of the focus and associated budgets is aimed at public outreach and education, not graduate education per se. NASA should consider what mix of NAI and NSCORT funding will best address the critical issue of interdisciplinary graduate training.

Broadening the Range of This Research

The committee senses in this summary of currently funded research a tendency to support previously well-defined, accepted areas of research. There is much to be done, so funding of different groups to do related work from independent points of view has great merit. Since the focus of work is in only seven areas in the NAI, there is a hint that research that seeks to broaden the bounds of the astronomy/astrobiology interface is not promoted in the current funding structure. It is difficult to assess whether this redundancy gave any cause for concern in the evaluation of the new and renewed NAI nodes. In the Exobiology program, where there should be more flexibility to promote innovative, if somewhat risky, ideas, the focus seems even tighter, on interstellar chemistry. The Origins science was substantially single-PI research and so might also show more range, but it tends to overlap strongly with the major themes of the NAI. To a certain extent this represents the "sweet spot" of current research, but may also indicate a "bandwagon" effect and a certain conservatism on the part of referees and funding agencies.

Finding: Review of current astronomically oriented research shows that work is concentrated in relatively few areas, more so in the Exobiology program than at the NAI.

Recommendation: The committee recommends that NASA continue to ensure that an appropriate diversity of topics is included within the astrophysics component of astrobiology and that its support be coordinated with funding through other relevant programs.

Even where astrophysical research is supported in the NAI, there is rather little current evidence for integrated activity. This may change with the new NAI teams, which have a more explicit astronomical imperative, but the goal of integration needs to be encouraged and monitored. There are research areas where interactivity is explicitly defined. ARC proposes to do laboratory and computational definition of molecules of biological significance followed by astronomical searches for them. GSFC proposes to analyze complex organics formed in grain-catalyzed reactions and radiation-processed ices and then compare the results with astronomical observations. UA proposes to determine signatures of prebiotic compounds and then search for them in space. Nevertheless, the current astronomy supported by the extant NAI teams consists substantially of observations of star formation and protostellar disks. While this is clearly astronomy, it is not clear that the work being done would pass the filter defined above in the context of the Exobiology program—namely, that astronomy that is most relevant to astrobiology is astronomy that directly influenced either the origin or later evolution and sustainability of life. Perhaps the question should be this: Would the astronomy nominally supported by current NAI nodes have passed muster as "astrobiology" in the Exobiology program? NASA should request that NAI annual reports include information on interdisciplinary work, specifically the integration of astronomical research with other disciplines. NAI teams, in particular, should make an explicit effort to promote joint research between astronomers and researchers in other disciplines. Evidence for this would consist of astronomers writing papers with biologists or geologists or at least citing that literature (and vice versa) and dual degree programs.

Recommendation: The committee recommends that NASA develop metrics to evaluate the degree to which truly interdisciplinary work involving astronomy and astrophysics is being done in the current NAI nodes.

The Terrestrial Planet Finder (TPF)[2] mission and Darwin,[3] the parallel program of the European Space Agency, will search for terrestrial planets and attempt to detect evidence of life. The successful planning and execution of the NASA TPF mission will require a great deal of interdisciplinary input from astrobiologists working with astrophysicist colleagues. As a specific example, stellar astrophysicists viewing their research objects through the lenses of astrobiology must now try to understand potential TPF target stars as the astrophysical environment and energy source for potential life-sustaining planets, not just as stars.

TPF will require the attention of the astronomical community in at least three ways: work on improving star lists; work on improving predicted signals from various types of planets in various evolutionary or temporary states; and work on developing techniques and concepts for planet detection and characterization. The astronomical context will be important to learn about the atmospheric lifetime or practical detectability of a biomarker in a given astrophysical environment—that is, the scenario under which TPF will operate. Biosignatures can be generated in part by radiation from the parent star, as happens when ozone is generated from molecular oxygen. Biomarkers are also detectable in either stellar reflected light in the visible or as a function of planetary atmospheric temperature structure in the mid-infrared. (This planetary temperature structure is also a function of chemical composition of the atmosphere, all of which—chemical composition and temperature structure—is driven by the spectral energy distribution and variability of the host star.) The astronomical perspective forces us to consider the nature and detectability of biosignatures for host stars that are unlike our own Sun, and it requires strong interdisciplinary collaboration between stellar astronomers, planetary atmospheric physicists, atmospheric chemists, and spectroscopists.

The specific point that large departures from equilibrium are likely to be driven by biological processes was made by Lovelock.[4] It is based on the idea that enzymes are highly selective, whereas inorganic catalysts are not. Thus we may identify a biomarker long before we identify the process that gave rise to it. The Astrobiology Roadmap also notes as follows: "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." The opportunity for interdisciplinary work in these areas is great.

At least two teams in NAI (VPL and UA) are already working on TPF-related problems; however, the main resources associated with the mission(s) come from mission funds, not astrobiology resources.

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[2] Available at <http://planetquest.jpl.nasa.gov/TPF/tpf_index.html>. Last accessed April 27, 2005.
[3] Available at <http://ast.star.rl.ac.uk/darwin/>. Last accessed April 27, 2005.
[4] J.E. Lovelock. 1965. "A Physical Basis for Life Detection Experiments." *Nature* 207:568-570.

4

Areas That Could Benefit from Augmentation and Integration

The astrophysical context of life consists of the structures that host life, the substances that compose it, and the astronomical radiant and particle fluxes that affect it. In a somewhat broader framework, one can consider the relevant astrophysical techniques to observe and determine these factors to be part of the intellectual astrophysical context of astrobiology. An example would be the search for biomarkers that require astronomy for remote detection but that could be defined in a manner (chemical disequilibrium) rather disconnected from any specific astrophysical context. The issue in Chapter 3 raised by the duplication of astronomical topics within the NASA Astrobiology Institute (NAI) nodes is not only one of multiple teams exploring similar astronomical projects but is also an issue of whether other astronomical topics of astrobiological interest may have been overlooked. Some of these overlooked topics are merely small gaps in otherwise active areas, but others are largely unexplored.

The one topic of astrophysical research that is being richly explored in an ever more fully realized astronomical context is the search for planets. Planets are being sought around a wide variety of host stars, including white dwarfs, and in a wide variety of environments—for instance, isolated stars, binary stars, and stars in stellar clusters. This research is clearly in the realm of astrobiology but for the time being must be rather disconnected from the biological and geological aspects of astrobiology. The notion of habitable zones has been expanded with our growing understanding of extremophiles, but there is much to be done in terms of placing this work on habitable zones in the broadest astronomical context. Because these topics are already the focus of great and warranted attention, the committee does not stress them in this report.

While there is a great deal of astronomical work on the formation of stars and planets and the chemistry of interstellar clouds, there are gaps in this work, on the delivery of material to planetary surfaces and the processing that occurs. The problem of understanding the delivery of organics should be connected to the topics of star formation and cosmochemistry and the origin of life. It is only in this context that these fields are important to the astrobiology community. Meteoritics provides valuable information, but this discipline does not seem to be well supported in the current NAI framework. Another topic that does not appear to be well covered is the influence of astronomical events on the history of life—for instance, the stellar flares and supernovas that would alter the cosmic ray flux into the atmosphere and onto the surface. Specifically, the biological effects of radiation and particle fluxes should be explored. Cosmic rays and high-energy photons may both produce ionization in cells, but their production, propagation, atmospheric penetration, and deposition are different. This report places some emphasis on particle and photon irradiation both because such radiation is a ubiquitous feature of the astronomical environment that is relevant to biology and because it is relatively understudied. Consideration of the astrophysical context of life elucidates the fact that all planets will exist in variable environments. While somewhat abstracted from a specific astronomical context, there are basic issues of how much variability is healthy, or even needed, for the robust evolution of complex life. These issues raise questions about molecular evolution in an astronomical context.

With finite personnel and finite time, the committee may not have addressed all the areas that could come within the purview of this report. Some representative areas that it believes are relatively understudied and especially amenable to focused effort in the near future are these:

- The galactic environment,
- Cosmic, solar, and terrestrial irradiation,
- Interstellar and protostellar nebular chemistry,
- Bombardment,
- Prebiotic chemistry and photosynthesis, and
- Molecular evolution in a variable astronomical context.

The committee addresses these topics in some detail below. For each topic it attempts to outline relevant astronomical issues that are currently rather divorced from other disciplines of astrobiology but that are deemed to be life-oriented and hence solidly within the rubric “astrobiological research.” The committee also attempts to identify for each topic where interdisciplinary work could be needed.

GALACTIC ENVIRONMENT

Current Work and Gaps

One of the broadest questions one can ask is that about the role of the galactic environment in the origin, development, sustainability, and evolution of life. The galactic environment refers to the astronomical environment in which any life-hosting body resides. The galactic environment consists of the large-scale and highly irregular environment of the Galaxy, with its dense bulge and spiral arms filled with stars and gas of varying composition, analogous to the varied environments in the biosphere of Earth. The galactic environment is also defined by the particular type of star, its location in a dense or rarified portion of the interstellar medium, the star’s location with respect to the spiral arms or the central bulge, and the presence or absence of nearby perturbations caused by catastrophic or milder events that can affect life. As does life on an evolving Earth, the galactic ecological niche will inevitably vary with time as the star wanders through the Galaxy and encounters different conditions and as the star itself evolves. Stars like the Sun could very well have been born in rich clusters where neighboring young stars bathed the solar system with external radiation. In time, the clusters dissolved, leaving the Sun to wander its solitary way, as it does today. Some have referred to this overall galactic environment as a “disturbed galactic ecology.”

The question has been raised of whether there is a galactic habitable zone in the same sense as the habitable zones around the Sun and other stars, defined principally by the ability to sustain liquid water.

The galactic habitable zone has been delineated as an annulus in the Galaxy not too close to the bulge, where excess supernovas may be dangerous, and not too far from the center, where a paucity of heavy elements may prevent terrestrial planet formation.[1,2] One point of view is that this annulus may be rather narrow, giving Earth a special, and rare, location with respect to both its host star and the Galaxy.

There are many issues to be explored in terms of the space- and time-varying conditions of a given potentially life-hosting stellar system. What is an optimal location or galactic environment for the development and sustainability of life in relation to the spiral arms, the galactic center, and the regions of heavy-element formation? Where, exactly, is the Sun with respect to the galactic center? Where is the co-rotation point, the radius where the Keplerian velocity of the Sun about the Galaxy matches the pattern speed of the spiral arms and therefore drifts but little with respect to patches of newborn stars? The galactic radius of the Sun and its co-rotation point are uncertain by 10 to 20 percent, rendering uncertain the rate at which the Sun encounters a variable galactic environment or moves at rest relative to its immediate surroundings. What are the conditions in the interstellar gas that the Sun or other stars are likely to encounter? The range in density of interstellar gas is large, with potentially significant effects on the ram pressure of the astrosphere and the ability of the astrosphere to screen cosmic rays. When in the development of the Galaxy might it first have hosted life? Must the average concentration of elements be high, or is it sufficient for pockets of enhancement to exist? If so, when would this first occur? What are the effects of rare, but powerful, explosions?

An example of the sort of cross-disciplinary work that can bind astronomy with other aspects of astrobiology in a galactic context is the model presented by Shaviv,[3] which connects the modulation of cosmic rays as the Sun passes through spiral arms with effect on cloud cover and hence climate and conditions in the biosphere. While the validity of the statistical correlations has been strongly challenged,[4] this idea is worth deeper investigation. More work is needed to develop chronometers associated with meteoric data on cosmic ray fluxes. In addition, there may be other means to modulate the cosmic ray flux—for instance, the variable interstellar medium density and associated ram pressure, which determine the extent of the heliosphere and its ability to screen cosmic rays.

Finding. The question of whether there is a galactic habitable zone and how it may have evolved raises a large number of interesting issues that have not been adequately explored.

Areas of Relevant Independent Astronomical Research

While some issues are already clearly in the realm of astrobiology, numerous issues in assessing the galactic environment will remain in the domain of pure astronomy in the near future. Among these are the assessment of the heavy element concentration necessary for planet formation; the correlation of the heavy element abundance of the parent star and the existence of planets and determination of the reason for any such correlation; the location of the Sun with respect to the co-rotation radius; the variability of

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[1] G. Gonzalez, B. Brownlee, and P. Ward. 2001. "The Galactic Habitable Zone: Galactic Chemical Evolution." *Icarus* 152: 185.

[2] P.D. Ward and D. Brownlee. 2000. *Rare Earth: Why Complex Life Is Uncommon in the Universe*. Copernicus, New York, N.Y.

[3] N.J. Shaviv. 2003. "The Spiral Structure of the Milky Way, Cosmic Rays, and Ice Age Epochs on Earth." *New Astronomy* 8: 39-77.

[4] S. Rahmstorf, D. Archer, D.S. Ebel, O. Eugster, J. Jouzel, D. Maraun, G.A. Schmidt, J. Severinghaus, A.J. Weaver, and J. Zachos. 2004. "Cosmic Rays, Carbon Dioxide, and Climate." *EOS Transactions of the American Geophysical Union* 85(4): 38-41.

the density of the interstellar medium in the vicinity of the Sun; and the statistical properties of the interstellar medium of relevance to arbitrary exoplanets and their host stars.

Areas of Potential Interdisciplinary Interaction

The issue of a galactic habitable zone raises a raft of interesting questions. Is there an optimal location in the Galaxy? How does one decide? If there is, where is it? How many supernovas are too many, and where in the Galaxy does that zone lie? Can the galactic bulge harbor habitable planets? Can star clusters? Classical habitable zones depend on the presence of liquid water independent of whether there are bugs in that water. In contrast, many of the issues related to a galactic habitable zone cannot be addressed without direct reference to biology. For instance, an attempt to understand where life can comfortably exist and where it will be severely challenged requires knowledge of how life resists and adapts to environmental insults. The question whether modulation of cosmic ray flux can affect climate may sidestep direct issues of biology, but it involves a number of other disciplines. Meteoritics and mineralogy are needed to assess the variation in the cosmic ray flux. Other means of assessment should be explored. Dating of ice ages is an important ingredient, involving climatology, paleoclimatology, and ice-age geology. Because cosmic rays can affect the ionization state of the atmosphere, their modulation as characterized by astronomers should be investigated by atmospheric chemists and photochemists. In general, the topic of galactic habitability requires an interchange among all these disciplines as well as among cell biologists, microbiologists, and molecular biologists who study thermal and radiation damage to cells and genomes. One relevant task is to assess the potential significance of biomolecular damage induced by cosmic rays, which are subject to astronomical influences, relative to damage induced by radiation from environmental sources. Also, what if life elsewhere is not based on DNA?

For completeness, the committee mentions the possibility of the transport of life between stars, or interstellar "panspermia." The possibility of the interchange of microbes between planets, Mars, and Earth has been studied; the conclusions are somewhat optimistic if microbes can be shielded within rocks of centimeter size.[5,6] The issue of transport of life between stars, while enticing, does not appear to the committee to be an especially fruitful topic at this time. The transport times are expected to be long, the radiation doses high, and the probability of planet-fall small.[7] In any case, this notion just puts off the ultimate question, how the transition from chemistry to biochemistry occurred (see the section "Prebiotic Chemistry and Photosynthesis"). There is, as yet, no indication of an environment more hospitable for the origin of life than Earth. A bright idea might render the transport of life between the stars fruitful, but the committee does not consider it further in this report.

Missions, Role of Other Agencies

Missions to characterize the local interstellar medium (ISM) through which the Sun has passed and will pass in the future are relevant. The keys to characterizing the three-dimensional morphology,

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[5] National Research Council. 1998. *Evaluating the Biological Potential in Samples Returned From Planetary Satellites and Small Solar System Bodies*. Space Studies Board. National Academy Press, Washington, D.C.

[6] C. Mileikowsky, F.A. Cucinotta, J.W. Wilson, B. Gladman, G. Horneck, L. Lindegren, J. Melosh, H. Rickman, M. Valtonen, and J.Q. Zheng. 2000. "Risks Threatening Viable Transfer of Microbes Between Bodies in Our Solar System." *Planetary and Space Science* 48: 1107.

[7] H.J. Melosh. 2003. "Exchange of Meteorites (and Life?) Between Stellar Systems." *Astrobiology* 3: 207.

densities, and temperatures of the local ISM are (1) high-resolution spectroscopy and (2) access to strong resonance lines. The ultraviolet (UV) has many strong resonance lines, but it requires going above Earth's atmosphere, and unfortunately, the only two high-resolution spectrographs in space are in questionable condition. The de-orbiting in a few years of the Hubble Space Telescope (HST) is under active consideration, and the Far Ultraviolet Space Explorer (FUSE) is near the end of its active life. The Cosmic Origins Spectrograph designed for HST may yet be installed in a servicing mission, or it might be launched as a free flyer. The European Space Agency might fly a UV mission with suitable resolution sometime after 2008.

Missions that could better characterize the cosmic ray spectrum—especially at low energies, where solar modulation is strong but variable—would be useful. A study of lunar rocks to determine the record of cosmic ray variation in relatively pristine material would be of great interest.

Recommendation. NASA should promote the study of topics related to galactic habitability, including (1) correlating stellar heavy element abundance with the existence of planets, (2) characterizing the interaction among stellar winds, the interstellar medium ram pressure, and the resulting cosmic ray flux, and (3) determining which regions of the Galaxy could give rise to and sustain life.

COSMIC, SOLAR, AND TERRESTRIAL IRRADIATION

Current Work and Gaps

The effects of irradiation manifest themselves in many ways. Optical light is a source of energy by way of photosynthesis. UV photochemistry may have played an important role in the prebiotic synthesis of organic compounds on early Earth (see the section "Prebiotic Chemistry and Photosynthesis"). UV radiation, primarily from the Sun, affects molecular structure by, for instance, forming cyclobutane pyrimidine dimers, misconnections in the strands of DNA that interfere with the ability of the molecule to reproduce. UV radiation can also activate transposable genetic elements that are active in gene transfer. High-energy photons (x rays and gamma rays) are a source of ionization damage in cells. The energetic particles generated by the Sun and those arriving from outside our solar system as cosmic rays produce cascades of secondary particles that also induce ionizations in cells, with similar effects. Although incident ionizing radiation must pass through the thick atmosphere of Earth, about 1 percent of its energy will reach the ground as biologically active UV auroral radiation.[8] Irradiation is both a mutagen and a selective agent, thus affecting both steps in natural selection. Irradiation can also affect life indirectly by influencing climate.

The idea that the evolution of terrestrial and extraterrestrial life is influenced by irradiation sources was presented by Sagan and Shklovskii.[9] Contemporary literature often treats UV and ionizing radiation from a parent star as primarily destructive and that from galactic sources only as a potential cause of mass extinctions. The case can be made, however, that the role of irradiation extends beyond these destruction scenarios and that irradiation has been significantly involved in the origin and evolution of life. The significance of the irradiation environment depends on, among other things, the proportion of

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[8] D.S. Smith, J. Scalo, and J.C. Wheeler. 2004. "Transport of Ionizing Radiation in Terrestrial-like Exoplanet Atmospheres." *Icarus* 171: 229-253.

[9] C. Sagan and I.S. Shklovskii. 1966. *Intelligent Life in the Universe*. Holden-Day, San Francisco, Calif.

cellular mutation caused by (1) cosmic and geological background radiation (see below), (2) nonirradiative, exogenous factors, and (3) other factors that contribute to diversity, such as lateral transfer of genes, gene duplication, and the evolution of developmental systems involving DNA, cellular and organismic structure, and social and ecological interactions. The relative significance of these various factors will undoubtedly change as life evolves from a primitive state to more sophisticated biochemistries.

There are hints that irradiation has interacted with life for a very long time. Mechanisms specific to the repair of irradiation-induced damage are found in organisms from prokaryotes to humans. The mechanisms involved in the ancient process of lateral gene transfer and the more recent process of meiosis are often the same as those involved in repair of DNA damage due to UV and ionizing radiation. That early organisms were already subjected to UV radiation is suggested by the fact that both obligately and facultatively anaerobic bacteria show intrinsic resistance to UV damage and use photoreactivation to repair UV-induced pyrimidine dimers. Photosynthesis is an important interaction between light and life (see the section "Prebiotic Chemistry and Photosynthesis"). The detection of cyanobacterial biomarkers in Archean rocks[10] and the genetic sequencing of major bacterial families[11] suggest that the five major photosynthetic lineages and oxygenic photosynthesis arose by the mid-Archean, 2.8 to 3.0 billion years ago, and perhaps much earlier (although one of the phyla, the green no-sulfur bacteria, may have acquired parts of the photosynthetic machinery from the other phyla only 2.3 billion years ago[12]). There are extremely radiation-resistant microbes, such as *Deinococcus radiodurans*, that contain a large (but not exhaustive) suite of radiation repair mechanisms.[13,14] All of these facts point to an important, early, and ongoing role for radiation in the evolution of life on Earth, including a role in issues of habitability. It is natural to suspect that analogous processes will occur for life on planets with other host stars.

Finding. Optical, UV, and ionizing radiation have had a significant influence on life from the early stages in its evolution on Earth, and this will probably be so for exoplanets that harbor life.

ARC proposes to study the effects of various forms of radiation on the survival of life in extreme environments and to examine specific biota for radiation resistance by doing exposure experiments. The Search for Extraterrestrial Intelligence Institute (SETI) will consider iron as a UV blocker and study the survival of organisms in the high-UV environment of Chile but not in the broader astronomical context of a young Sun or a host star of another stellar type. The Virtual Planetary Laboratory (VPL) is beginning to study the effects of illumination of planetary atmospheres by stars of various types. Otherwise, the topic of astronomical irradiation is underrepresented in the efforts of the current NAI teams and of the Exobiology program.

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[10] J.J. Brocks, G.A. Logan, R. Buick, and R.E. Summons. 1999. "Archaean Molecular Fossils and the Early Rise of Eukaryotes." *Science* 285: 1033-1036.

[11] J. Xiong, W.M. Fischer, K. Inoue, M. Nakahara, and C.E. Bauer. 2001. "Molecular Evidence for the Early Evolution of Photosynthesis." *Science* 289: 1724-1730.

[12] J. Raymond, O. Zhaxybayeva, J.P. Gogarten, S.Y. Gerdes, and R.E. Blankenship. 2002. "Whole-Genome Analysis of Photosynthetic Prokaryotes." *Science* 298: 1616-1620.

[13] J.R. Battista. 1997. "Against All Odds: The Survival Strategies of Deinococcus Radiodurans." *Annual Review of Microbiology* 51: 203-224.

[14] "Deinococcus Radiodurans—A Radiation-Resistant Bacterium." Available at <http://www.usuhs.mil/pat/deinococcus/index_20.htm>. Accessed on April 26, 2005.

Areas of Relevant Independent Astronomical Research

The characteristics of host stars, including the Sun, when they are young and life might first form need to be better understood. There are indications from the study of solar analogues—that is, stars like the Sun at different stages in their evolution—that high-energy chromospheric activity and stellar winds were much more intense in the past. In addition, young stars are more susceptible to flares and variability. This irregular behavior might have contributed to temporal variability of the environment and hence to genetic diversity (see the section "Molecular Evolution in a Variable Astronomical Context"). The fluctuating radiation environment needs to be better characterized for a range of stellar types. Consideration should be given to the spectral distribution at the source and after transmission through various types of planetary atmospheres in order to evaluate the effect on atmospheric structure and chemistry, climate, and potential surface biota.

Sporadic external events like supernovas[15] and gamma-ray bursts[16] can affect biological processes by brute extinction if they are sufficiently close and intense, but such events will be rare. Exposures to the light from supernovas last only weeks to months, and the most intense stage of gamma-ray bursts lasts only tens of seconds. Only half the planet would be exposed, and even then life in sheltered environments might survive. To quantify other, more subtle possible biological issues, it is necessary to determine by direct or statistical methods the rate of occurrence and the spectral output of various astronomical sources of potential biological significance. As an example, a supernova explodes in our Galaxy about every 100 years. The number of explosions near a given planet increases as approximately the distance squared in the flat plane of the galactic disk. A typical supernova would have to be very close, perhaps a parsec, to beat the solar UV background at Earth, and such events are very unlikely.[17] More distant supernovas could still affect outer moons in our solar system, where the solar flux is smaller, or planets around a dimmer, less UV-powerful star. Even more distant supernovas might affect life on a planet by producing cosmic rays directly or by impacting the astrosphere of a star and allowing more ambient cosmic rays to reach the planet. Exposure to the short-term irradiation of a nearby supernova is likely to have a very different effect than immersing a solar system in the subsequent supernova remnant, which would be characterized by efficient particle acceleration. If a supernova remnant envelops a planetary system, the ambient cosmic ray flux could be enhanced for 10,000 years or more. There are issues surrounding the formation and propagation of associated cosmic rays that would determine the exposure of a life-bearing planet to ionizing particle radiation that are still not well understood.

Finding. Life on a young planet could be exposed to an intense, intrinsically variable irradiation field, and a variety of galactic sources might affect the UV, ionizing radiation, and particle flux incident on a planet.

Recommendation. NASA, other funding agencies, and the research community should devote funding and effort to characterizing the UV, ionizing radiation, and particle flux incident on evolving, potentially life-hosting planets and moons.

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[15] N. Gehrels, C.M. Laird, C.H. Jackman, J.K. Cannizzo, B.J. Mattson, and W. Chen. 2003. "Ozone Depletion from Nearby Supernovae." *Astrophysical Journal* 585: 1169-1176.

[16] J. Scalo and J.C. Wheeler. 2002. "Astrophysical and Astrobiological Implications of Gamma-Ray Burst Properties." *Astrophysical Journal* 566: 723-737.

[17] Gehrels et al. Op. cit.

Areas of Potential Interdisciplinary Interaction

If photon and particle irradiation plays a role in the chemistry and structure of the atmosphere and the climate of a host planet and in the origin, evolution, and sustainability of life on that planet, then characterizing the significance of that radiation means that the biological, atmospheric, and geological influences need to be understood. For instance, one must know the state of the Archaean atmosphere—that is, whether it contained sulfur or aerosol screens—in order to evaluate the intensity of surficial UV. The effect of irradiation on climate requires careful modeling of the time-dependent atmospheric chemistry and structure. One needs to know the biological dose rates for a spectrum of mutagenic responses to evaluate whether a particular fluctuating chromospheric emission or a nearby supernova can have a significant effect on biological processes. The study of astronomical irradiation sources must be closely coupled to the other areas of astrobiology in order to properly assess the rate of significant events and their impact.

Ultraviolet and Ionizing Radiation Damage and Repair

One area where photon and particle irradiation intersect with biology is the processes associated with radiation damage and repair. Photon and particle irradiation are two of many sources of exogenous damage to genomes. Irradiation can cause direct damage in the form of pyrimidine dimers, single- and double-strand breaks, cross-strand exchange, and multiple lesions. Irradiation can also produce indirect damage by forming oxygen radicals,[18] as can other processes, both exogenous and endogenous. Irrespective of their source, reactive oxygen species cause damage to proteins, lipids, and DNA. Survival of a cell exposed to radiation depends on the extent of genomic damage during irradiation, the efficiency of repair, and the extent of cellular damage inflicted during recovery by metabolism-induced oxidative stress. While irradiation can cause some damage similar to endogenous effects, it also produces damage such as cross-strand attachments and multiple lesions, for which there is no endogenous analogue. The repair processes for this unique damage must have evolved relatively independently of repair processes for endogenous damage. Understanding the genetic history of these repair processes unique to radiation may give new clues to the evolution of life on Earth. Irradiation damage can be so severe as to lead to apoptosis, but it can also be one contributor to unrepaired damage and hence to mutation and evolution.

An important source of mutation is replication error. This must have been especially true early in the evolution of life, when proofreading was less efficient. In modern life, endogenous damage and replication errors are repaired with remarkable efficiency. The rate of damage due to toxic reactive oxygen species (hydroxyl radicals, hydrogen peroxide) produced as a consequence of cellular metabolism is estimated to be higher by orders of magnitude than that due to current background levels of ionizing radiation.[19] On the other hand, the net rate of mutation after repair mechanisms have done their work is roughly equivalent for radiation and endogenous effects. This is why one avoids too many chest x rays. The difference is presumably due to the very high efficiency of repair processes for replication error and endogenous damage compared with the less efficient repair of damage by ionizing radiation.

Selection for the ability to repair errors in replication, chemical damage, irradiation damage, and other lesions in the genetic material would have been intense from the very beginnings of life. Studies of

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[18] G. Hanel, B. Gstir, S. Denifl, P. Scheier, M. Probst, B. Farizon, M. Farizon, E. Illenberger, and T.D. Märk. 2003. "Electron Attachment to Uracil: Effective Destruction at Subexcitation Energies." *Physical Review Letters* 90(18): 188104.

[19] J.A. Imlay. 2003. "Pathways of Oxidative Language." *Annual Review of Microbiology* 57: 395.

the regulation of repair processes are ongoing in many laboratories, using the latest techniques in high-throughput analysis of transcription and protein expression. A great deal of additional biochemical experimentation, coupled with molecular phylogenetic studies, will be required to learn more about the origins of DNA repair pathways, including those that are unique to the repair of irradiation damage. In principle it should be possible to gain a reasonable understanding of DNA repair pathways in the last common ancestor, but learning about DNA repair at earlier stages, characterized by rampant gene swapping, will be much more difficult.

A better understanding of the origins, nature, and control of DNA damage repair is clearly important for understanding the response of organisms to geological background radiation (see the section "Interstellar and Protostellar Nebular Chemistry"), solar UV, and cosmic ionizing radiation. However, these studies of radiation damage repair are also important for understanding biomedical problems, including the genesis and treatment of cancer, genetic diseases, and certain aspects of aging. Solar UV irradiation is the most powerful carcinogen to which humans are routinely exposed.[20] The primary danger of exposure of humans to high-energy particles in space is an enhanced risk of cancer. Thus, certain areas of interest to astrobiology overlap with subjects of fundamental interest to NIH. NASA and the National Cancer Institute fund the development of nanoscale biomedical technologies that detect, diagnose, and battle radiation exposure, cancer, and other diseases at the cellular level. Consideration could also be given to the effect that astrophysical irradiation has on molecules other than DNA—for instance, on the structure of protein molecules.

Finding. Understanding the origins, nature, and control of DNA damage repair is also important for understanding the response of organisms to solar and cosmic UV and ionizing radiation and to geological background radiation. These studies are also important for understanding certain biomedical problems, including the genesis and treatment of cancer, genetic diseases, and certain aspects of aging.

Recommendation. NASA, other funding agencies, and the research community should devote funding and effort to exploring the variability of damaging UV and ionizing radiation over the course of life on Earth and how such conditions might be manifested on other life-hosting bodies.

Radiation Health and Safety

One area where cosmic irradiation intersects practical issues of health and safety is the exposure of humans in space to photon and particle radiation. This is an issue for astronauts serving on the International Space Station, and former NASA administrator Sean O'Keefe listed it as one of the three major open problems (along with propulsion and adequate on-board power) facing human exploration of Mars. In the absence of adequate shielding, astronauts on a return trip to Mars would receive something like 400 times the yearly average dose for U.S. citizens. Essentially every cell in the human body would be hit once by an ionizing photon, proton, or heavier particle.

NASA funds ground-based experiments using radiation sources and analysis tools like PET and MRI scans and DNA sequencing to better understand the effects when living tissue is exposed to cosmic radiation. Such experimentation is taking place in the Space Radiation Laboratory at Brookhaven

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[20] A. Sarasin. 2003. "An Overview of the Mechanisms of Mutagenesis and Carcinogenesis." *Mutation Research/Reviews in Mutation Research* 544: 99-106.

National Laboratory. A principal focus of these studies is the interaction with tissue of energetic particles from cosmic radiation, about which much less is known than the interaction with tissue of particles from natural terrestrial radiation, which are mostly gamma rays. The goal is to better understand the biological mechanisms of radiation damage and repair. At issue are questions such as whether exposure to proton damage will weaken the response of cells to occasional heavy ions like iron and whether proton irradiation will trigger cell defense mechanisms, making them more robust to heavy ion damage.

Finding. There are areas of potential interaction between astronomers who study the sources and composition of cosmic radiation and physicists and biologists who are attempting to understand the nature of irradiation damage in the context of human survival in space.

Irradiation and Geology

Heat from natural radioactivity plays a role in the geological forces that shape the Earth, and those geological forces in turn affect the distribution of natural long-lived radioactive elements. The geological record may also provide indications of past astronomical events.

One issue that combines astronomy and geology is the question of whether other habitable planets will have plate tectonics. Plate tectonics might be an inevitable outcome for rocky planets that have substantial internal heat sources and liquid water at their surfaces to cool magma and lubricate plate movement. An internal heat source does seem to be a necessary requirement for a habitable planet, since some form of volcanism is necessary to recycle carbonate rocks, as well as other life-supporting elements like nitrogen and phosphorus. An internal heat source, however, is something that is almost unavoidable on any large planet. Planets that formed too early or too late in the history of the Galaxy may lack the radioactive elements (uranium, potassium, and thorium) that help to generate heat within Earth's interior, but roughly half the geothermal heat flow comes from heat that was generated during accretion. A planet that was somewhat more massive than Earth might not need any radioactive elements to maintain plate tectonics.

Radiation exposure from sources in the crust varies strongly with time and position on the surface owing to geological effects and the chemical evolution of a planet's crust, oceans, and atmosphere. The chemical, geochemical, and mechanical processes that lead to concentrations of natural radioactivity include the fractional crystallization of magma chambers, concentration of uranium-bearing sediments in placer deposits, recycling of eroded crustal materials, and precipitation of dissolved uranium at oxidation-reduction fronts. All of these processes are affected by a planet's geological activity, including volcanism, tectonics, and erosion. Differences in planetary parameters can thus combine to influence the radiation environment in which the biota live and evolve.

Through time, Earth's crust has become steadily enriched in elements with large ionic radii, which tend to exclude these elements from the crystal structures of minerals, such as olivine, that crystallize first in a magma melt. These elements include uranium, potassium, and thorium, the primordial radionuclides responsible for much of the natural radioactivity on Earth. One of the chain of decay products of uranium is the radioactive gas radon (^{86}Rn). The alpha decay of radon to polonium is the second leading cause of lung cancer after smoking. Radiation doses to organisms living in contact with rocks will depend on the radionuclide concentrations and the time since those radionuclides were first formed. Geological models that would help to understand under what conditions volcanism and tectonics are possible in exoplanets would be very valuable in general. Models could be also developed for the concentrations of long-lived radioactive species on Earth and on exoplanets, considering the recycling of continental crust materials under a variety of weathering and erosion rates, subduction rates, sedimentation, and initial radionuclide concentrations.

Dose rates from geologic materials vary spatially over at least two orders of magnitude on Earth today. The processes outlined above have acted to concentrate radioactive elements into the Earth's crust and to create radiological hot spots from an initially homogeneous Earth.[21] Such processes have led, for example, to rich sedimentary uranium ore deposits in South Africa, Texas, and Australia, as well as to the formation of the extinct Oklo natural nuclear reactor in the nation of Gabon, in western Africa. At a somewhat milder, but still significant level, the state of Kerala, in India, has one of the highest levels of natural radioactivity on record. The dose rate of about 10 mSv per year is about 10 times the worldwide background. A study of DNA mutations in Kerala showed not only that the mitochondrial DNA (mtDNA) has higher levels of germ-point mutations but also that the radioactivity accelerates mutations at nucleotide positions that have been evolutionary hot spots for at least 60,000 years.[22]

The question of how evolution might respond to the spatially variable radiation environment as it evolved on Earth and as it would evolve on other planets must center on the relative significance of mutations induced by background radiation and those caused endogenously.

Finding. Natural background radioactivity is expected to vary with time and space on Earth and other geologically active bodies. The degree and variation of the background radioactivity will be a function of geological activity, including volcanism, tectonics, and erosion.

Recommendation. NASA, other funding agencies, and the research community should devote funding and effort to the development of planetary geology models to better understand the presence and nature of volcanism and tectonics on other planets as a function of the age of formation of the planet, the initial concentration of long-lived radioactive species, the accretion history, and the mass of the planet.

Recommendation. NASA, other funding agencies, and the research community should devote funding and effort to geological field work and models (1) to characterize the rates of damage and mutation due to background radioactivities on evolving Earth and other potentially life-hosting bodies and (2) to compare them with the rates due to other endogenous and exogenous radioactivities.

In addition to their insults to the biosphere, cosmic rays produce observable signatures of their present and past intensity at Earth. Cosmic ray nuclear interactions transmute elements in the atmosphere, producing cosmogenic nuclei, some of which are radioactive. It is this process that is the source of ^{14}C and provides the means for carbon dating. In addition to this short-lived isotope, longer-lived species are also created cosmogenically; these precipitate out of the atmosphere and are stored in natural archives such as ice cores and ocean sediments, which contain a record of certain aspects of the astronomical environment.

For example, the measured concentrations of ^{10}Be (with a half-life of 1.5 million years) in ice cores give a record of the cosmic ray flux incident on Earth for the past 100,000 years. The concentrations vary as the solar cycle modulates the protective heliosphere. Cosmic rays can also be modulated during

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[21] G. Faure. 1986. *Principles of Isotope Geology*, 2nd ed. John Wiley and Sons, New York, N.Y.

[22] L. Forster, P. Forster, S. Lutz-Bonengel, H. Willkomm, and B. Brinkmann. 2002. "Natural Radioactivity and Human Mitochondrial DNA Mutations." *Proceedings of the National Academy of Sciences U.S.A.* 99(21): 13950-13954.

episodes of the reversal of Earth's magnetic field. These reversals happen irregularly, but on average every 200,000 years in recent geologic time. The field drops to 20 percent of its original strength during a reversal and adopts a complex multipole character but can still provide substantial shielding to surface life from energetic particles. Field reversal episodes tend to last about 5,000 years, long enough for some adaptation. Although there has been some discussion of a correlation between field reversals and the extinction of radiolarians,[23] there is no clear biological record. The last reversal occurred 780,000 years ago,[24] so it is not clear that field reversals have affected the presently available ^{10}Be record. Interestingly, two sharp peaks in ^{10}Be are observed at 35,000 and 60,000 years ago.[25] These are apparently not associated with field reversal and may suggest a temporary increase in the cosmic ray flux in the solar neighborhood due to a supernova explosion.[26]

Another more recent geological record of environmental variability is the nitrate concentration in antarctic ice cores over the last few thousand years. X rays and gamma rays affect atmospheric chemistry by ionizing nitrogen gas and producing an excess of nitrate, which is deposited in ice layers. The fluctuating level of nitrates in ice cores is presumably related to solar variability. There are also four distinct spikes that are several times higher than the background fluctuations. It has been suggested that these spikes could record the supernova of 1006 and earlier events.[27] An equally interesting alternative is that the spikes are due to giant solar flares.[28] In any case, these ice core features underscore the variable nature of Earth's irradiation environment and show the usefulness of geological archives in tracing this variability.

In contrast to the above examples, where the species of interest are made on Earth by cosmic rays or high-energy photons, ^{60}Fe is made in supernova explosions and the atoms must be subsequently transported to Earth. A few dozen atoms of ^{60}Fe have been detected in manganese and iron deposits in the deep ocean.[29] Since ^{60}Fe has a half-life of 1.5 million years, these atoms must have been created recently. If this material had indeed been produced by a supernova, it might have occurred within 30 pc of the Sun and within 5 million years of the present.[30] If this is correct, the ^{60}Fe data give important clues about the history of specific nearby supernova events and should be studied carefully in the context of the effect of such events on Earth and other planets.

More experiments such as these are needed to confirm the supernova origin of live ^{60}Fe in deep-ocean crust. Additional searches should be made for other radioisotopes of key importance, such as ^{244}Pu. Such results would put the initial detection on a stronger footing, solidify the case for a recent near-Earth supernova, and motivate further searches for signatures from still more ancient events. Improvement in the estimates of the terrestrial radioisotope background hinges on a more accurate

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[23] J.D. Hays. 1971. "Faunal Extinction and Reversals of the Earth's Magnetic Field." *Geological Society of America Bulletin* 82: 2433-2447.

[24] "Magnetic Reversals." Available online at <http://www.geolab.nrcan.gc.ca/geomag/reversals_e.shtml>. Accessed on April 27, 2005.

[25] G.M. Raisbeck, F. Yiou, D. Bourles, C. Lorius, J. Jouzel, and N.I. Barkov. 1987. "Evidence for Two Intervals of Enhanced ^{10}Be Deposition in Antarctic Ice During the Last Glaciation Period." *Nature* 326: 273-277.

[26] J. Ellis, B.D. Fields, and D.N. Schramm. 1996. "Geological Isotopic Anomalies as Signatures of Nearby Supernovae." *The Astrophysical Journal* 470: 1227.

[27] C.P. Burgess and K. Zuber. 2000. "Footprints of the Newly Discovered Vela Supernova in Antarctic Ice Cores?" *Astroparticle Physics* 14: 1.

[28] R. Stothers. 1980. "Giant Solar Flares in Antarctic Ice." *Nature* 287: 365.

[29] K. Knie, G. Korschinek, T. Faestermann, C. Wallner, J. Scholten, and W. Hillebrandt. 1999. "Indication for Supernova Produced ^{60}Fe Activity on Earth." *Physical Review Letters* 83: 18-21.

[30] B.D. Fields and J. Ellis. 1999. "On Deep-Ocean ^{60}Fe as a Fossil of a Near-Earth Supernova." *New Astronomy* 4: 419-430.

measurement of the micrometeor flux on Earth. Current limits are set by the Long Duration Exposure Facility satellite.[31] Corroboration of this result (e.g., from ^{26}Al concentrations in ice cores) would be very helpful.

Recommendation. NASA, other funding agencies, and the research community should devote funding and effort to search for cosmogenic material and other live radioactive elements in ice cores and ocean sediments.

Missions, Role of Other Agencies

The NSF supports basic research in astronomy that can provide grist for the astrobiological studies of cosmic radiation. Relevant topics would be the nature of solar analogues and the generation and propagation of cosmic rays in supernovas.

The NSF Tree of Life and DOE Genomes to Life programs will provide basic genetic information on which to base biochemical experiments and molecular phylogenetic studies designed to learn more about the origins of DNA radiation repair pathways.

It will generally be the responsibility of agencies other than NASA, primarily the NSF, to acquire relevant ocean sediment and ice-core data.

The NIH supports biomedical studies of the origin and treatment of cancer, genetic diseases, and aging that could have astrobiological significance in terms of understanding the role of radiation in the evolution of life.

INTERSTELLAR AND PROTOSTELLAR NEBULAR CHEMISTRY

Current Work and Gaps

The biogenic elements, such as carbon, hydrogen, oxygen, nitrogen, sulfur, phosphorus, and iron, have a long cosmic history that is largely known from spectroscopic observations of circumstellar and interstellar gas and dust, as well as from the analyses of carbonaceous chondrites. For example, both molecular clouds and meteorites contain a varied and complex suite of organic compounds, a large fraction of which are similar to terrestrial biomolecules.[32] Among the molecules identified in interstellar gas are formaldehyde (H_2CO), methanol (CH_3OH), ethanol (C_2H_5OH), and methylcyanoacetylene (CH_3C_3N). Moreover, molecular distribution and isotopic composition studies of meteorite organics have revealed that the pathways of their synthesis spanned both interstellar and planetesimal phase processes. For instance, meteoritic amino acids are believed to have formed in an icy asteroidal parent body during the production of liquid water and by the reaction of accreted interstellar volatiles, such as hydrogen cyanide, ammonia, aldehydes, and ketones. This belief is based on extensive knowledge of meteorites and interstellar isotope ratios.

In the study of interstellar molecules and prebiotic chemistry there are three important topics:

- What chemical compounds are present in interstellar space, and what is their chemistry?

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[31] S.G. Love and D.E. Brownlee. 1993. "A Direct Measurement of the Terrestrial Mass Accretion Rate of Cosmic Dust." *Science* 262: 550-553.

[32] See, for example, <www.astrochemistry.net>. Accessed April 27, 2005.

- What chemical compounds are transported to early planets, what are the transport and delivery processes, and how do these processes vary with the nature of the host star, the nature of the planet, and the location of the planet in the system?
- What additional chemical processing would modify these seed compounds to lead to biologically relevant precursors of life?

The first topic is the subject of astronomical studies at many NAI nodes and in astronomy research in general. Many of the observational programs are complemented by efforts in chemical modeling and by the measurement of spectral signatures in laboratory studies. The last two topics have been noticeably understudied and could benefit from enhanced attention.

Several new NAI teams are planning to address these deficiencies. For example, the team at Goddard Space Flight Center (GSFC) proposes to focus on understanding how life could emerge from cosmic and planetary precursors. GSFC specifically proposes to study icy planetesimals and their potential for delivering prebiotic organics to planets. The University of Hawaii team proposes to focus on water in the Universe. Special effort will be put into observations and modeling of the abundance and distribution of water in the interstellar medium, molecular clouds, and circumstellar disks. The University of Arizona roadmap addresses the search for new extrasolar planets; observational studies of protostellar disks; and interstellar organic chemistry from observational, theoretical, and laboratory spectroscopic aspects.

Areas of Relevant Independent Astronomical Research

Astrochemistry studies the raw material of planets and small bodies and therefore indirectly contributes to knowledge about the origin of life. Complex molecules formed in interstellar clouds are unlikely to survive the radiation environment involved in forming a star and protoplanetary system. Rather, it is likely that prebiotic compounds such as amino acids, sugars, and nucleobases are formed on the parent bodies of meteorites in our solar system.

Carbonaceous chondrites offer a record of prebiotic chemistry as found in a planetary body and at a stage that is, in some sense, close to the onset of life. Extensive studies of the isotopic and molecular distribution of matter in these meteorites show they contain a wide variety of organic compounds, some of which are similar to biomolecules. To date, however, very little is known about the conditions and processes that that could have formed, altered, and destroyed organic compounds during the intervening periods of interstellar cloud collapse, star formation, and solar nebular evolution. This paucity of knowledge constitutes a large gap in our understanding of prebiotic chemical evolution. It is the result of various physical and analytical difficulties. One is the difficulty of observing the nebulas of other stellar systems with sufficient spatial resolution. Another is that our understanding of solar processes is restricted by the sporadic nature of the data collected from meteorites, micrometeorites, and interplanetary dust particles, which has meant that nebular conditions are being determined mainly on the basis of theory. For example, evolution of the material in the outer solar nebula during interstellar cloud collapse has been modeled, as has been the distribution of early solar planetesimals. The possible patterns of nebular shock events, as suggested by the composition of meteorite and certain types of interplanetary dust particles, have also been investigated.

Important issues are the distribution of organic compounds in the presolar disk as a function of condensation temperature (in analogy to ices); the transport of meteorites, dust particles, and associated compounds through protoplanetary atmospheres; and the role of the composition of the atmospheres themselves in the chemistry of transport. Although these areas of research have been funded in part by

NASA within the programs on cosmochemistry and origins of the solar system, huge gaps exist in the research, partly owing to the current experimental limitations pointed out above.

Finding. Interesting unanswered questions exist regarding the transport of organic material from the interstellar medium and protostellar disks to planet surfaces.

Recommendation. NASA, other funding agencies, and the research community should devote funding and effort to research in the chemistry of the circumstellar accretion disks that evolve from molecular clouds, considering both gas- and solid-state phases and the delivery of chemical compounds to planet surfaces for an appropriate range of planets and planetary environments.

Areas of Potential Interdisciplinary Interaction

Recent analyses of carbonaceous meteorites show that some of the organic molecules they contain have terrestrial counterparts, such as amino acids and polyols ("sugar alcohols," which resemble, in part, both sugars and alcohols), that may reach such high levels of deuterium enrichment as to suggest a close synthetic relationship to cold, hydrogen fractionation interstellar chemistry. This finding poses the question of the ultimate complexity of interstellar chemistry. The presence of over 130 different, unambiguously identified chemical compounds in interstellar and circumstellar gas suggests that even more complicated species exist. Many of the molecules detected, including methanol, ethanol, ethyl cyanide, dimethyl ether, glycol aldehyde, and methylamine, are, in principle, relevant to presumed prebiotic conditions. The connection between these interesting chemical species and prebiotic chemistry is controversial and is discussed below in "Prebiotic Chemistry and Photosynthesis." These endeavors are a prime area for collaborative efforts by astronomers and chemists.

Finding. There is a need to better understand the complexity of interstellar and circumstellar chemistry as it may relate to the origin of life.

Recommendation. NASA, other funding agencies, and the research community should devote funding and effort to research that helps to complete the molecular inventory and to test reaction pathways. Such research should combine laboratory spectroscopy to establish astronomical signatures; the determination of organic reaction mechanisms; and observational studies.

Missions, Role of Other Agencies

Missions to asteroids, comets, moons such as Titan, and, possibly, Saturn's rings are needed and encouraged to sample and analyze the surface organic chemistry. NASA's New Horizons mission to Pluto and other Kuiper Belt objects may provide access to a good reservoir of minimally altered material from the early solar nebula. These missions will need either more sophisticated in situ analysis, which will require considerable instrument development, or sample return missions.

A large millimeter-wave radio telescope in space would be ideal for extrasolar planetary studies and for probing the chemistry of protostellar disks and presolar nebulas. The technology of millimeter heterodyne spectroscopy has developed sufficiently to make a large radio telescope in space a feasible project. Groundwork has been already laid by the European Space Agency far-infrared and submillimeter Herschel project, which is due to launch in 2007. The Herschel telescope is severely limited, however, by the small diameter of the radio dish (3.5 m) and therefore does not possess the angular resolution to unravel the details of chemical processes in presolar disks. A much larger diameter telescope is needed, perhaps as a piggyback on another mission.

BOMBARDMENT

Current Work and Gaps

Large-scale bolide impacts can have important and sweeping effects on the evolution of a planet as well as the organisms that may inhabit it. In Earth's history, planetoid, asteroid, and comet impacts are thought to have played a role in stark reductions of biodiversity perhaps every 100 million years on average, and there are records of a number of bombardment clusters, or periods of multiple impacts.

The Moon itself was created by a massive bombardment event: the glancing collision of Earth with a Mars-sized object during the late stages of the accretion process. An associated issue is whether stable planetary obliquities require a large moon. If they do, and if the formation of a large moon is inherently unlikely, then most earthlike planets could experience chaotically varying obliquities. It is not clear that a high obliquity would actually make an earthlike planet uninhabitable. Continents located near the equator would experience an unusual seasonal cycle, with two summers and two winters each year, but their climates would not be subject to the extremes of temperature that would occur at high latitudes. Surface temperatures over an equatorial continent could remain temperate, even at very high obliquity. In any case, whether a moonless planet's obliquity would vary chaotically depends on the spin rate and initial obliquity, as well as on the masses and orbital periods of the other planets. If Earth's spin period were less than about 12 hours, its obliquity would vary regularly (and with small amplitude), just as it does today. We have no way of predicting what Earth's initial spin rate would have been if this particular large impact had not occurred, but there is no reason to believe that it would have been as slow as today. The committee concludes that it is extremely difficult to predict whether other earthlike planets will be in the chaotic obliquity regime, so we cannot yet determine whether this is a widespread problem for planetary habitability. Even if it is, it does not appear to be one that would preclude the existence of complex life.

The early history of the inner solar system witnessed large basin impacts on Earth (causing the formation of the Moon), on the Moon (South Pole-Aitken Basin and others), and on Mars (Hellas and Argyre). Both theoretical models and analysis of various isotope systems indicate that the bulk Earth accreted within the first 100 million years of solar system history. This means that the main accretion process was complete by ~4.4 billion years ago. This date is in accord with the oldest lunar samples, which have crystallization ages of 4.44 billion years. We know from other Moon rocks, however, that the Moon was still being hit by large impactors as late as 3.8 billion years ago. The six manned Apollo missions between 1969 and 1973 collected soil and rock from the vicinity of three large lunar impact basins, including Mare Imbrium—a 1,200-km-diameter impact feature on the near side of the Moon. Many of the rocks collected from these impact basins have crystallization ages near 3.8 billion years. Prevailing scientific opinion thus holds that all of the terrestrial planets were subjected to an extended bombardment by late-arriving planetesimals that persisted long after the main accretion period had concluded. This period of late heavy bombardment has been extrapolated back in time beyond the terrestrial record to infer essentially continuous planetary sterilization by heavy impacts, known as the Hadean era.

Other workers have questioned this paradigm,[33] suggesting the lunar record may only reflect a pulse of late delivery of material roughly 4 billion years ago that, while intense, did not obliterate the surface

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[33] G. Ryder. 2003. "Bombardment of the Hadean Earth Wholesome or Deleterious?" *Astrobiology* 3(1).

or any budding life forms and may have created environments hospitable to the emergence of life. Such a pulse could have occured, for example, as a result of a late collision between two planet-sized bodies. The available lunar rock record does not allow us to distinguish between the two competing hypotheses (although some proponents of the late cataclysm hypothesis insist that it does).

We know that the impactor that formed the Imbrium crater on the Moon must have been ~100 km in diameter. An object this size hitting early Earth would have created a transient rock vapor atmosphere that would have radiated energy both upward and downward and would ultimately have vaporized the top 100 m of the oceans. The rock vapor itself produced surface temperatures of ~2000 K for approximately one month.[34] The steam atmosphere persisted for roughly 1,000 years.[35] Thus, the surface environment may have been effectively sterilized by such bolide impacts. Some organisms could have survived these catastrophes, however, especially those living in midocean ridge hydrothermal vent systems, deep below the seafloor, or deep beneath a continental surface. In any case, large bolide impacts would have selected for hyperthermophilic organisms or those with robust heat shock response, that is, organisms with optimum growth temperatures exceeding 80ºC. This, in turn, provides a possible explanation for the apparent clustering of hyperthermophiles near the base of the evolutionary rRNA tree. The committee notes that this clustering and the timing of the base of the tree are themselves controversial.

Carbon isotopic data have been cited as evidence for the emergence of life back to ~3.8 billion years,[36] suggesting that life may have managed to arise during the late heavy bombardment period. This evidence, however, is indirect and has been strongly challenged, so it remains very controversial. Some authors[37] believe that isotopically light carbon could have abiotic origins. They specifically suggest that Rosing's Isua kerogens may be meteoritic in origin. The role of large bolide impacts in life's origins is therefore intriguing but not well constrained by data. Was such a bombardment necessary rather than inimical? Or did such a heavy bombardment not exist for a prolonged period, and, if not, what does that say about the epoch of the formation of the first life? At present, the evidence for the time of the emergence of life is sufficiently weak that it is constrained only to any time between 4.3 and 3.3 billion years ago. We need better constraints, and at least some of these constraints involve bolide impacts.

Finding. The question whether the late heavy bombardment was an isolated episode or just a gradual, continuous decline in bolide impact frequency and intensity is unresolved, but the answer has important implications for both the timing of life's origin and for the types of organisms that might have existed at early times.

Bolide impacts are also thought to be responsible for the delivery of the current volatile veneer, especially water, because most of the light elements are inferred to have been lost in the large-scale impact that created the Earth-Moon system. At the same time, bolide impacts into the ocean will vaporize large quantities of water, as noted above. In the case of the terrestrial planets, most of the water may well have been brought in the form of hydrous minerals or adsorbed water, but the contribution

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[34] N.H. Sleep, K.J. Zahnle, J.F. Kasting, and H.J. Morowitz. 1989. "Annihilation of Ecosystems by Large Asteroid Impacts on the Early Earth." *Nature* 342: 139-142.

[35] Ibid.

[36] M.T. Rosing. 1999. "^{13}C-depleted Carbon Microparticles in >3700-Ma Sea-floor Sedimentary Rocks from West Greenland." *Science* 283: 674-676.

[37] For example, R. Schoenberg, B.S. Kamber, K.D. Collerson, and S. Moorbath. 2002. "Tungsten Isotope Evidence from ~3.8-Gyr Metamorphosed Sediments for Early Meteorite Bombardment of the Earth." *Nature* 418: 403-405.

from comets remains uncertain. The three Oort Cloud comets measured thus far show a deuterium to hydrogen ratio about twice the value found in Earth's oceans. On the other hand, near-surface water on Mars appears to have the same isotopic ratio as the comets, suggesting that both Mars and Earth received some cometary endowment. On Earth, the cometary water would have been thoroughly mixed with water from the planet's interior as a result of geological activity (eruption, subduction). On smaller Mars, the hydrosphere has remained isolated from the lithosphere, as demonstrated by studies of the oxygen isotopes in martian meteorites. The actively discussed alternative is delivery by asteroids.[38] Substantial work on the delivery and evolution of water is proposed by the new NAI nodes, at GSFC and the University of Hawaii, as remarked above.

Recent work has shown that a number of light molecules can survive the impact process and that original textures can survive unmelted.[39] The material in certain impact sheets is as much as 30 percent extraterrestrial. This supports the notion that a substantial inventory of organics was delivered from exogenous sources. The role of this material in the origin of life is controversial, as noted in the section "Prebiotic Chemistry and Photosynthesis."

While the influence of impacts on the origin of life remains largely unknown, there is little doubt that one or more impacts had a deleterious effect on some species at the K-T boundary. An impactor of 10-15 km diameter hit Earth on the Yucatan Peninsula of Mexico, near the present town of Chicxulub, contributing to a major mass extinction of species, including the dinosaurs. Another perspective is that the demise of the dinosaurs opened new ecological niches in which mammals flourished, leading, eventually, to humans. In their groundbreaking paper on this subject, Alvarez et al.[40] suggested that the K-T impact would have raised a global dust cloud that reduced light levels below the threshold for photosynthesis for up to 6 months. Surface temperatures could also have plummeted tens of degrees, although the temperature decreases would have been moderated in regions near the oceans. These cold conditions may have been preceded by a period of intense heat lasting several hours, caused by radiation from finely divided impact ejecta as they reentered Earth's atmosphere.[41] Among the barriers to advancement of research on impacts are the erasure of Earth's early crust (so that no early impacts are preserved) and the lack of definitive age dates for many large lunar impacts and for those on the martian surface.

Areas of Relevant Independent Astronomical Research

Statistically, large impacts must have continued sporadically. Monitoring of near-Earth objects (NEOs) is intended to give warning of such an event. Accurate monitoring of the trajectories of such objects may also help shed light on their points of origin within the asteroid belt and on the processes that deflected them into their current trajectories. Understanding how the asteroid belt is evolving today may help us better understand what it may have looked like in the distant past, when life was getting started on Earth. These surveys will help to constrain the statistics of past impacts. Ongoing observa-

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[38] A. Morbidelli, J. Chambers, J.I. Lunine, J.M. Petit, F. Robert, G.B. Valsecchi, and K.E. Cyr. 2000. "Source Regions and Timescales for the Delivery of Water to the Earth." *Meteoritics and Planetary Science* 35: 1309-1320.

[39] E. Pierazzo and C.F. Chyba. 1999. "Amino Acid Survival in Large Cometary Impacts." *Meteoritics and Planetary Science* 34(6): 909-918.

[40] L.W. Alvarez, W. Alvarez, F. Asaro, and H.V. Michel. 1980. "Extraterrestrial Cause for the Cretaceous-Tertiary Extinction." *Science* 208: 1095-1108.

[41] H.J. Melosh, N.M. Schneider, K.J. Zahnle, and D. Latham. 1990. "Ignition of Global Wildfires at the Cretaceous/Tertiary Boundary." *Nature* 343: 251-254.

tional and theoretical planetary astronomy work on the dynamics of small bodies in the solar system, including the Kuiper Belt, may be relevant both to the nature of NEOs and to the origin and nature of the late heavy bombardment.

Areas of Potential Interdisciplinary Interaction

Geological work is needed to identify ejecta material in the rock record and to understand the geochemical and textural features that might unambiguously distinguish impacts from other phenomena. Well-known examples of likely geological structures are located at Chicxulub (where there is some drilling already), Sudbury, Vredefort, and Lake Acraman.[42] In particular there should be detailed examination of the recent controversial evidence for a putative impact at the Permian/Triassic boundary.[43,44] There are well-exposed structures in China and Antarctica, but the antarctic sites are relatively inaccessible. Recent work on tungsten anomalies suggests reworked sediments from Australia and Greenland contain material of extraterrestrial origin.[45] Further work needs to be done on various rare earth and metal anomalies other than iridium that can be clearly linked to extraterrestrial impactors. Presently, evidence that connects biological mass extinction and radiation to impactors is largely circumstantial. This is an area that could be improved by integrating advances in geochronology with biostratigraphy. There is evidence for the survival of organic compounds in shock heating.[46] There should be laboratory studies of impacts onto organic-bearing materials of different construction—wet, dry, a range of compositions—over a range of energies. These investigations should study both the destruction and modification of organic materials. Work could be done to incorporate a shock heating scale into a survivability zone surrounding large impacts. One issue is whether this zone varies depending on its material: water, permafrost (as one might find on Mars), ice (as one might find on Europa), or solid rock. Known organism survivability data from nuclear test programs are pertinent.

Recommendation. NASA, other funding agencies, and the research community should devote funding and effort to geological and geochemical work to identify ejecta material in the rock record surrounding large impact basins. In particular, it will be necessary to study existing evidence and search for additional signs of impact at the Permian/Triassic boundary. There is a need to document various anomalies in noble gas isotopic signatures and rare earth and other metal abundances that can be clearly linked to extraterrestrial impactors.

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[42] K. Grey, M.R. Walter, and C.R. Calver. 2003. "Neoproterozoic Biotic Diversification: Snowball Earth or Aftermath of the Acraman Impact?" *Geology* 31(5): 459-462.

[43] L. Becker, R.J. Poreda, A.G. Hunt, T.E. Bunch, and M. Rampino. 2001. "Impact Events at the Permian-Triassic Boundary: Evidence from Extraterrestrial Noble Gases in Fullerenes." *Science* 291: 1530-1533.

[44] A.R. Basu, M.I. Petaev, R.J. Poreda, S.B. Jacobsen, and L. Becker. 2003. "Chondritic Meteorite Fragments Associated with the Permian-Triassic Boundary in Antarctica." *Science* 302: 1388-1392; L. Becker, R.J. Poreda, A.R. Basu, K.O. Pope, T.M. Harrison, C. Nicholson, and R. Iasky. 2004. "Bedout: A Possible End-Permian Impact Crater Offshore of Northwestern Australia." *Science* 304: 1469-1476.

[45] R. Schoenberg, B.S. Kamber, K.D. Collerson, and S. Moorbath. 2002. "Tungsten Isotope Evidence from Approximately 3.8-Gyr Metamorphosed Sediments for Early Meteorite Bombardment of the Earth." *Nature* 418(6896): 403-405.

[46] E. Pierazzo and C.F. Chyba. 1999. "Amino Acid Survival in Large Cometary Impacts." *Meteoritics and Planetary Science* 34(6): 909-918.

Missions, Role of Other Agencies

For those interested in the timing and pace of early biological evolution, it is important to know whether "impact frustration" impeded the origin of life and, if it did, when this period of high impact rate came to an end. There is a need to better study the lunar rock samples already in hand. Molten spherules resulting from impacts may be scattered over much of the lunar surface; accurate dating of such isolated spherules could assign an impact date to each spherule examined. The resulting age distribution, if it is sufficiently accurate, could show the dates of all major impacts, not just the three impacts that have so far been precisely dated from the Apollo and Soviet sample-return missions.[47]

The best way to resolve this issue would be to return to the Moon and to acquire more lunar samples.[48] Having a broader database that covered a larger fraction of the lunar surface would allow us to decide whether the late bombardment was continuous or a one-time event. A key location to sample and date is the South Pole-Aitken Basin on the lunar farside. This is not only the largest impact basin on the Moon (and in the solar system), but it is also the oldest. Rock fragments from South Pole-Aitken Basin and nearby smaller but later basins will address fundamental questions of inner solar system impact processes and chronology. Key measurements would include radiometric ages of impact-melt rocks from the basin-forming event and chemical, isotopic, and petrologic investigations of igneous and volcanic rocks from the deep crust and upper mantle of the Moon. Samples of materials produced by this enormous impact event will help decipher the following: timing and effects of early, large impacts on planetary structure, differentiation, and orbital dynamics; the depth to which the impact penetrated (from sample composition and mineralogy); and composition and origin of the impacting object (through trace-element and isotopic analyses). We need to determine the energy, velocity, and mass of the projectiles to extrapolate from impact conditions on the Moon (with its lower gravity) to the conditions expected on Earth. Determining the composition of the asteroid or comet would also be valuable. The age of the South Pole-Aitken Basin will constrain the period of late, heavy bombardment and will provide a critical test of the hypothesis that the heavy bombardment was punctuated by a cataclysm, or spike, in the flux of large impactors. A complete program for the science goals of an exploration of South Pole-Aitken Basin is given in the report *New Frontiers in the Solar System*.[49] The committee notes that the proposed South Pole-Aitken Basin sample return mission, dubbed "Moonrise," was selected for a detailed mission concept study in July 2004. This investigation proposes to land two identical landers on the surface near the Moon's south pole and to return over 2 kg of lunar materials from a region of the Moon's surface believed to harbor materials from the mantle.

The placement of broadband seismometers on the Moon could reveal the crustal structure of the basins and the intact lunar crust. The impact physics needs to be modeled with actual target structure information and realistic projectiles.

Obtaining lunar samples may become easier in light of the President's plan, announced in early 2004, to return astronauts to the Moon no later than 2020. Studies should also continue of the lunar rock sample already collected. We also need age dates for bolide impacts on Mars; this could give a second defined chronology for major impact events such as Hellas and Argyre in conjunction with events on

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[47] N.E.B. Zellner, P.D. Spudis, J.W. Delano, D.C.B. Whittet, and T.D. Swindle. "Impact History of the Apollo 16 Landing Site from Analysis of Impact Glasses." *Journal of Geophysical Research*, in review.

[48] National Research Council (NRC). 1997. *Lessons Learned from the Clementine Mission*. Space Studies Board. National Academy Press, Washington, D.C., p. 42.

[49] NRC. 2003. *New Frontiers in the Solar System: An Integrated Exploration Strategy.* Space Studies Board. The National Academies Press, Washington, D.C., pp. 59-61.

Earth and the Moon. Better Mars impact age dates should also become attainable in the context of the President's new plan.

Sample return by Stardust[50] from Comet Wild 2 in January 2006 will give fresh insight into the composition of comet material that might be delivered to Earth. The ejection of comet interior material expected from the Deep Impact mission,[51] scheduled for July 2005, will allow measuring the composition of the interior of the crater and its ejecta in Comet 9P/Tempel 1.

An important complement to spacecraft missions is terrestrial drilling programs. Relevant activities are supported by the NAI, Japanese research organizations, and the Agouron Institute, a nonprofit research organization in Pasadena and La Jolla that sponsors innovative research in geobiology.

Recommendation. NASA should develop missions that return to the Moon to acquire more lunar samples to help determine when the "impact frustration" of life's origin ended by sampling more sites—particularly sites that are older than the six sites sampled by the Apollo astronauts and the three sites sampled by the Soviet robotic sample-return missions and, especially, the oldest and largest impact basin on the Moon, the South Pole-Aitken Basin.

PREBIOTIC CHEMISTRY AND PHOTOSYNTHESIS

Current Work and Gaps

A major unsolved problem of astrobiology is the transition from prebiotic chemistry to life. This issue abuts with astronomy because, as outlined in the section "Interstellar and Protostellar Nebular Chemistry," accretion from the interstellar medium to protostellar systems and thence to planet surfaces is one possible source of the biomolecules that may be the raw material from which life arose. An important question faced by the field of prebiotic chemistry is whether astrochemistry is a contributor to the origination of life or a detriment to it. Over 130 compounds have been detected to date (see the section "Interstellar and Protostellar Nebular Chemistry"), and the list continues to grow as the sensitivity of detection improves. Embedded within the list are numerous compounds of clear biological interest—but it remains unclear whether these compounds could have been transported intact to the surface of early Earth in significant amounts and, even if they were, whether they would have been important in subsequent chemical transformations leading to the origination of life.

The central unsolved problem of prebiotic chemistry is that all such experimentally observed syntheses result in complex mixtures of compounds—tarry gunk, in short. In contrast, replicating chemical systems would seem to require for their emergence simple mixtures of a few relatively pure compounds. The low-temperature ion-molecule chemistry that mediates astrochemical synthesis confronts kinetic barriers to some reaction pathways in the low temperature of the interstellar medium but nevertheless generates a large range of compounds formed from small numbers of carbon, hydrogen, nitrogen, and oxygen atoms.

Until interstellar chemistry is better understood, the problem of combinatorial chemical complexity will not be fully solved. This problem is not unique to astrochemistry. The classic example in prebiotic chemistry is the formose reaction, in which formaldehyde under alkaline aqueous conditions spontaneously forms sugars—not just the ribose needed to make RNA but every possible isomer of every sugar,

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[50] "Stardust: NASA's Comet Sample Return Mission." Available at <http://stardust.jpl.nasa.gov/>. Accessed April 27, 2005.
[51] "Deep Impact." Available at <http://deepimpact.jpl.nasa.gov/>. Accessed April 27, 2005.

sugar alcohol, and sugar acid. The synthesis of mixtures of stereoisomers is merely a particularly difficult subset of this larger problem: the synthesis of intractable mixtures in which the biologically desirable compounds are but a tiny proportion of the material.

Why is the synthesis of complex mixtures such a problem? Consider the problem of the prebiotic synthesis of a genetic polymer such as RNA. We know from molecular studies of cellular biochemistry, including the structure of the ribosome, that RNA must have played a key role at some stage in the early evolution of life, but the origins of the RNA world remain obscure, and the synthesis of a polymer of the complexity and chemical fragility of RNA remains a daunting problem, made much worse by the fact that an RNA-like polymer assembled from nucleotides formed with a mixture of different sugars would be of little use. If the presence of L-isomers in the prebiotic world had the same effect it does in current biochemistry, even the presence of the ribose stereoisomer L-ribose (instead of the normal D-ribose) would be fatal, as such isomers are known to poison nonenzymatic, template-directed RNA replication in laboratory studies. The presence of other sugars would lead to the synthesis of polymers with different sugars at different positions in the polymer chain. Such molecules are probably not replicable. Even if they were, this positional information could not be copied, making the emergence of a self-replicating autocatalytic system difficult, if not impossible. There is no known pathway that would lead to the prebiotic synthesis of chemically homogeneous nucleotides.

To address the problem of the origin of life in a credible way, the difficulties associated with accreting interstellar matter must be tackled and not ignored. The problem has generated two philosophically distinct responses. One camp has been convinced that further study would reveal chemical pathways, catalysts, and purification and concentration processes that would resolve the issue, such that the formation of undesirable mixtures could either be avoided in the first place or resolved subsequently. An example might be the recent discovery by Ricardo et al.[52] that the addition of borate minerals favor the synthesis of pentose sugars, including ribose. The second response has been to argue that processes leading to such complex mixtures were not relevant to the origin of life, and that self-organizing autocatalytic and/or surface-catalyzed processes starting from the simplest, most basic precursors (H_2O, CO_2, CH_4, NH_3, and so forth) would produce primitive metabolic systems, which over time would grow in complexity until biomolecules complex enough to give rise to cellular life were generated in situ.

Neither approach has fully solved the problem, but in recent years several advances have been made through novel experimental approaches. There is a growing appreciation of the useful potential of mineral surface catalysis, and its coordination with ions in solution, for both the primary synthesis of small-molecule building blocks and their subsequent reaction to generate larger and more complex molecular structures. It is clear that there is a great deal to be done in this area and that many new ideas will be needed to solve this central problem. The NAI could play a crucial role by fostering creative new approaches to this problem, for until it is solved we will not know the relevance of astrochemistry to the origin of life.

Finding. There is no known pathway that would lead from complex interstellar molecules to the prebiotic synthesis of chemically homogeneous nucleotides.

Ultimately, life requires a continuous input of chemical energy and a mechanism for forming the required building blocks from simple precursors. This process must have begun fairly early in the history of Earth's biosphere. Oxygenic photosynthesis is currently the predominant source of energy

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[52] A. Ricardo, M.A. Carrigan, A.N. Olcott, and S.A. Benner. 2004. "Borate Minerals Stabilize Ribose." *Science* 303: 196.

and of reduced carbon compounds for life on Earth. When and how did this capacity emerge? Presumably it involved a progression of simpler steps that preceded the highly complex system of today's oxygen-producing phototrophs and the structured biosphere that is dependent on them. We would like to know more about the possible chemistries and steps leading to the development of oxygenic photosynthesis and the corresponding changes in the biosphere that occurred during this transition.

A terrestrial planet offers opportunities for an additional universe of chemistry not available in interstellar space or protostellar nebulae: chemistry in aqueous solution. Oceans, lakes, and ponds could contain a suite of organic chemicals and the ionic residues of weathered minerals. This mixture of organic compounds, cations, and a flux of photons of appropriate wavelengths to excite chemical bonds could produce new compounds, some of which might be useful to early life forms; other compounds might eventually return to the atmosphere or be decomposed in another part of the ocean. For example, tars and recalcitrant materials might be deposited on exposed surfaces, where they could be photodegraded to small molecules that could return to the upper atmosphere to participate anew in polymerization reactions. An alternative route might involve chemical processes at hydrothermal systems. Heat and pressure at volcanic spreading zones could provide free energy and catalytic conditions for very different reactions than might occur at the ocean surface. Such a system of linked processes located in different parts of the planet might form prebiotic chemical cycles of the biogenic elements that could provide a continuous turnover of feedstocks for early life forms.

Recommendation. NASA, other funding agencies, and the research community should devote funding and effort to better understand how carbon, nitrogen, and sulfur cycles might work on a prebiotic planet with an ocean and an incident flux of photons and particles, and how these cycles might couple with primitive life forms to provide feedstocks for their formation and energy for their metabolism.

A related issue is the production of the thermodynamic gradients that are required to sustain metabolic processes. The thermodynamic gradients that drive the present biosphere are largely sustained by atmospheric oxygen, itself a product of photosynthesis. The photosynthetic energy initially used in the synthesis of compounds can be remobilized by reoxidizing the compounds or products derived from them at locations and times remote from the initial synthesis. Even the metabolism of deep-sea vent communities now depends on the supply of oxygen from photosynthesis. While the concentration of oxygen in the atmosphere has remained stable over millions of years, the metabolic flux of oxygen is sufficient that the total complement of O_2 turns over in about 1,200 years[53]—an instant in geologic time. This illustrates that an active biosphere would rather quickly consume vestigial thermodynamic energy gradients present in the original charge of organics from space, and primitive metabolic systems would ultimately become dependent on a renewable energetic system. Photons from the central star are the most plausible source of such energy, and photosynthesis of some form is likely to have started early in the history of our biosphere.

While it is natural to think of photosynthesis as a biological process, it may be useful to consider that light-driven synthetic reactions may have preceded life. The solution-phase photochemical transformation of organic molecules, especially in combination with ions of transition elements in seawater, could have been driven by the absorption of photons of visible light from the Sun or other host star. Inputs of

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[53] M. Bender, T. Sowers, and L. Labeyrie. 1994. "The Dole Effect and Its Variations During the Last 130,000 Years as Measured in the Vostok Ice Core." *Global Biochemical Cycles* 8: 363-376.

light energy could thus have driven cycling between different redox states of metal ions and organic compounds in a prebiotic ocean. The central role of iron and manganese in the molecular mechanisms used by current photosynthetic organisms may give clues to the prebiotic chemistries that preceded biological photosynthesis.

Photosynthetic mechanisms of the vast array of photosynthetic organisms of Earth's biosphere and the evolutionary relationships between these mechanisms has been a major area of research for many decades, an area that beautifully exemplifies the integration of disciplines, from solid state physics through biochemistry to ecology and Earth-system science. Arizona State University, one of the first teams of the NAI, focused on the evolution of photosynthesis and its role in Earth's history. The importance of understanding the photochemistry that could occur on a prebiotic planet cannot be understated.

Areas of Relevant Independent Astronomical Research

Interstellar chemistry itself may offer some alternative perspectives on the problem of tars and recalcitrant matter that may not be conducive to the origin of life. Unlike typical organic reactions, which take place at room temperature or higher, most chemical reactions in interstellar gas must take place at between 10 K and 100 K. Such reaction barriers will limit the pathways normally available at higher temperatures. In this sense, interstellar chemistry is more selective than terrestrial chemistry. One example is found in the interstellar isomers that have the general chemical formula $C_2H_4O_2$. While methyl formate ($HCOOCH_3$) is a very abundant molecule in dense clouds with a spectrum that exhibits hundreds of lines, glycolaldehyde ($CHOCH_2OH$) and acetic acid (CH_3COOH) are barely detectable in the same regions. Glycoaldehyde is a good sugar precursor, but methyl formate has no obvious utility in biochemistry.

Finding. The kinetically controlled chemistry in the interstellar medium may lead to selection of products that would not be favored under conditions of thermodynamic control.

In addition to better understanding the inventory of compounds available from the interstellar medium, much work must be done to understand what fraction of these compounds survives the accretion processes into protostellar nebulae and thence onto planetary surfaces and how long they survive on the planetary surface. The first two challenges are in the realm of astronomy, the last is undoubtedly in an interdisciplinary realm because it requires an understanding of photochemistry under the influence of the host star flux and myriad other physical and chemical processes.

The fundamental question is whether organic compounds present in interstellar clouds contribute to the organic chemistry of presolar nebulas and then, perhaps in a series of stages, to a young planet's inventory of organic compounds conducive to the formation of life. These issues overlap and draw on many of the topics discussed throughout this document. Questions of material transport and processing (see the section "Interstellar and Protostellar Nebular Chemistry") are amenable to study by computational modeling at a variety of stages, from the condensation of molecular clouds into presolar nebulas to the impact of comets onto inner rocky planets (see the section "Bombardment"). Laboratory studies can also contribute at a variety of stages. Spectra measured in the laboratory are essential for the interpretation of radioastronomy observations (see the section "Interstellar and Protostellar Nebular Chemistry"), and laboratory studies of chemical transformations during high-velocity impacts provide essential data for the modeling of cometary impact processes (see the section "Bombardment"). Infrared spectra data of dusty circumstellar disks are already beginning to provide interesting information.

Recommendation. NASA, other funding agencies, and the research community should devote funding and effort to carry out coordinated theoretical, laboratory, and observational studies of interstellar chemistry, accretion, condensation, and transport processes to determine the inventory of compounds that was delivered to a young planet, when they were available, where they were available, and in what quantities.

Areas of Potential Interdisciplinary Interaction

Even if the inventory of astrochemical compounds on the surface of a young planet could be determined, the main challenge is to determine the chemistry that would lead to life. There are relatively few established chemists working in the area of prebiotic chemistry, and yet these few have recently made important advances, such as the synthesis of pyrimidines,[54] of ribose,[55] and of alternatives to RNA.[56] The committee feels that encouraging creative chemists to enter this field and bring in new approaches is the only way for progress to be made—certainly, abandoning the field will not accelerate progress. This work should complement, not compete with, efforts to explore the chemistry of environments such as cometary ice crusts, which may shed light on early nebular chemistry.

Consideration could also be given to the assembly of molecules by mechanisms other than gene mutation.[57] There is potential here to explore fundamental principles relating to solid-phase biochemistry (e.g., using clay minerals) on the one hand and solution chemistry on the other and to explore how the galactic environment might impact molecular diversity using synthesis routes other than DNA. This regime might best first be explored with models. There should be support for studies to explore how diversity could be generated within prenucleotide chemical reactions and how nongenetic selection might take place, perhaps through basic structural principles such as energy and architectural constraints. The power of molecular biology, including directed evolution of catalytic RNAs and in vitro synthesis of proteins, could be leveraged in this context.

Recommendation. NASA and other interested agencies should develop and support programs that encourage basic research on prebiotic chemistry.

Among the interdisciplinary issues relevant for prebiotic chemistry are the effects of photochemistry on the production of biogenic compounds; physical and chemical processes such as evaporation, absorption on mineral surfaces, polymerization within membrane vesicles, and photopolymerization on ices that would concentrate the abundances of key precursors to life; and studies of energy inputs that would establish the thermodynamic gradients that lead to life.

More attention should be given to phosphorous chemistry as well as organic chemistry. Phosphorus is key to life as we know it, although relatively obscure in terms of its astronomical nucleosynthesis. Ions of many elements now essential for life may have played key catalytic roles in primordial chemistry. Transition elements (iron, manganese, copper, and cobalt) could have played important roles in redox

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[54] J.P. Ferris, R.A. Sanchez, and L.E. Orgel. 1968. “Studies in Prebiotic Synthesis. III. Synthesis of Pyrimidines from Cyanoacetylene and Cyanate.” *Journal of Molecular Biology* 33(3): 693-704.

[55] A. Ricardo, M.A. Carrigan, A.N. Olcott, and S.A. Benner. 2004. “Borate Minerals Stabilize Ribose.” *Science* 303: 196.

[56] A. Eschenmoser. 1994. “Chemistry of Potentially Prebiological Natural Products.” *Origins of Life and Evolution of the Biosphere* 24: 238-240.

[57] D.E. Ingber. 2000. “The Origin of Cellular Life.” *BioEssays* 22: 1160-1170.

reactions and could have played a role similar to that currently played by oxygen in producing thermodynamic gradients.

Astronomical studies can help to constrain the abundance and distribution of critical trace elements (phosphorus, iron, manganese, copper, and cobalt) and the spectrum and intensity of light from a variety of host stars early in their evolution, all of which could affect the processes of photochemistry described here.

To further these studies, stronger links need to be developed between astrochemistry and organic chemistry to evaluate the mechanisms of gas-phase chemistry, gas-phase/surface chemistry, radical chemistry, and photochemistry in the production of interstellar molecules. Interstellar chemists and planetary scientists need to interact closely in order to make better connections between interstellar, cometary, and meteoritic molecular abundances, including isotope ratios. Better connections need to be made between chemists and those modeling planetary disks in order to properly evaluate transport of the chemical products to the planet surface.

Finding. Chemists, atmospheric scientists, biologists, and geophysicists need to interact in order to understand the chemical environments and geochemical cycles of carbon, oxygen, nitrogen, sulfur, phosphorus, and metal ions on prebiotic Earth and how these processes might be related to the formation of biomolecules and primitive metabolic systems.

Recommendation. NASA, other funding agencies, and the research community should devote funding and effort to pursue studies of abiotic photochemistry in concert with astronomical sources of trace elements and energy to determine whether trace elements play a role in photochemical sources of organic compounds and/or high-energy activated compounds.

One distinguishing characteristic of terrestrial life is that the function of biopolymers relies on the exclusive one-handedness of their monomeric components—that is, all protein amino acids have an L-configuration, while sugars in RNA, DNA, and polysaccharides have a D-configuration. Substitutions along the polymers with enantiomers of opposite handedness usually result in loss of function. The unknown origin of this homochirality has been the subject of debate, speculation, and studies for well over a century since Pasteur first elucidated the chirality concept. The scope and rationale of these investigations have paralleled a more general query about the origin of life: Was biological homochirality the product of prebiotic processes or the result of selection brought about by life itself? Was it due to choice or chance? Was it at first broad-scaled or of limited extent?

A trait so pervasive as to define life processes has elicited many universal theories to explain the underlying physical process that could have caused the original chiral symmetry to break. Chiral effects due to randomness and chance; parity violation of subatomic weak interactions, such as in β-decay; circular dichroism toward photolyzing light;[58] and magnetochiral dichroism of irradiated chiral molecules in magnetic fields[59] have been invoked in this context, and some of them have been extensively studied. The finding in meteorites of some amino acids carrying an excess of the L-enantiomer, the same form as in terrestrial protein,[60] has further encouraged the idea of a prebiotic origin for chiral asymmetry.

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[58] J. Bailey, A. Chrisostomou, J.H. Hough, T.M. Gledhill, A. McCall, S. Clark, F. Menard, and M. Tamura. 1998. "Circular Polarization in Star Formation Regions: Implications for Biomolecular Homochirality." *Science* 281: 672-674.

[59] G.L.J.A. Rikken and E. Raupach. 2000. "Enantioselective Magnetochiral Photochemistry." *Nature* 405: 932-935.

[60] J.R. Cronin and S. Pizzarello. 1997. "Enantiomeric Excesses in Meteoritic Amino Acids." *Science* 275: 951-955.

Finding. Star-forming regions could provide circular polarization and so, indirectly, relate to the origin of biomolecular homochirality.

Recommendation. NASA, other funding agencies, and the research community should devote funding and effort to pursue the unanswered questions about the extent to which the astrophysical environment could have fostered the breaking of symmetry in prebiotic organic pools.

Missions, Role of Other Agencies

NASA flight missions will contribute by returning comet samples, and sophisticated in situ chemical analysis of icy bodies left over from the formation of the solar system will tell us a great deal about the sources and processing of organic compounds during the early history of the solar system.

Both the Terrestrial Planet Finder (TPF) and the Darwin mission will attempt to find earthlike planets and examine them for evidence of life. Atmospheric oxygen, in particular ozone, O_3, is the most easily recognizable sign of life on Earth that could be identified remotely. The evidence that this oxygen is biogenic would be strongly bolstered by detecting the presence of a reduced biogenic gas, such as methane. There are substances that could be detected that are associated with life on Earth, such as H_2O and CO_2, but that need not be biogenic. The issue of false positives remains a serious one.

There is also a potential puzzle about the delay in developing an oxygen atmosphere on Earth. Some photosynthetic organisms may have been operating as early as 3.7 billion years ago,[61] yet Earth did not develop an oxygen atmosphere as a result of photosynthesis for another approximately 1.2 billion years or so. This raises interesting questions about the biological and geological processes that contributed to this lag. The prevailing theory is that the crust is a very efficient repository for oxygen and that time is required to oxidize soluble Fe^{2+} to insoluble Fe^{3+} oxides. The crust eventually gets saturated and further oxygen production increases the atmospheric oxygen. An important question is, then, When is O_3 a sign of photosynthesis and when of geological processes? This question is interesting in its own right but also has significant repercussions for the design of TPF and Darwin. It is important to consider other possible atmospheric gases (perhaps CH_4 and NO_2) that might indicate the presence of a photosynthetic biosphere on another planet with a geological and biological history different from that of Earth.

Sample return by the Stardust mission and analysis of the comet impact by the Deep Impact mission (see the section "Bombardment") will also give insight into prebiotic chemistry.

Another relevant body for research on prebiotic chemistry is Titan, whose atmosphere is comparable in column density to that of Earth and is bathed in solar photons—albeit at 1 percent the flux density of Earth. The atmospheric chemistry of Titan is dominated by photochemical reactions involving N_2 and CH_4 and the consequent production of complex hydrocarbons and nitriles. Since some CO_2 exists in the atmosphere, Titan's atmosphere is often thought of as intermediate between that of Mars and that of primordial Earth, implying abiotic organic synthesis, which is relevant for the origin of microbial life. Models of the photochemistry of the Titan atmosphere and its interaction with surface processes is an active area of research. Because the input of stellar radiation is likely to be irregular owing to frequent flares in young and low-mass stars, one goal would be to study the stochastic chemistry of a simple N_2-CO_2 atmosphere (including relevant by-products) and its attenuation properties, in order to estimate the surficial and suboceanic flux distribution (in wavelength and time) of a prebiotic

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[61] M.T. Rosing and R. Frei. 2004. "U-rich Archaean Sea-floor Sediments from Greenland—Indications of >3700 Mya Oxygenic Photosynthesis." *Earth and Planetary Science Letters* 217: 237-244.

terrestrial planet. When fully analyzed, the data collected during the passage of the Huygens probe of the Cassini mission through Titan's atmosphere in January 2005 will offer an initial test of models.

Recommendation. NASA should carry out missions to asteroids, comets, moons such as Titan, and, possibly, Saturn's rings to sample and analyze the surface organic chemistry.

MOLECULAR EVOLUTION IN A VARIABLE ASTRONOMICAL CONTEXT

Current Work and Gaps

As part of their perspective, the University of Washington NAI team asks whether mass extinctions are "fertilizer or poison or both in the garden of complex organisms?" The issue is much broader and more fundamental than mass extinctions.

The life processes we witness on Earth now are daunting in their complexity. It is beyond the pale to attempt to predict what life would be like elsewhere, but we can attempt to define basic principles that life would obey, and we can begin to explore the range of variation that is possible, given other astronomical environments and the possibility of, for instance, other coding systems. How might the rate or modes of evolution at the cellular level change if the host star experienced constant flares, as the Sun did in its youth, or if the coding bases did not absorb strongly in the UVC and UVB spectral regions, or if different biochemical pathways were made available or suppressed? Do strong fluctuations in the thermal and radiation environment enhance or suppress the rate of development of complexity at the genomic and cellular level? Which genetic processes are especially robust in, or even best suited for, strongly fluctuating environments? Of fundamental importance is to understand what level of disturbance is beneficial for the origin and development of complexity of life. Is a truly quiescent portion of the Galaxy attainable for any host star, including the Sun, and, even if so, is that the optimal condition for the evolution of complex life?

How evolving populations react to environmental variability, especially extreme stress, remains an unsolved problem. The mechanisms underlying the robustness of organisms are diverse; they include error correction machinery at the level of DNA, physiological plasticity at the level of individual traits or behaviors, and hypermutability at the level of entire populations. There are several lines of argument that suggest that diversity and hence evolution might be enhanced by an environment that is complex, whether in space or time or some material properties. *Pseudomonas fluorescens* evolves rapidly to generate many mutants under novel environmental conditions, resulting in the evolution of niche specialists.[62] Directed in vitro and in silico (artificial life) evolution experiments both indicate that genome lengths (one metric of complexity) grow only in information-rich environments.[63] The effect of harsh and fluctuating environments on the diversity of ecological communities, especially the "intermediate disturbance" hypothesis—that maximum diversity occurs at intermediate frequencies of disturbance—has been discussed extensively.[64] A relevant example may be the apparent increase in mutation rates in stationary-phase cultures experiencing the stress of overcrowding and nutrient starvation. There is

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[62] P.B. Rainey and M. Travisano. 1998. "Adaptive Radiation in a Heterogeneous Environment." *Nature* 394: 69-72.

[63] C. Adami, C. Ofria, and T.C. Collier. 2000. "Evolution of Biological Complexity." *Proceedings of the National Academy of Sciences U.S.A.* 97: 4463-4468.

[64] P. Chesson and N. Huntly. 1997. "The Roles of Harsh and Fluctuating Conditions in the Dynamics of Ecological Communities." *American Naturalist* 150: 519-553.

evidence in mammals that a complex sensory environment triggers the expression of genes responsible for neural plasticity, opening the way for increased neural complexity.

Another line of evidence for the role of environmental variability in complexity comes from considering evolution as a learning process. Experiments using neural networks as the phenotype for digital genomes show that learning is more efficient when mutation occurs in bursts rather than at a constant rate.[65] Mutations that increase fitness can be regarded as random measurements of the environment and genomes can be regarded as the selection-imprinted genetic memory of past environments.[66]

Robust modes of inheritance can be resistant to environmental insult but may be limited in the speed with which they are able to adapt to novel environmental conditions, particularly in environments that change over time. Alternatively, some processes controlling inheritance may be adapted to respond to sudden environmental change. An example is the process associated with heat-shock proteins, which acts to buffer phenotypic variability. The result is to hide the effects of mutations, allowing genetic diversity to accumulate. That diversity can then become manifest when the environment suddenly changes as the result of a heat shock or some other insult and the hidden mutations become expressed in the phenotype. Other examples are the DNA mutases,[67] which have a high error rate when they synthesize DNA, in contrast to the replicative DNA polymerases, which copy DNA sequences with high accuracy. Yet other DNA polymerases bypass specific types of DNA lesions during replication. These genetically programmed processes allow mutation when survival is threatened by increasing genetic diversity and adaptability. These polymerases are part of a process that allows them to function only when high mutation rates are valuable. That researchers recognize the existence of hypermutable states[68] and are widely discussing their evolutionary significance illustrates the potential for a strong coupling between genome-level processes and environmental variability.

The notion that substantial variation of the environment could be advantageous for evolution by stimulating the development of complexity stands in contrast to the perspective presented by Ward and Brownlee[69] and Gonzalez et al.[70]—namely, that the development of complex organisms requires a substantially stable environment. Too much variability is surely detrimental to life, but given the ability of life to adapt to what were recently considered to be beyond the tolerable limits of heat, cold, acidity, radiation, salinity, and other factors, it is worth considering the possibility that environmental fluctuations within very broad but reasonable limits are conducive to the development of complexity. Planets subjected to a strongly fluctuating astronomical environment might be a favorable site for complex life. It may be true in general, as it apparently was on Earth, that complex multicellular organisms do not evolve until levels of atmospheric oxygen rise sufficiently. At that point, however, life might develop more complexity faster on planets orbiting low-mass flare stars or on planets in a galactic neighborhood with a higher supernova rate than our own solar neighborhood. The arguments given above suggest that an effort should be made to quantify the nature of astronomical fluctuations in terms of quality (heat, radiation, etc.) and intensity on all relevant timescales and to design laboratory and simulation experi-

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[65] D.E. Moriarty and R. Miikkulainen. 1999. "Learning Sequential Decision Tasks Through Symbiotic Evolution of Neural Networks." *Advances in the Evolutionary Synthesis of Neural Systems.* V. Honavar, M. Patel, and K. Balakrishnan, eds. MIT Press, Cambridge, Mass.

[66] Adami et al. 2000. Op cit.

[67] M. Radman. 1999. "Mutation: Enzymes of Evolutionary Change." *Nature* 401: 866-869.

[68] P.L. Foster. 2000. "Adaptive Mutation: Implications for Evolution." *BioEssays* 22: 1067-1074.

[69] P.D. Ward and D. Brownlee. 2000. *Rare Earth: Why Complex Life Is Uncommon in the Universe.* Copernicus, New York.

[70] G. Gonzalez, B. Brownlee, and P. Ward. 2001. "The Galactic Habitable Zone: Galactic Chemical Evolution." *Icarus* 152: 185.

ments that can provide insight into the basic questions of whether and how life is affected by an astronomically fluctuating environment.

Most evolutionary theory assumes a steady exogenous mutation rate and asks how populations evolve as a function of the volatility and physiological impact of environmental fluctuations. Evolutionary models predict that if the genes responsible for high rates of mutation are linked to the genes that improve fitness upon mutation, endogenous mutation rates should remain relatively high when organisms frequently face novel conditions. Other models suggest that because of the high cost of further improving fidelity, endogenous mutation rates should decrease in a relatively constant environment. Still other models have shown that there are mutation rate thresholds above which populations simply cannot evolve. None of these models, however, considers mutation rates that vary over time as a result of exogenous factors. We should also consider these types of questions when the mutation rate is itself fluctuating as a result of the changing environment. Some work in this direction consists of numerical simulations suggesting that sudden large increases in mutation rates can speed the rate at which the complexity of specific phenotypes develops.[71]

These issues require study at the fundamental conceptual level to determine what degree of disturbance is favorable for the evolution of life and how the answer to that question might depend on the constituents and structure of life elsewhere. They could be explored both in the laboratory using the range of coding bases available today and by appropriate computer simulations, in close collaboration between biologists, computer scientists, and astronomers.

Areas of Relevant Independent Astronomical Research

Characterizing the galactic environment of the Sun or the astronomical environment of other potentially life-hosting bodies is relevant (see the sections "Galactic Environment" and "Cosmic, Solar, and Terrestrial Irradiation"). It is also important to understand the spatial and temporal variability of bolide impacts, which strongly perturb the thermal environment on Earth or on other potentially life-hosting bodies (see the section "Bombardment").

Areas of Potential Interdisciplinary Interaction

One approach to this topic would be to attempt to understand the variety of ways life responds to realistic representations of the fluctuating astronomical thermal and radiation environments. The aim would be to better understand the evolution of organisms that are subjected to the types of thermal and radiation environments expected for planetary systems experiencing a range of bolide impact histories and planets orbiting stars of various masses and ages in different parts of the Galaxy.

A variety of laboratory evolution experiments could explore the effects of irradiation on a variety of natural organisms, including well-studied microbes such as *Escherichia coli*.[72] Given the strong expectation that the ambient radiation on young planets will be intrinsically variable, these experiments could investigate whether or not there are qualitative differences between steady and variable radiation exposures at the same mean flux level.

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[71] D.E. Moriarty and R. Miikkulainen. 1997. "Forming Neural Networks Through Efficient and Adaptive Co-Evolution." *Evolutionary Computation* 5: 373.

[72] V.L. Kalinen, V.N. Petrov, and T.M. Petrova. 1981. "Isolation and Characteristics of Radioresistant Bacillus Subtilis and Bacillus Thuringiensis Mutants." *Radiobiologia* 21(5): 676-682 (in Russian).

A variable UV light source could be designed to simulate the spectrum and variability of astronomical UV radiation from stars of different characteristics, from flares, from supernovas, and so on and then used to study gene activation as a result of that radiation. Such a light source could also be used to drive directed evolution experiments in many generations exposed to this light source. Subsequent gene sequencing and structure analysis would permit study of the robustness of repair mechanisms and the possibility of novel repair pathways in extraterrestrial environments (for instance, the flare-dominated environment of a low-mass star; see the section "Cosmic, Solar, and Terrestrial Irradiation"). Coordinated experimental, theoretical, and computational work could address the interplay of astronomical and planetary environments, chemistry, mutation, diversity, fitness, and cooperation.

In addition, with the invention of alternative amino acid coding systems, there is the potential to engineer microbes based on such alternative coding systems and to study their response in directed evolution experiments that simulate astronomical bolide impact and UV or ionizing radiation environments. The point of such experiments would be not to explicitly attempt to mimic life on another planet but to use these engineered microbes to begin to explore the possible range of response and sensitivity in this extension of parameter space. The goal would be to better understand the guiding principles for the character and limits of life that evolves anywhere in a naturally fluctuating astronomical environment.

Artificial life experiments can explore a much wider range of parameter space than in vitro directed evolution experiments. Further study of simulated life promises to improve our understanding of the principles behind the growth of complexity in living systems. Experiments using neural networks as the phenotype for digital genomes are especially promising.

Astrophysicists who work on irradiation need to team with biologists who can examine the effects of these same types and levels of irradiation on molecules and cells in defined experimental systems (e.g., using directed evolution in vitro), both in solution and in the solid phase (e.g., using clay minerals as catalysts). Similar studies could be done on prebiotic chemistry.

Finding. We do not fully understand the strongly variable effects of astronomical bolide impacts or of the irradiation of the surfaces, oceans, and atmospheres of planets and moons on genetic and cellular evolution.

Recommendation. NASA, other funding agencies, and the research community should devote funding and effort to promote understanding of (1) the evolution of earthlike organisms and (2) organisms with other coding mechanisms that are subjected to the fluctuating thermal and radiation environments expected for planetary systems with various impact histories and planets orbiting stars of various masses and ages in different parts of the Galaxy.

Recommendation. NASA and other relevant agencies should foster in vitro and in silico studies to learn how the stochastic variability of the environment, including the mutational environment, affects the evolution of life, especially by promoting complexity and the evolution of evolvability.

Programs of Other Agencies

The NSF Tree of Life and DOE Genomes to Life programs will provide basic genetic information that can be used for biochemical experiments and molecular phylogenetic studies designed to learn more about the response of DNA radiation repair pathways to fluctuating thermal and radiation environments.

The NIH supports biomedical studies of the origin and treatment of cancer, genetic diseases, and aging. These studies could be significant for astrobiology because they would improve our understanding of the role of variable thermal and radiation environments in the evolution of life.

5

Integrating Astronomy with the Other Disciplines of Astrobiology

As it discussed the challenges of integrating astronomical research into the general enterprise of astrobiology, the committee realized that the issue of integration was broader and generic to this intrinsically interdisciplinary subject—that is, astrophysics is but one of many disciplines that need to be brought to bear on astrobiology. It decided to attempt to address some of these more generic issues of fostering a healthy interdisciplinary interaction among fields that are themselves so complex that they require a focused, reductive approach.

The committee has identified three factors that currently limit the integration of astronomy and astrophysics with astrobiology and, indeed, that limit the integration of robust interdisciplinary research of any kind: (1) a lack of common goals and interests, (2) lack of a common language, and (3) insufficient background in allied fields on the part of experts to allow them to do useful interdisciplinary work.

COMMON GOALS AND INTERESTS

In a highly interdisciplinary enterprise such as astrobiology, a common background must be established at some level before common goals can be set. Physics may be the lowest common denominator in all the fields surrounding astrobiology, and more emphasis on the fundamental physical processes involved in the chemistry, geology, biology, and astronomy of life may be warranted. Even after common goals are set, there is a need to overcome communication barriers (jargon is one such) and allow an informed chain of communication. How do we get microbiologists productively talking with astrophysicists and vice versa? NASA mission-driven research related to astrobiology (the Terrestrial Planet Finder, Mars missions, the Jupiter Icy Moons Orbiter, and so on) and associated funding opportunities can facilitate integrative research and cross-disciplinary collaborations and thus build on the astrobiology and exobiology basic research grant programs within NASA. In practice, fruitful interdisciplinary work may require a focused goal that mandates such interaction. Broad common goals for astrobiology can be established by the roadmapping process, as was done for the Astrobiology Roadmap, and by reports such as the current one.

COMMON LANGUAGE

The committee recommends a number of approaches for overcoming communication barriers:

- Continue and expand cross-disciplinary discussions on the origin and evolution of life on Earth and elsewhere, as are already being promoted by the NASA Astrobiology Institute (NAI).
- Continue intellectual exchange through interdisciplinary meetings, focus groups, a speaker program, and workshops, all targeted at integrating astronomy and astrophysics with other astrobiology subdisciplines and identifying additional possibilities for astrophysical research.
- Promote a professional society (and cross-disciplinary branches within existing societies) that will cover the full range of disciplines that make up astrobiology, from astronomy to geosciences to biology. The International Society for the Study of the Origins of Life, which holds triennial meetings, may provide an appropriate basis for this. The BioAstronomy conferences sponsored by the International Astronomical Union,[1] the astrobiology conferences held at NASA-Ames Research Center, and the Gordon Research Conferences on the Origin of Life are useful but do not fulfill the needed roles of a professional society.
- Broaden the definition of outreach activities within the NAI beyond general public awareness and K-12 education to achieve the greater degree of cross-fertilization that is needed among NAI senior researchers, postdoctoral fellows, and students.
- Reach out to university faculty in general, not just to NAI members and affiliates. This is essential for astrobiology to be embraced as a discipline and for extending and perpetuating support beyond NAI/NASA, which is otherwise unlikely to happen.

BACKGROUND AND EDUCATION

Education at all levels is a central issue. The challenge of cross- and interdisciplinary training is formidable. The committee urges NASA to take multiple approaches that both invest in the training of the next generation and give the larger scientific community opportunities for interdisciplinary training and collaboration. It calls for NASA astrobiology programs to provide opportunities for individuals or institutions to propose and carry out innovative approaches to interdisciplinary training. The highest priority should be placed on training the next generation of truly interdisciplinary scientists. It is also important to help current researchers who seek to learn about disciplines outside their own. One approach could be to establish specific astrobiology-oriented educational initiatives (programs, degrees, internships) for all levels of scientists. In addition, a distinguished speaker series would allow programs outside the NAI nodes to gain exposure to interdisciplinary endeavors within astrobiology.

The committee advocates four educational approaches to integrating astrophysics with astrobiology and increasing intellectual exchange and collaboration across all disciplines of astrobiology: student research training, a graduate student exchange program, postdoctoral fellowships, and faculty enrichment.

Student Research Training

Preparing scientists to attack interdisciplinary research problems is best accomplished as early in their career as possible. Indeed, students matriculating within established disciplinary programs typically

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[1] See <http://www.ifa.hawaii.edu/~meech/iau/>. Accessed April 28, 2005.

identify with a discipline during the first year of their studies. The challenge is to provide a balance between research training that equips scientists with broad theoretical knowledge and skill in the use of experimental tools while still imparting meaningful depth to their expertise. The problem of scientific entrenchment grows more pronounced with time, as scientists become increasingly invested in the theoretical paradigms, experimental approaches, analytical methods, and publication venues in which they have been successful. The committee therefore endorses the idea that the next call for proposals for NAI nodes should encourage academic institutions to develop astrobiological curricula at both the graduate and undergraduate levels that would augment studies in established disciplines. It would be very useful to know if the graduate student training programs at current NAI and NASA Specialized Centers of Research and Training (NSCORT) nodes have been successful. Are students graduating who are trained both broadly on the issues of astrobiology and in sufficient depth to pursue research on specific topics? To what degree are they prepared to participate in truly interdisciplinary research? To what degree have they actually done so?

The committee calls on NASA to fund a graduate fellowship program that would support high-caliber students in astrobiology, but not necessarily at NAI institutions. Fellowships would ensure continuity of funding for students at times of turnover in NAI centers. A prestigious and well-funded fellowship program would support and encourage the strongest students in astrobiology, regardless of their home institution.

Graduate Student Exchange Program

Graduate student training could be enhanced by exchange programs that allow students to matriculate in programs of disciplines other than their original discipline. Funds that would allow a student to study for some time at another institution or in another department within their own institution would give him or her a chance to learn new methodologies and gain experience in a related field of study. Graduate students are commonly funded as research assistants on specific projects or as teaching assistants. These positions typically do not afford the student either the time or resources for spending time away from their home department or institution. Exchange fellowships for 6 months to a year would not entail a large financial investment but could have a lasting impact on a young scientist.

Postdoctoral Fellowships

NAI already has an excellent fellowship program for postdoctoral studies. The postdoctoral fellows round out the expertise requirements of astrobiology. The Institute is working on a limited range of astrobiology issues, with additional work being funded through Exobiology. Postdocs are needed to fill crucial roles, and the manner of selection of NAI nodes does not ensure that even the most crucial roles are within the institute. NAI is encouraged to continue this program and to add resources that provide a means for recent Ph.D.'s to advance their research activities outside the discipline in which they were recently trained. As circumstances warrant, NAI postdoctoral fellows should be allowed or encouraged to serve at non-NAI institutions. Some astrobiology postdoctoral fellowships could be funded and administered from NASA Headquarters rather than by the NAI. Once again, it would be useful for NAI nodes to provide data on how successful the current program is. Are postdoctoral fellows participating in truly interdisciplinary research, or pursuing the narrower discipline in which they were trained?

Faculty Enrichment

The greatest challenge is to encourage established scientists to gain meaningful knowledge in disciplines outside their immediate area of expertise. The responsibilities of senior scientists are demanding, and little time is available for pursuits that are not targeted at immediate results. Most scientists are, however, driven by a love of knowledge, and they eagerly welcome the chance for intellectual enrichment provided through university sabbatical programs. A sabbatical enrichment program that provides resources for faculty to retool and take advantage of educational opportunities at other institutions would help established scientists counter forces that keep them entrenched within their disciplines. The NAI is encouraged to provide a sabbatical-enrichment program specifically designed to facilitate the interdisciplinary training of established scientists. At the same time, visiting scientists can share their own expertise, further enhancing cross-disciplinary discourse.

Recommendations

NASA should encourage NAI teams to institutionalize education and training in astrobiology. In particular, the committee recommends that the next competition for NAI nodes encourage the creation of academic programs for interdisciplinary undergraduate and graduate training in astrobiology.

In order to provide opportunities for graduate training within and outside the NAI nodes, NASA should establish an astrobiology graduate student fellowship program similar to existing programs in space and Earth science. These fellowships should be open to students enrolled in any accredited graduate program within the United States.

NASA should encourage the NAI to foster cross- and interdisciplinary training opportunities for graduate students and faculty, as already exist for postdoctoral fellows. In particular, the committee recommends that exchange programs be created to allow students to matriculate in programs outside their home field and that resources be made available for a sabbatical program for the interdisciplinary training of established scientists.

NASA should encourage the NAI nodes and the NASA Specialized Centers for Research and Training nodes to engage in a self-study as part of their reporting processes to assess the progress of graduate training and postdoctoral programs in training truly interdisciplinary scientists who actively engage in interdisciplinary research.

The NAI should sponsor a distinguished speaker series in astrobiology. It would identify accomplished speakers and provide travel support for them to present their interdisciplinary research at universities and colleges. The speakers should be selected on the basis of both disciplinary and demographic diversity. The institutions hosting the speakers would be required to involve multiple academic departments or programs.

Appendixes

A

Context and Statement of Task

CONTEXT

Policy

This study is proposed to address issues raised in the recent assessment of astrobiology programs at NASA (*Life in the Universe: An Assessment of U.S. and International Programs in Astrobiology*, 2002). The committee that wrote the report found that research in certain key areas of astrophysics relevant to understanding the astronomical environment in which life arose on Earth (and, potentially, elsewhere in the universe) was not well represented within the broad range of issues being addressed by NASA's Astrobiology program. This report is intended to highlight the potential contributions astronomers can make to the new field of astrobiology.

Technical

Life on Earth originated and has evolved over the last 3.5 billion plus years in a complex and highly variable astronomical environment. The Earth was assembled from interstellar gas already enriched in prebiotic molecules that were themselves the product of generations of stellar nucleosynthesis and chemical evolution in interstellar clouds. Asteroid and comet impacts have apparently altered the course of evolution, and interstellar dust continues to sift down onto the Earth. Long-lived radioactivities from stellar explosions heat Earth's molten core, driving plate tectonics, and suffuse the mantle in the form of potassium-40.

Life on or near to the surface of the Earth is strongly affected by the evolving radiation output from the Sun, interrupted by solar flares. Life is exposed to a continuous flux of cosmic rays that has probably varied significantly over geological times. Statistically, the Earth has been exposed to perhaps thousands of jolts of biologically significant radiation from supernovae and the possibility of exposure to an exotic event such as a gamma-ray burst has been considered.

Qualitatively, the same history affects other solar system bodies and extrasolar planets that might harbor life, but the effects will be varied in import and detail. Thus, there are compelling reasons to argue that a full and complete picture of the origin and evolution of life on Earth and elsewhere must integrate the astrophysical context of life.

One of the goals of the burgeoning intellectual field of astrobiology is to embed the core topics of biology, biochemistry, and paleogeology in the broadest appropriate context of astronomy. Relevant aspects of astronomy should inform the biology, chemistry, and geology, and vice versa, in order to facilitate intellectual exchange between those fields and to maximize the synergism within this innately multidisciplinary field.

An example of the mutual interchange of all these fields comes in the attempt to define "habitable zones." Classic habitable zones are those around host stars of different and evolving luminosity in the standard liquid-water paradigm, but the existence of extremophiles has led to other, more novel, paradigms. On a broader scale, the question has been raised as to whether there are habitable zones within galaxies. The latter concerns issues of the level of heavy elements required to support the growth of terrestrial planets and the degree to which galactic commotion is inimical to life.

STATEMENT OF TASK

The committee will study the means to augment and integrate the activity of astronomy and astrophysics in the intellectual enterprise of astrobiology, in NASA's Astrobiology program, and relevant programs in other federal agencies. The goals of this study are as follows:

1. Identify areas where there can be especially fruitful collaboration among astrophysicists, biologists, biochemists, chemists, and planetary geologists;
2. Define areas where astrophysics, biology, chemistry, and geology are ripe for mutually beneficial interchanges and define areas that are likely to remain independent for the near future; and
3. Suggest areas where current activities of NSF and other federal agencies might augment NASA programs.

Examples of research questions that may be relevant in this study include the following:

1. What is the role of galactic ecology in the development and sustainability of life?
   - —Is there a galactic habitable zone?
   - —What are the habitable zones around host stars in the liquid-water paradigm and plausible alternative paradigms with other solvents or biochemistry?
   - —Given a liquid water planet, how will the evolution of life depend on the mass of the parent star through its radiation, mass ejection, flares, and stellar wind?
   - —How does the "faint young sun" issue affect terrestrial life and life elsewhere?
   - —What sort of geochemical evidence can be summoned (e.g., He-3, Be-10, Fe-60) that constrains extraterrestrial influences?
2. What are the links between interstellar and prebiotic chemistry?
   - —What is the role of gas-phase interstellar chemistry in producing basic bio compounds?
   - —How do protostellar disks provide the conditions for life-supporting planets?
   - —How were organic compounds distributed, processed, and differentiated on early Earth, on satellites, on extrasolar planets?
   - —What is the role of meteoric chemistry?

3. What are the effects of bombardment?
   - What role does bombardment play in the origin of life on Earth or elsewhere?
   - Did life emerge during the heavy bombardment of the Hadean era?
   - How do rocky planets get wet?
   - What are the frequency and effect of subsequent bombardments?
4. What is the biological role of radiation?
   - What fraction of mutations are due to copy errors, to influences from within the biosphere, and to external astronomical sources?
   - Is the level of mutations a selected biological phenotype?
   - To what degree and under what conditions is chiral asymmetry, and possibly homochirality, induced by radiation?
   - What is the evolutionary origin of radiation repair mechanisms and what commonality is there between these mechanisms, gene transfer, and meiois, all of which involve annealing strands of DNA?
   - Is photosynthesis a requirement for a highly developed biosphere?
5. What programmatic activities at NASA and other agencies can be developed to detect/confirm/verify factors relevant to the topics outlined above?
   - Are there in vitro or in silico experiments that can inform these issues outlined above?
   - How do current and proposed NASA missions support prospects for the remote sensing of the geology, climate, weather, chemistry, and biology of planets around other stars?
   - What additional missions can be developed to address these issues?

B

Related Reports and Programmatic Activities

NRC REPORT *LIFE IN THE UNIVERSE*

In response to the NASA Authorization Act of 2000 and a subsequent request from Edward J. Weiler, NASA's associate administrator for the Office of Space Science, the NRC Committee on the Origins and Evolution of Life (COEL) was tasked with assessing the state of the NASA astrobiology program and providing a report by mid-2002 assessing the direction of the NASA astrobiology program. The assessment was to focus on (1) the program described in the 1998-1999 Astrobiology Roadmap, (2) astrobiology aspects of the 2000 Origins Roadmap, and (3) relevant portions of the Year 2000 Office of Space Science Strategic Plan, a survey of initiatives for seeking life in the universe conducted by other U.S. federal and nongovernmental groups. Similar activities by foreign space agencies were also to be considered, enhancements to the U.S. program that might be warranted were to be identified, and ways to coordinate NASA efforts with those of other parties were to be recommended.

Life in the Universe[1] contained the following statements and recommendations that are of direct relevance to the current study:

> **ADDITIONAL ENHANCEMENTS TO NASA'S ASTROBIOLOGY PROGRAM**
>
> Research efforts that are directly identified as astrobiology are dominated today by the biological and geological sciences. Yet the intellectual sphere covered by objectives in astrobiology includes much of the planetary sciences and the stellar and planetary aspects of the astronomical search for origins. Involvement of planetologists and astronomers has been hampered by a strong skepticism, even suspicion, in those communities regarding the scientific value of astrobiology as an intellectual endeavor. The committee believes that some of this skepticism will decline as astrobiology demonstrates results and as the future emerging field is better defined both intellectually and programmatically (that is, through

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[1] National Research Council. 2003. *Life in the Universe: An Assessment of U.S. and International Programs in Astrobiology.* Washington, D.C.: The National Academies Press, p. 5.

> future roadmaps). But there remains the difficulty of interaction between research areas whose techniques, technical language, and experimental approaches are very different. The long-term success of astrobiology in addressing its objectives will depend on a deeper and more extensive exchange of ideas with the traditional space sciences.
>
> COEL commends NASA for developing a strong and well-balanced Solar System Exploration program that forms an important foundation for much of the central endeavor of astrobiology.
>
> **Recommendations**
>
> The NASA Astrobiology Institute should initiate a much broader suite of focus group programs with planetary scientists, beyond those currently devoted to studies of Mars and Europa, to create a deeper level of mutual understanding and appreciation of the two research areas, and to provide new perspectives for future solar system exploration.
>
> NASA should foster more extensive links between the Astrobiology and the Astronomical Search for Origins programs. In the short term, these linkages require cooperation between the NAI and major astronomical institutions, such as the Space Telescope Science Institute and universities with extensive astronomical programs, in creating joint workshops and focus groups to educate researchers in both areas and to initiate more extensive and novel research endeavors.
>
> Panels evaluating NAI membership proposals must be broadly constituted to ensure expert evaluation of research programs that are intellectually strong but have a discipline balance very different from that found in the existing NAI nodes.
>
> NASA should study the feasibility and desirability of creating and funding an institute, akin to the NAI, dedicated to consortium-based science and technology (e.g., involving multi-institution teams) related to the astronomical search for origins on the full range of spatial and temporal scales.

The current study is undertaken in part to follow up on this perspective and these recommendations from *Life in the Universe*.

NASA'S ORIGINS ROADMAP

As part of the NASA strategic planning process, the Origins theme in the Office of Space Science's Astronomy and Physics Division revised its roadmap.[2] This roadmap was the product of deliberation and discussion by the Origins Subcommittee of NASA's Space Science Advisory Committee, working with representatives from NASA's field centers and with substantial input from the astronomical community. The roadmap sets out a plan for a 20-year period at the beginning of the millennium, with particular emphasis on activities advocated for new mission starts in the near term (2005 to 2010) or mid-term (2010 to 2105) time frame. Topics that overlap with the enterprise of astrobiology are woven through the document. Among the high-level questions to be addressed are, Where did we come from? Are we alone? These questions are posed more specifically in the Origins Technology Roadmap:[3]

> **The Questions . . . The Quests**
>
> - *Search for our earliest origins*
>   - What were the earliest structures produced within the universe?
>   - How did galaxies form?

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[2] Available at <http://origins.jpl.nasa.gov/library/roadmap03/index.html>. Last accessed April 29, 2005.

[3] Available at <http://origins.jpl.nasa.gov/library/techroadmap/roadmap04.html>. Last accessed April 29, 2005.

  - —How did primeval gas form the first stars?
  - —Where and when were the heavy elements (C, N, O, . . .) formed?

- *Search for life beyond our solar system*
  - —How do stellar and planetary systems form and evolve?
  - —What is the distribution and characteristics of planets around nearby stars?
  - —How did the physical and chemical conditions necessary for life arise in the universe? Are there life-supporting planets orbiting nearby stars?

The first set of questions is arguably relevant to the broader astrobiological context, and the second set is indistinguishable from some of the central goals of astrobiology.

NASA's Astrobiology Roadmap

NASA's Astrobiology program completed its most recent roadmap in 2003.[4] That document contained the following prefatory material:

> Astrobiology is the study of the origins, evolution, distribution, and future of life in the universe. It requires fundamental concepts of life and habitable environments that will help us to recognize biospheres that might be quite different from our own. 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 needed 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 for the most comprehensive and inclusive understanding of biological, planetary and cosmic phenomena.
>
> This NASA Astrobiology Roadmap outlines these multiple pathways for research and exploration and indicates how they might be prioritized and coordinated. The roadmap embodies the efforts of more than 200 scientists and technologists, including NASA employees, academic scientists whose research is partially funded by NASA grants, and many members of the broader community who have no formal association with NASA.
>
> ### Fundamental Questions
>
> 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?
> - What is the future of life on Earth and beyond?
>
> ### Principles
>
> The following basic principles are fundamental to the astrobiology program:
>
> - 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.
> - Astrobiology encourages planetary stewardship through an emphasis on protection against forward and back biological contamination and recognition of ethical issues associated with exploration.

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[4] Available at <http://astrobiology.arc.nasa.gov/roadmap/>. Last accessed April 29, 2005.

- 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.
- 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.

Life is a central theme that unifies NASA's vision and mission. A golden age has begun for the life sciences, an age in which science and technology will benefit enormously from a fundamental understanding of the full potential of living systems. This Roadmap outlines how to achieve a better fundamental understanding both of our own world and also of potential habitable worlds and life beyond Earth. This is an agenda for inspiring the next generation of planetary explorers and stewards to sustain the NASA vision and mission.

The Astrobiology Roadmap is formulated in terms of seven science goals that outline the key domains of investigation. Within each of these goals, more specific science objectives, a total of 18, present more specific high-priority efforts for the next 3 to 5 years that are intended to be integrated with NASA strategic planning. The science goals are as follows:

Goal 1. Understand the nature and distribution of habitable environments in the universe . . .
Goal 2. Explore for past or present habitable environments, prebiotic chemistry and signs of life elsewhere in our solar system . . .
Goal 3. Understand how life originates from cosmic and planetary precursors . . .
Goal 4. Understand how past life on Earth interacted with its changing planetary and solar system environment . . .
Goal 5. Understand the evolutionary mechanisms and environmental limits of life . . .
Goal 6. Understand the principles that will shape the future of life, both on Earth and beyond . . .
Goal 7. Determine how to recognize signatures of life on other worlds and on early Earth.

RELEVANT ACTIVITIES IN OTHER AGENCIES

National Science Foundation

Life in Extreme Environments

Life in Extreme Environments (LExEn) was a successful interdisciplinary program run from 1997 to 1999 by the Directorates for Biological Sciences, Engineering, Geosciences, Mathematical, and Physical Sciences and the Office of Polar Programs of the National Science Foundation. The LExEn research program explored "the relationships between organisms and the environments within which they exist, with a strong emphasis upon those life-supporting environments that exist near the extremes of planetary conditions. In addition, the LExEn program [supported research in] planetary environments in our own solar system and beyond to help identify possible sites for life." This program placed heavy demands on both the financial resources and, especially, the personnel of the NSF since neither new funds nor new personnel to manage the complex cross-disciplinary effort were available. The success of this program was a credit to the dedicated NSF staff who worked so hard on it.

Ridge Interdisciplinary Global Experiments (RIDGE)

The Ridge Interdisciplinary Global Experiments (RIDGE) program[5] is designed to support research aimed at understanding the geological, chemical, biological, and physical oceanographic interactions between the oceans and hydrothermal circulation of seawater through the ocean crust.

> Ridge 2000 is a Multidisciplinary Science Research Program focused on integrated geological and biological studies of the Earth-encircling mid-ocean ridge system and funded by the National Science Foundation. The overall objectives of the program, its scientific rationale, and many programmatic details are covered in the Ridge 2000 Science Plan. Central to Ridge 2000 Science is the recognition that the origin and evolution of life in deep-sea ecosystems are inextricably linked to, and perhaps an inevitable consequence of, the flow of energy and material from Earth's deep mantle, through the volcanic and hydrothermal systems of the oceanic crust, to the deep ocean. The Ridge 2000 Program recognizes that the complex linkages between life and planetary processes at mid-ocean ridges can only be understood through tightly integrated studies that span a broad range of disciplines. With this tenet in mind, Ridge 2000 seeks a focus and coordination of research activities at a few carefully chosen areas. Ridge 2000 Time Critical Studies are designed to enhance detection of volcanic and other transient events on the mid-ocean ridge and to facilitate rapid-response missions that can observe, record, and sample critical transient phenomena. These studies are largely limited to the Northeast Pacific at this time. Three sites have been chosen as type areas for the initial Ridge 2000 Integrated Studies Programs: The East Lau Basin Spreading Center in the Western Pacific Ocean was chosen for a back-arc basin spreading center; the Endeavour Segment of the Juan de Fuca Ridge in the Northeast Pacific Ocean as an intermediate rate spreading center, and 8-11°N on the East Pacific Rise off of Central America for a fast spreading center.

The RIDGE program supports a substantial amount of work that is related to the astrobiological topics of the origin of life and extremophiles.

Polar Programs

The NSF Office of Polar Programs,[6] in particular the U.S. Antarctic program (USAP), support only research that can be done exclusively in Antarctica or that can be done best from Antarctica. The NSF is currently participating in the NASA review of the Astrobiology Science and Technology for Exploring Planets (ASTEP) proposals, which support research aimed at detailed, collaborative analysis of Earth's extreme environments in order to better understand analogous systems elsewhere. The Antarctic is one of those environments. Successful ASTEP antarctic proposals will require the logistical support of the Office of Polar Programs.

Tree of Life Program

The overall goal of the Assembling the Tree of Life program[7] is to construct a framework phylogeny, or Tree of Life, for all 1.7 million described species on Earth. Phylogeny, the genealogical map for all lineages of life on Earth, provides an overall framework to facilitate information retrieval and biological prediction. The Tree of Life activity supports large teams working across institutions and disciplines to resolve phylogenetic relationships for large groups of organisms on the Tree of Life.

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[5] Available at <http://ridge2000.org>. Last accessed April 29, 2005.

[6] Available at <http://www.nsf.gov/div/index.jsp?org=opp>. Last accessed April 29, 2005.

[7] Available at <http://www.nsf.gov/pubs/2005/nsf05523/nsf05523.htm>. Last accessed April 29, 2005.

Department of Energy

Genomics:GTL Program

The Genomics:GTL program (formerly the Genomes to Life[8] program) of the U.S. Department of Energy is intended to use the new genomic data and high-throughput technologies for studying the proteins encoded by the genome to explore the amazingly diverse natural capabilities of microbes.

> Building on the successes of the Human Genome Project, DOE has initiated an ambitious program to achieve the most far-reaching of all biological goals: a fundamental, comprehensive, and systematic understanding of life.
>
> DOE's Genomics:GTL (formerly Genomes to Life) program will make important contributions in the quest to venture beyond characterizing such individual life components as genes and other DNA sequences toward a more comprehensive, integrated view of biology at the whole-systems level. The DOE offices of Biological and Environmental Research and Advanced Scientific Computing Research have formed a strategic alliance to meet this grand challenge.
>
> The plan for the program is to use DNA sequences from microbes and other organisms, including humans, as starting points for systematically tackling questions about the essential processes of living systems. Advanced technological and computational resources will help to identify and understand the underlying mechanisms that enable organisms to develop, survive, carry out their normal functions, and reproduce under myriad environmental conditions.
>
> This approach ultimately will foster an integrated and predictive understanding of biological systems and offer insights into how both microbial and other cells respond to environmental changes. The applications of this level of knowledge will be extraordinary and will help DOE fulfill its broad missions in energy, environmental remediation, and global climate change mitigation.
>
> What are the goals of the Genomics:GTL program?
>
> - Identify the protein machines that carry out critical life functions;
> - Characterize the gene regulatory networks that control these machines;
> - Explore the functional repertoire of complex microbial communities in their natural environments to provide a foundation for understanding and using their remarkably diverse capabilities to address DOE missions;
> - Develop the computational capabilities to integrate and understand these data and begin to model complex biological systems.

Progress in these areas is likely to be important for the astrobiological goals of understanding the origin and evolution of life as well.

ASTROBIOLOGY IN EUROPE

The European Astrobiology Network Association (EANA)[9] was created in 2001 to coordinate the different national research centers and to promote research in astrobiology in Europe. The specific objectives of EANA including the following:

- To bring together European researchers interested in astrobiology programs and to foster their cooperation.

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[8] Available at <http://doegenomestolife.org/>. Last accessed April 29, 2005.

[9] Available at <http://www.graz-astrobiology.oeaw.ac.at/eana.html>. Last accessed April 29, 2005.

- To attract young scientists to this quickly evolving, interdisciplinary field of research.
- To enhance the public understanding of astrobiology.
- To interface EANA with European bodies such as ESA, the European Science Foundation (ESF), and the European Commission and with non-European institutions.
- To create a Web site for establishing a database on astrobiology.

EANA's executive council consists of national members representing 12 European nations active in the field: Austria, Belgium, Denmark, France, Germany, Italy, Portugal, Spain, Sweden, Switzerland, The Netherlands, and the United Kingdom.

EANA is affiliated with the NASA Astrobiology Institute. The formal affiliation was signed in 2002 at the Graz Workshop by Rosalind Grymes, Deputy Director of NAI, during a reception hosted by the governor of Styria in historic Eggenburg Castle. EANA is also a member of the International Astrobiology Circle, including the Astrobiology Society of Britain,[10] the Australian Centre for Astrobiology,[11] the Spanish Centro de Astrobiología,[12] the French Groupement de Recherche en Exobiologie (GDR-Exobio),[13] and the Swedish Astrobiology Network.[14] Collaborative research areas in Europe's astrobiology network include cosmochemistry, star and planetary formation, the chemistry of the origin of life, terrestrial life as a reference, and the search for habitats and signatures of life beyond Earth. EANA organizes annual conferences: the first European Exo/Astrobiology Workshop, in Frascati, Italy, in May 2001, was attended by 200 scientists; national and international activities in exo/astrobiology were presented. The Second European Workshop on Exo/Astrobiology, held in Graz, Austria, in September 2002, was attended by 320 participants and was oriented toward planetology. The third European Exo/Astrobiology Workshop, hosted by the Centro de Astrobiología in Madrid in November 2003, focused on the search for life on Mars. Annual EANA executive council meetings are held during those conferences. EANA intends to incorporate more countries into the network; applications from Hungary, Poland, Romania, Finland, and Russia have been received.

Europe hosts the largest astrobiology institute, headed by Juan Perez-Mercader. The Centro de Astrobiología, 30 km north of Madrid, is focused on interdisciplinary research within astrobiology. The International Space Science Institute (ISSI),[15] in Bern, hosts an international team on prebiotic matter in space, a consortium of 12 scientists, each representing a specific research field. Team activities include the organization of workshops, collaborative programs in laboratory research and astronomical observations, compilation of a database on organic molecules in space, and publications in refereed journals and books.

The organization of astrobiology in Europe is very different from in the United States. Astrobiology does not receive any financial support from European organizations, with the exception of small grants for young researchers attending astrobiology conferences. Astrobiology research is currently organized and financed exclusively by national organizations and then mostly on an individual country basis. Astrobiology activities and funding vary greatly from country to country. Astrobiology in Europe is not tied to space research or the European Space Agency (ESA); however, Europe's involvement in space

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[10] See <http://www.astrobiologysociety.org>. Last accessed April 29, 2005.
[11] See <http://aca.mq.edu.au>. Last accessed April 29, 2005.
[12] See <http://www.cab.inta.es>. Last accessed April 29, 2005.
[13] See <http://www.exobio.cnrs.fr>. Last accessed April 29, 2005.
[14] See <http://www.astrobiologi.se>. Last accessed April 29, 2005.
[15] See <http://www.issi.unibe.ch>. Last accessed April 29, 2005.

missions such as Mars Express, Cassini-Huygens, Rosetta, and others provides an important basis for astrobiological research related to planetary exploration. A new European space research program, Aurora,[16] was endorsed by the European Union Council of Research and the ESA Council in 2001 and is currently in study phase. Aurora is part of Europe's strategy for human exploration of our solar system and for the stimulation of new technology. Europe's future in astrobiology will strongly depend on a coherent funding system involving large European organizations. The implementation of a comprehensive space policy within Europe, which is currently being discussed, could benefit astrobiology in Europe. Continuation and further development of the ESA-Aurora program and the successful outcome of planetary missions currently in orbit (e.g., Mars-Express, Cassini-Huygens) will be an important trigger for the funding of future European research programs in astrobiology. The European Space Science Committee (ESSC) is the ESF expert committee on European space research issues.[17] ESSC aims to promote and facilitate the definition and the organization of space research programs in Europe by providing an independent forum on European space policy. By evaluating European space missions and in particular the Aurora program, ESSC and ESF are indirectly supporting astrobiology. Furthermore, ESF and ESSC try to establish a coordinated program within Europe between the science community and official organizations such as the Marine Board and the Polar Board (ESF) to explore new avenues of research on life in extreme environments.

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[16] See <http://www.esa.int/SPECIALS/Aurora>. Last accessed April 29, 2005.

[17] See http://www.esf.org>. Last accessed April 29, 2005.

C

Glossary

Aitken Basin	Largest impact basin known, located in the Moon's southern polar region
alpha decay	Radioactive decay of a nucleus by the emission of an alpha particle, the nucleus of a helium-4 atom
amino acid	Class of basic molecules that make up proteins
apoptosis	Cell death
Archean	Period in Earth's history from 3.8 to 2.5 billion years ago, when life arose
Argyre	Major impact basin on Mars
asteroid	Rocky fragments left over from the formation of the solar system
astrosphere	Zone of interaction between a star and its interstellar environment
beta decay	Radioactive decay of a nucleus by the emission of an electron (or positron) and an electron antineutrino (or electron neutrino)
biosphere	Life zone of Earth, which includes all living organisms and all organic matter that has not yet decomposed
bolide	Meteor that often explodes as a fireball
carbonaceous chondrite	Stony meteorite that contains carbonaceous compounds
Chicxulub	Impact basin in Mexico, which was created at the end of the Cretaceous and the beginning of the Tertiary
chirality	Degree to which an object is different from its mirror image
chromosphere	Visually transparent layer above the Sun's visible photosphere

clay	Generic term for an aggregate of hydrous silicate particles less than 4 μm in diameter
comet	Relatively small planetary body similar to an asteroid but composed largely of ice
cosmic rays	High-energy particles originating outside Earth
cross strand exchange	Process in which bases along one double helix strand separate and link across to a separate double helix and vice versa
Darwin	European Space Agency's large infrared-wavelength space interferometer
Deep Impact	NASA mission to collide a spacecraft to create a deep crater in Comet Tempel 1
Deinococcus radiodurans	Gram-positive aerobic bacteria, the most radiation-resistant organism known
dichroism	Differential absorption of left- and right-hand circularly polarized light in a material
DNA	Deoxyribonucleic acid, the molecule that carries genetic information
DOE	U.S. Department of Energy
dose	Absorbed amount of radiation
dose rate	Rate at which tissue absorbs radiation
double-strand break	Break in both strands of the DNA molecule, usually caused by oxidative stress or certain forms of radiation
D-ribose	Right-handed form of a five-carbon sugar, found in all living cells
early stars	Stars that formed primarily from hydrogen and helium and are deficient in heavier elements
endogenous	Organic matter synthesized on Earth and necessary for the appearance of life (see *exogenous*)
exogenous	Organic matter delivered from space and necessary for the appearance of life (see *endogenous*)
Exploration Initiative	U.S. multiagency Vision for Space Exploration
field reversal	Periodic reversal of the magnetic field of a star or planet
flare star	Star that sporadically flares in brightness by an order of magnitude or more
gamma ray	Most energetic form of electromagnetic radiation
gamma-ray burst	Energetic cosmic event that produces a burst of gamma rays
habitable zone	Radial zone in which certain parameters thought to be necessary for life are met
Hadean	Era in Earth's history 4.5 to 3.8 billion years ago, before life is thought to have arisen

heliosphere	Huge magnetic bubble created in interstellar space by the outrushing solar wind and associated magnetic field
Hellas	Major impact basin on Mars
Herschel	European Space Agency's far-infrared and submillimeter telescope project, due to launch in 2007
homochirality	Molecules possessing structure with the same handedness
hypermutable	Genes that have a high rate of mutation
impact basin	Large crater produced by a meteorite impact
in silico	Relating to processes that occur in computer simulations
in vitro	Relating to processes that occur in a laboratory
in vivo	Relating to processes that occur in living matter
isotope	Atoms of a chemical element whose nuclei have the same atomic number, Z, but different atomic weights due to different numbers of neutrons
K-T boundary	Boundary between the Cretaceous and Tertiary periods, about 65 million years ago
Kuiper Belt	Area of the solar system extending from within the orbit of Neptune (at 30 AU) to some 50 AU from the Sun
Lake Acraman	Large meteor impact crater in South Australia
L-enantiomer	Molecule with left-handed chirality
L-isomer	Molecule with left-handed chirality
Long-Duration Exposure Facility	NASA experiment involving a satellite that was retrieved after several years to determine the effects of long-term exposure to space
L-ribose	Left-handed form of a five-carbon sugar
LUCA	Last Universal Common Ancestor (of life)
magma chamber	Underground pocket containing molten rock
meiosis	Reproduction through cell division
metals	To astronomers, any element except hydrogen or helium
mtDNA	Mitochondrial DNA
NAI	NASA Astrobiology Institute
NASA	U.S. National Aeronautics and Space Administration
NSCORT	NASA Specialized Centers of Research and Training
NEO	Near-Earth object, an asteroid or comet that comes relatively close to Earth
NIH	U.S. National Institutes of Health
NSF	U.S. National Science Foundation

obliquity	Angle between the plane of a planet's orbit and that of the planet's equator
Oklo	Series of natural fission reactors that were active in the Oklo Valley of Gabon, Africa, about 1.5 billion years ago
Oort Cloud	Spherical cloud of comets with semimajor axes between 1,000 and 50,000 AU
oxygen radical	Oxygen atom with an unpaired electron. Radicals are powerful oxidizing agents that can cause structural damage to proteins and nucleic acids.
panspermia	Hypothesis that life originated elsewhere in the universe and migrated through space to Earth and, potentially, elsewhere
photosynthesis	Biochemical process by which the energy of light is converted into chemical energy in plants, algae, and certain bacteria
phototroph	Organism that uses light as its main source of energy
phylogenetic	Of or related to the evolutionary development of a group of genetically related organisms
placer deposit	Alluvial deposit of sand and gravel representing stream beds
planetesimal	Small rocky and icy object that existed at an early stage in the development of the solar system
polymerase	Enzymes that catalyze the polymerization of nucleic acids
polyols	Polyhydric alcohols or sugar alcohols
polysaccharides	Polymers made up of chains of simple sugars. Examples include starch, cellulose, and glycogen
protein	Complex, high-molecular-weight organic compound that consists of amino acids joined by peptide bonds
Pseudomonas fluorescens	Common nonpathogenic, gram-negative bacteria that produces a soluble greenish fluorescent pigment, particularly under conditions of low iron availability
P-T boundary	Geologic boundary between the Permian and Triassic periods, about 250 million years ago
pyrimidine dimer	Two adjacent pyrimidine nucleotides, usually thymine, in which the pyrimidine residues are covalently joined by a cyclobutane ring. These dimers stop DNA replication.
pyrimidines	Organic compounds with a heterocyclic ring: two nitrogen atoms taking the place of carbon atoms at positions 1 and 3 relative to each other around the six-member ring
radiolarians	Single-celled organisms that form protective skeletons, usually made of silicon dioxide
ram pressure	Force per unit area required to stop the solar wind flow

redox state	Chemical reaction environment determined by the balance of negatively and positively charged atoms
replication	Reproduction from a template
ribose	Five-carbon sugar
RNA	Ribonucleic acid, a molecule involved in transcription of the instructions in DNA. Some theorize that RNA was the precursor to DNA.
single-strand break	When one strand of the DNA molecule is broken, usually by oxidative stress or certain forms of radiation
solar flare	Eruption of hot gas and radiation from the Sun's photosphere
solar neighborhood	Sun and nearby stars
Stardust mission	NASA mission to return dust from Comet Wild 2
subduction	Geologic process by which one tectonic plate is forced under another
Sudbury	Ancient impact basin in northern Canada
supernova	Stellar explosion
tars	Complex hydrocarbons with high viscosity and melting point
tectonics	Theory that Earth's lithosphere exists as separate and distinct plates that float on a fluid-like asthenosphere
Titan	Largest moon of Saturn
TPF	NASA's Terrestrial Planet Finder
transition elements	Elements located in groups IB to VIIIB of the Periodic Table. They have many of the characteristics of metals.
ultraviolet	Electromagnetic radiation more energetic than visible light
UVB	Ultraviolet sunlight that penetrates the ozone layer and reaches Earth's surface
UVC	Ultraviolet sunlight with shorter wavelength than UVB that is filtered out by Earth's ozone layer
VPL	Virtual Planetary Laboratory, hosted by Caltech and the Jet Propulsion Laboratory
volatile	Substance with a low evaporation temperature
Vredefort	300-km impact crater in South Africa, formed about 2 billion years ago
x ray	Electromagnetic radiation more energetic than ultraviolet light

D

Committee Member and Staff Biographies

COMMITTEE MEMBERS

JACK W. SZOSTAK (*Co-chair*) is the Alexander Rich Distinguished Investigator at Massachusetts General Hospital and a professor of genetics at Harvard Medical School. A distinguished molecular biologist, Dr. Szostak has made groundbreaking contributions in several different areas of biology, most recently to the understanding of the origins of biological catalysis. He has contributed more than 100 articles to scientific journals. He served as co-chair of the Nucleic Acids Gordon Research Conference in 1993 and of the Keystone Symposium on RNA in 1996, and he was the Harvey Society Lecturer in 1998. Dr. Szostak was awarded, along with Gerald Joyce, the National Academy of Sciences award in molecular biology in 1994 and the Hans Sigrist Prize from the University of Bern in 1997. He participated in the SSB's workshop "Research Issues Regarding Alternative Life Forms (Weird Life)." Dr. Szostak is a fellow of the American Academy of Arts and Sciences.

J. CRAIG WHEELER (*Co-chair*) is the Samuel T. and Fern Yanagisawa Regents Professor of Astronomy at the University of Texas at Austin and past chair of the department. His research interests cover supernovas and black holes. He has published more than 200 scientific papers and a novel and has edited four books. A popular science lecturer, Dr. Wheeler has received many awards for his teaching. He was a visiting fellow at the Joint Institute for Laboratory Astrophysics (JILA), the Japan Society for the Promotion of Science, and a Fulbright fellow in Italy. He has served on a number of advisory committees, including at the National Science Foundation and the National Aeronautics and Space Administration, and on the organizing committee of the International Astronomical Union Commission on Stellar Constitution. He is currently serving as president-elect of the AAS. Dr. Wheeler previously served on the NRC Steering Committee for the Task Group on Space Astronomy and Astrophysics, 1996-1997.

STEVEN A. BENNER is a professor in the Department of Chemistry at the University of Florida. Dr. Benner's research involves various facets of biochemistry and biorganic studies, with emphases on bioinformatics, experimental paleobiochemistry, nucleic acid chemistry, small molecule evolution, astrobiology, and nanotechnology. His lectures have had titles such as "Genomic Sequences as Organic Molecules: An Evolutionary Approach to Understanding What They Do," "Reconstructing the Chemical Past: Experimental Paleobiochemistry," and "Redesigning Nucleic Acids: Obtaining Molecular Evolution in the Laboratory."

JOSEPH A. BERRY is staff member in the Department of Plant Biology, Carnegie Institution of Washington, and a professor in the Department of Biological Sciences at Stanford University. Dr. Berry's research interests are in photosyntheses and respiration and in how biochemical and biophysical mechanisms propagate to the planetary scale. Recently, he devoted a substantial portion of his time to an interdisciplinary research project sponsored by NASA under its Earth Observing System, the goal of which was to assemble a scientific basis for modeling the interactions between the biosphere and the atmosphere on a global scale. Dr. Berry was a member of the NRC Global Climate Change Study Panel in 1991 and 1992.

RUTH BLAKE is an assistant professor of geology and geophysics and of environmental engineering at Yale University. Her research interests cover geomicrobiology and microbial geochemistry/biochemistry, low-temperature aqueous/experimental geochemistry, and stable isotope geochemistry. Dr. Blake has studied the use of oxygen isotope variations in phosphate from fish remains to decipher ancient climate from deep-sea cores. She also participated in Yale's Distinguished Lecturers Series as an expert on microbes in the deep biosphere.

WENDY M. CALVIN is the Arthur Brant Research Associate Professor at the University of Nevada, Reno. Before that, from 1992 to 1999, Dr. Calvin served as research geophysicist for the U.S. Geological Survey Astrogeology Team, in Flagstaff, Arizona. Specializing in infrared spectroscopy, Dr. Calvin emphasizes understanding the nature and association of water, volatile ices, and minerals in order to better understand the physical and chemical processes occurring in a variety of planetary and space environments. She is skilled in both visible/near-infrared emissions and surface thermal emissions. Her current research includes studies of alteration minerals on Mars to understand climate history and variability and volatile element transport and sequestrations. She was a coinvestigator for the camera that was on the Mars Climate Orbiter mission in 1998 (MARCI). Dr. Calvin was a member of the NRC Committee on Planetary and Lunar Exploration from 1997 to 2000.

MICHAEL J. DALY is an assistant professor in the Department of Pathology at the Uniformed Services University of the Health Sciences in Bethesda, Maryland. His research interests focus on microbial genetics and the DNA repair mechanisms of the highly radiation-resistant organism *Deinococcus radiodurans*. Most recently, Dr. Daly has been engineering *D. radiodurans* for the bioremediation of toxic organic compounds, radionuclides, and heavy metals in radioactive waste sites. He is also interested in adaptations to microorganisms that may enable them to survive in cryptobiotic states for millions of years. Dr. Daly served on the NRC Task Group on the Forward Contamination of Europa (1999-2000).

KATHERINE H. FREEMAN is professor of geosciences at Pennsylvania State University (PSU) and associate director, PSU Biogeochemical Research Initiative in Education (NSF-IGERT). Her current research interests are in organic geochemistry and isotopic biogeochemistry. From 1993 to 1997, Dr. Freeman served as a member of the review panels for the Program in Chemical Oceanography and the Program in Environmental Geochemistry and Biogeochemistry. In 1999 she served on the NRC Committee on Basic Research Opportunities in the Earth Sciences.

J. PETER GOGARTEN is a professor of molecular and cell biology at the University of Connecticut. His research interests are molecular evolution; evolution of the eukaryotic endomembrane system; origin and early evolution of cellular life; horizontal gene transfer; and genome comparison. Dr. Gogarten is currently involved in several research programs, including one on the evolution of proton pumping ATPases and another on the role of horizontal gene transfer. His professional activities include serving as chair of the 2005 Origin of Life Gordon Conference, as a member of the Exobiology Discipline Working Group (NASA), and as co-head of the Plant Cell Culture Facility of the University of Connecticut's Biotechnology Center. Dr. Gogarten is a member of the International Society for the Study of the Origin of Life, the American Association of Plant Physiologists, and the New England Complex Systems Institute.

JAMES F. KASTING is a professor of geosciences and meteorology at Pennsylvania State University. He is a specialist in atmospheric evolution on Earth and on the other terrestrial planets. Before coming to Penn State University in 1988, he spent 2 years at the National Center for Atmospheric Research in Boulder, Colorado, and 7 years in the Space Science Division at NASA-Ames Research Center. Dr. Kasting is a former member of the NRC Committee for the US-USSR Workshop on Planetary Sciences.

ANTHONY KEEFE is a senior scientist in the Discovery of Therapeutic Biopolymers group at Archemix Corporation. Before that, Dr. Keefe served as a postdoctoral research fellow in the Department of Genetics at Harvard Medical School. He has also served as a senior research associate at NASA's Ames Research Center and was a postdoctoral fellow at the University of California, San Diego. Dr. Keefe's research and interests include protein engineering, in vitro translation, plasmid engineering, synthetic organic and inorganic chemistry, mass spectroscopy, and electrochemistry. He has written widely on the above areas and holds several patents.

MARTIN KELLER is the director of the Diversity and Discovery Group at Diversa Corporation. Diversa is a global leader in developing and applying proprietary technologies to discover and evolve novel genes and gene pathways from diverse sources. Dr. Keller is responsible for studies of microbial diversity, proteomics biopanning, and flow cytometry. Dr. Keller has received grants to study fluorescent activated cell sorting for enzyme screening and served as co-principal investigator for DOE's Genomes to Life program on stress response pathways.

SANDRA PIZZARELLO, an exobiologist, is a faculty research associate in the Department of Chemistry and Biochemistry at Arizona State University. Dr. Pizzarello's research activity over the last 24 years has focused on the study of organic components of carbonaceous chondrites. The work has contributed to the recognition, identification, and molecular and isotopic characterization of their main extractable organic constituents. She is currently assessing the organic content of the Tagish Lake meteorite, a new, pristine carbonaceous chondrite that fell in Canada. Dr. Pizzarello is principal investigator for a NASA study on chiral analyses of organic compounds in carbonaceous meteroites and she is also coinvestigator and collaborator for a NASA study on hydrogen isotopic compositions of individual organic compounds in carbonaceous meteorites.

JANET L. SIEFERT is a faculty fellow in the Department of Statistics, Rice University. She also serves as a faculty mentor at the W.M. Keck Center for Computational and Structural Biology. Her research interests are phylogeny reconstruction, prokaryotic biochemical systems and ecosystem evolution, origin of life, RNAs, and astrobiology. She is the recipient of numerous awards, including the Ruth Satter Memorial Citation of Merit, the award of the Association for Women in Science, and the Boehringer Ingelheim Fonds short-term fellowship for study at the Gesellschaft fuer Biotechnologische Forschung. She collaborated with several colleagues recently on a project entitled "Phylogenetic Analysis and Molecular Modeling of Ribozyme Variants."

ROGER SUMMONS is a professor in the Department of Earth, Atmospheric, and Planetary Sciences at the Massachusetts Institute of Technology. He is also a member of the Earth System Initiative, where he and his team collaborate with microbiologists and ecologists to identify and study environmentally and geologically significant processes that are mediated by microorganisms. His laboratory research focuses on biogeochemistry of microbial ecosystems, chemistry of biomarkers and molecular fossils, isotopic biosignatures, geochemistry of petroleum, and coevolution of life and Earth's surface environment. Dr. Summons is a fellow of the Royal Australian Chemical Institute and a fellow of the Australian Academy of Science.

NEVILLE J. WOOLF is a professor in the Department of Astronomy and the Steward Observatory, University of Arizona. His research interests cover instrumentation, the search for extrasolar planets, and the development of interferometry. He served as a research associate astronomer at Lick Observatory and as a NRC senior fellow at NASA-Goddard Research Center. Dr. Woolf lectures on the possible existence of life on other planets.

LUCY M. ZIURYS holds a joint appointment as professor in the Department of Astronomy and the Department of Chemistry at the University of Arizona. She is currently on staff at the Steward Observatory. Dr. Ziurys's areas of specialization are interstellar chemistry; millimeter/submillimeter high-resolution laboratory molecular spectroscopy; millimeter/submillimeter observations of interstellar molecules; millimeter-wave devices for astronomical and laboratory applications; and laboratory production of transient molecules. Her honors and awards include NSF Presidential Young Investigator (1990) and Presidential Faculty Fellow (1992). In 1999 she won the prestigious Morino Lectureship from the University of Tokyo for her scientific work in the field of molecular spectroscopy and its application to the astrochemistry of the interstellar medium. Dr. Ziurys has been actively involved in the discovery of interstellar molecules in interstellar space.

STAFF

DAVID H. SMITH joined the staff of the Space Studies Board in 1991. He is the senior staff officer and study director for a variety of NRC activities, including the Committee on Planetary and Lunar Exploration and the Committee on the Origins and Evolution of Life. He received a B.Sc. in mathematical physics from the University of Liverpool in 1976 and a D.Phil. in theoretical astrophysics from Sussex University in 1981. Following a postdoctoral fellowship at Queen Mary College, University of London (1980-1982), he held the position of associate editor and, later, technical editor of *Sky and Telescope*. Immediately before joining the staff of the Space Studies Board, Dr. Smith was a Knight Science Journalism Fellow at the Massachusetts Institute of Technology (1990-1991).

ROBERT L. RIEMER joined the staff of the National Research Council in 1985. He served as senior program officer for the two most recent decadal surveys of astronomy and astrophysics and has worked on studies in many areas of physics and astronomy for the Board on Physics and Astronomy, where he served as associate director from 1988 to 2000, and the Space Studies Board. Prior to joining the NRC, Dr. Riemer was a senior project geophysicist with Chevron Corporation. He received his Ph.D. in experimental high-energy physics from the University of Kansas at Lawrence and his B.S. in physics and astrophysics from the University of Wisconsin at Madison.

RODNEY N. HOWARD joined the Space Studies Board as a senior project assistant in 2002. Before joining SSB, most of his vocational life was spent in the health profession—as a pharmacy technologist at Doctor's Hospital in Lanham, Maryland, and as an interim center administrator at the Concentra Medical Center in Jessup, Maryland. During that time, he participated in a number of Quality Circle Initiatives which were designed to improve relations between management and staff. Mr. Howard obtained his B.A. in communications from the University of Baltimore County in 1983. He plans to begin coursework next year for his master's degree in business administration.

CATHERINE A. GRUBER is an assistant editor with the Space Studies Board. She joined SSB as a senior program assistant in 1995. Ms. Gruber first came to the NRC in 1988 as a senior secretary for the Computer Science and Telecommunications Board and has also worked as a outreach assistant for the National Academy of Sciences-Smithsonian Institution's National Science Resources Center. She was a research assistant (chemist) in the National Institute of Mental Health's Laboratory of Cell Biology for 2 years. She has a B.A. in natural science from St. Mary's College of Maryland.