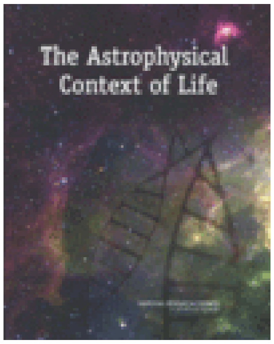
Free Executive Summary

The Astrophysical Context of Life



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

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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

[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

[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.

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.

[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,
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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.

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