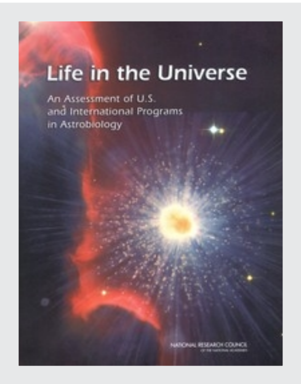

Life in the Universe: An Assessment of U.S. and International Programs in Astrobiology

DETAILS

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AUTHORS

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

Life in the Universe

An Assessment of U.S. and International Programs in Astrobiology

Committee on the Origins and Evolution of Life

Space Studies Board—Board on Life Sciences

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Preface

In the NASA Authorization Act of 2000, the U.S. Congress called for a National Academies' review of National Aeronautics and Space Administration (NASA) and other government and nongovernment programs regarding the detection of life in the universe. Both implicit and explicit in the congressional language were concerns over whether opportunities existed to enhance NASA's program via expanded coordination and cooperation among relevant activities both within NASA and outside.

The past few years have witnessed the discovery of planets around other stars; strong circumstantial evidence for a liquid-water ocean beneath the surface of Jupiter's moons Europa, Ganymede, and Callisto; controversial claims for biological activity in a martian meteorite; the discovery of life in extreme terrestrial environments; and a genuine revolution in our understanding and manipulation of the genetic mechanisms of the living cell. In response to the public and scientific excitement generated by these discoveries, NASA initiated a major new thrust in cross-disciplinary research activities among the biological, geological, astronomical, and planetological sciences. Astrobiology is motivated at its core by the goals of understanding the origin and evolution of life on Earth, the potential of life for future expansion into the cosmos, the incidence of habitable planets in the cosmos, the stability of Earth's present habitable environment, and the frequency and complexity of life elsewhere in the universe.

Two major programs in NASA are relevant to the intellectual endeavor of astrobiology. One is the Astronomical Search for Origins program, which uses astronomical tools to look broadly at an ensemble of scientific questions about the origins of galaxies, stars, and planetary systems including our own, and of life itself. The other is the Astrobiology program, which supports studies regarding the chemical and biological origins of life and searches for evidence of extinct or extant life beyond Earth. These two thrusts have much in common.

NASA's research program includes basic research in intramural and extramural laboratories, spaceflight missions, and advanced technology development. In addition to the more traditional portfolio of research grants and investigations conducted from Earth-orbiting and interplanetary spacecraft, the program includes the NASA Astrobiology Institute (a nontraditional "institute without walls," whose members are expected to collaborate on interdisciplinary research and yet be geographically dispersed) and substantial efforts in outreach and education. The Astrobiology program includes exobiology (strictly speaking, research concerned with the origin of life and its potential existence beyond Earth) and evolutionary biology (the history and mechanisms of the diversification of terrestrial life and its coevolution with Earth) that sometimes are conducted in collaboration with other agencies. An example is the exploration of Lake Vostok in Antarctica, to be conducted with the National Science Foundation as a major partner.[1] Other agencies also support scientifically relevant work—for example, research on extremophiles near deep-ocean hydrothermal vents (National Oceanic and Atmospheric Administration)[2] and in high-radiation-background environments (Department of Energy), waters of high heavy-metal content, extreme pH,[3] and subfreezing conditions. Exploring at the opposite end of the spectrum of potential evolved life forms is the privately financed Search for Extraterrestrial Intelligence (SETI) program, which uses the tools of radio astronomy to search for signatures of life outside the solar system (see Chapter 6 in this 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 (COEL)—a joint activity reporting to the Space Studies Board and the Board on Life Sciences of the National Research Council—was tasked with assessing the state of the NASA Astrobiology program and providing a report by mid-2002 presenting the following:

- An assessment of the direction of the NASA Astrobiology program, focusing 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 should also be considered;
- Identification of any enhancements to the U.S. program that might be warranted; and
- Recommendations for coordination of NASA efforts with those of other parties.

COEL was not asked to prepare a strategy for doing research in astrobiology; such an effort would require a separate study. The present study was formally initiated when COEL met in Irvine, California, in February 2001 to outline the report and to hear comments from NASA officials and NASA Astrobiology Institute principal investigators. The committee drafted the report at its July 2001 meeting in Washington, D.C., during which it heard from officials of other federal agencies involved in astrobiology, and in November 2001 at a meeting at the SETI Institute in Mountain View, California, where programs to search for signals from intelligent extraterrestrial life were examined. The report was completed in February 2002 at the University of Arizona in Tucson, where technologies relevant to the search for and characterization of extrasolar planets were discussed. The text was approved by the Space Studies Board and sent to external review in April 2002. The report was revised and updated in response to reviewer comments during a meeting held in Woods Hole, Massachusetts, in May 2002 and was approved for public release the following month. Copies of this report were distributed in an unedited, prepublication format in July 2002. This, the final edited text, was prepared in October 2002 and supersedes all previous versions of this report.

COEL's work in drafting this report was made easier thanks to the input provided by many individuals, including the following: Charles Beichman (Jet Propulsion Laboratory), Baruch Blumberg (NASA Astrobiology Institute), Daniel Brocious (Smithsonian Astrophysical Observatory), Christopher Chyba (SETI Institute), Mark Clampin (Space Telescope Science Institute), Laird Close (University of Arizona), Edward DeLong (Monterey Bay Aquarium Research Institute), David Des Marais (NASA Ames Research Center), Frank Drake (SETI Institute), Daniel Drell (Department of Energy), Jack Farmer (Arizona State University), Debra Fischer (University of California, Berkeley), Ronald Greeley (Arizona State University), Rosalind Grymes (NASA Astrobiology Institute), John Hill (Large Binocular Telescope Observatory), Gerda Horneck (German Aerospace Center), Scott Hubbard (NASA Headquarters), Bruce Jakosky (University of Colorado), Margaret Leinen (National Science Foundation), Alfred McEwen (University of Arizona), Christopher McKay (NASA Ames Research Center),

[1]J. Jouzel, J.R. Petit, R. Souchez, N.I. Barkov, V.Y. Lipenkov, D. Raynaud, M. Stievenard, N.I. Vassiliev, V. Verbeke, and F. Vimeux, "More Than 200 Meters of Lake Ice Above Subglacial Lake Vostok, Antarctica," *Science* 286: 2138-2141, 1999.

[2]C.L. Van Dover, *The Ecology of Deep-Sea Hydrothermal Vents,* Princeton University Press, Princeton, N.J., 2000.

[3]K.J. Edwards, P.L. Bond, T.M. Gihiring, and J.F. Banfield, "An Archaeal Iron-Oxidizing Extreme Acidophile Important in Acid Mine Drainage," *Science* 287: 1796-1799, 2000.

Michael Meyer (NASA Headquarters), Kenneth Nealson (University of Southern California), Hiroshi Ohmoto (Pennsylvania State University), Leslie Orgel (Salk Institute), Juan Perez-Mercader (Centro de Astrobiología), Carl Pilcher (NASA Headquarters), Bruce Runnegar (University of California, Los Angeles), Peter Smith (University of Arizona), Sean Solomon (Carnegie Institution of Washington), William Sparks (Space Telescope Science Institute), Jill Tarter (SETI Institute), and Joshua Zimmerberg (National Institutes of Health).

This report has been reviewed in draft form 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 review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. The committee wishes to thank the following individuals for their review of this report: Paul Butler (Carnegie Institution of Washington); A.G.W. Cameron (Lunar and Planetary Laboratory, University of Arizona); Heinrich D. Holland (Harvard University); Antonio Lazcano (Universidad Nacional Autónoma de México); Jack W. Szostak (Howard Hughes Medical Institute, Harvard Medical School, and Massachusetts General Hospital); and J. Craig Wheeler (University of Texas, Austin).

Although the reviewers listed above 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 Mary Jane Osborn (University of Connecticut Health Center). Appointed by the National Research Council, she 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 addressed. Responsibility for the final content of this report rests solely with the authoring committee and the institution.

Contents

Dedicated to the memory of

David Wynn-Williams (1946–2002),

who epitomized the spirit of astrobiology through his research, his teaching,

and his exploration of far-flung lands at the polar extremes of Earth.

We are not looking for a grand vision. We are looking for the beginnings of vision.

—John Baross, 2001

Executive Summary

The past decade has seen a remarkable revolution in genomic research, the discoveries of extreme environments in which organisms can live and even flourish on Earth, the identification of past and possibly present liquid-water environments in our solar system, and the detection of planets around other stars. Together these accomplishments bring us much closer to understanding the origin of life, its evolution and diversification on Earth, and its occurrence and distribution in the cosmos. A new multidisciplinary program called Astrobiology was initiated in 1997 by the National Aeronautics and Space Administration (NASA) to foster such research and to make available additional resources for individual and consortium-based efforts. Other agencies have also begun new programs to address the origin, evolution, and cosmic distribution of life. Five years into the Astrobiology program, it is appropriate to assess the scientific and programmatic impacts of these initiatives.

Edward J. Weiler, NASA's associate administrator for the Office of Space Science, tasked the Committee on the Origins and Evolution of Life (COEL) with assessing the state of NASA's Astrobiology[1] program and with providing by mid-2002 a report presenting the following:[2]

- An assessment of the direction of the NASA Astrobiology program;
- 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 should also be considered;
- Identification of any enhancements to the U.S. program that might be warranted; and
- Recommendations for coordination of NASA efforts with those of other parties.

STATUS OF NASA'S ASTROBIOLOGY PROGRAM

In preparing this study, the committee recognized that NASA's Astrobiology program, and astrobiology as a novel intellectual endeavor, are still at an early stage of definition and development. Nevertheless, remarkable progress has been made over a short period of time in defining the key scientific questions, initiating research and training programs, and developing collaborations on a national and international scale. As this intellectual endeavor matures toward becoming a scientific field in its own right, continued effort must be exerted to involve the appropriate breadth of disciplines and diversity of novel techniques in astrobiological research. These may change with time as progress is made on the search for life elsewhere in the universe and for a deep understanding of how life originated on Earth and evolved over 4 billion years.

The 1998-1999 roadmap for the Astrobiology program is the product of a successful initial planning effort that shaped the scope of astrobiology and gave the research area a set of objectives to guide research funding and the assembly of research groups. As with every such initial effort, there is room for improvement. COEL finds the current roadmap to be too broad and not selective enough in defining these three categories: the central research goals of astrobiology, those goals that are peripheral to astrobiology but still may contribute, and those research areas that are genuinely outside astrobiology as an intellectually coherent study.

Recommendations

- NASA should more carefully craft its definition of astrobiology as a discipline whose central focus is a selected set of issues directly linked to the origin, evolution, and ubiquity of life in the cosmos.
- An important operational goal of astrobiology is to inform NASA missions with respect to the techniques and targets for the search for life elsewhere, and the search for clues to the steps leading to the origin of life on Earth.
- The core scientific areas within astrobiology ought to be specifically and selectively defined as those that deal with the origin, evolution, and occurrence of life in the cosmos as embraced in NASA's research and analysis programs in the general areas of exobiology, evolutionary biology, planetary origin and evolution, cosmochemistry, and astronomical studies relating to the search for origins.
- Global change should be defined more carefully in the next roadmap with respect to the time scales that are relevant to the astrobiological goals of understanding environments conducive to the origin and evolution of life.
- A critical analysis should be undertaken of the relevance of microgravity research to the central scientific goals of astrobiology.

After almost 5 years of funded research within NASA's Astrobiology program, enough additional evolution of astrobiology has occurred that a new roadmap will be of value. COEL understands that NASA is now undertaking a new roadmap planning process.

The ongoing roadmapping process for NASA's Astronomical Search for Origins program, which concerns research into the origin and evolution of physical systems from cosmological to planetological scales, has the opportunity to address an area of concern that this committee considers in the body of this report in some detail: the relationship and interaction between the Astronomical Search for Origins and the Astrobiology programs (see Chapter 3). In particular, the research interactions between these two areas seem much weaker at present than they could be, and certainly much weaker than those between Astrobiology and the evolutionary biology or geobiological communities.

Recommendation

In the current respective roadmap processes, careful attention should be paid to the relationship between the Astrobiology and the Astronomical Search for Origins programs in order to identify overlaps, common areas of research, and approaches to enhance the level of interaction in research.

These limitations aside, the committee is impressed by the speed with which a community is being built in astrobiological research and education. Many of the standard indicators of the emergence of a bona fide new interdisciplinary field—journals, university programs, annual meetings, and so on—seem to suggest that Astrobiology is developing quickly and carving a special role for itself among NASA programs, and that an intellectually distinct discipline may be taking shape.

The enthusiasm and drive of scientists who have aligned their central research foci toward astrobiology, in particular those involved in the NASA Astrobiology Institute (NAI), made a deep impression on the committee. NASA Headquarters, NASA's Ames Research Center, and key members of the scientific community have done a good job of initiating the institute, encouraging a broader community of astrobiology researchers, and developing and implementing training and degree programs. Nonetheless, certain issues need to be addressed to ensure long-term scientific and programmatic success.

Recommendation

NASA should undertake a comprehensive review of the scientific and educational results of its Astrobiology program in general, and of the NASA Astrobiology Institute (NAI) in particular, at the end of a decade of activity, in order to assess the longer-term effects of the founding of the new program and the new institute on the research area. This review would include analysis of the significant scientific contributions that have arisen from the program. It should be undertaken no later than 2008, when the NAI is a decade old.

NASA's Astrobiology program has evolved, through the efforts of NASA Headquarters, into a tripartite structure of consortium science, individual principal investigator (PI) research, and technology-development programs. The highest-profile element is the NAI, originally conceived as a virtual institute relying on electronic communication technologies to allow extensive interactions between participating institutions (nodes) without geographic limitations. While the NAI has generated exciting and, in some cases, important research results even though it is less than 5 years old, the virtual institute development has lagged behind.

Recommendation

NASA should critically review the electronic communication needs and costs required to make the NASA Astrobiology Institute a virtual institute along the lines of the original vision established by NASA's Ames Research Center and the advisory committees tasked with evaluating the institute concept. Upgrades to accomplish this vision ought to be in place by the time the next round of node selections is made.

Because of the scale and high profile of its coordinated research, the NAI is important to the Astrobiology program. NASA has done a good job of publicizing NAI research and wrapping it into NASA planning for astrobiologically relevant missions. However, for astrobiology to mature as a long-term scientific field, NASA must also attract and recognize astrobiologically oriented researchers who are not affiliated with the NAI. Likewise, the NAI's research programs and its ability to place graduates of its programs in positions beyond the existing NAI nodes depend on enhancing scientific collaborations with non-NAI scientists. To date, the NAI has not adequately fostered such collaborations.

Recommendation

As a new interdisciplinary scientific endeavor, astrobiology spans a much larger volume of intellectual and capital resources than the NASA Astrobiology Institute itself. In its public materials, NASA should emphasize the broad base of national scientific capability in astrobiology, which is stabilized by three types of programs (consortium science, individual principal investigator research, and technology-development programs) and not just the institute itself.

The NAI itself should encourage collaborations not merely within the institute, but with outside investigators and facilities as well. A particularly important avenue for promoting cooperation has been the NAI's role in the establishment of "focus groups" to examine specific topical areas relevant to astrobiology. Membership on some, but not all, focus groups has been openly advertised and is available to all interested scientists.

Recommendation

The administration of the NASA Astrobiology Institute should consider an incentive in which the nodes are rewarded for broadening intellectual involvement in their research beyond the NAI boundaries. In particular, ensuring that the focus groups are open for participation by all interested parties will strengthen their effectiveness in fostering such interactions.

The consortium-based nature of NAI research requires long periods for the full benefits of the research to be realized. At the same time, the introduction of new nodes can create novel opportunities for the institute. NASA's challenge will be to balance these two kinds of opportunities appropriately over the lifetime of the NAI.

Recommendation

The current NASA Astrobiology Institute nodes should conduct careful, internal, nonadvocate reviews of their own programs to ensure that they continue to fulfill the original intent of the NAI in establishing astrobiology as a field of study. These reviews should honestly and frankly assess the extent to which the NAI model has been responsible for new discoveries and insights that traditional research and analysis programs might not be able to foster. NAI nodes should be required to reapply every 5 years for membership in the NAI. Weaker nodes should be retired so that the NAI has an opportunity to benefit from new ideas and approaches.

ENHANCEMENTS TO NASA'S ASTROBIOLOGY PROGRAM

In addition to the NAI, a second important experiment in consortium science is the NASA Specialized Center of Research and Training (NSCORT) program at two institutions—the Exobiology Center at the University of California, San Diego, and the New York Center for Studies of the Origin of Life at Rensselaer Polytechnic Institute—the first of which has been in existence for a decade. NSCORT science is co-located at each institution (or confined to a small number of geographically adjacent institutions) rather than being collaborative between a larger number of geographically dispersed institutions as is the case with the NAI. The success of the older of the two NSCORT consortia in producing talented and accomplished graduates recommends this program, and COEL sees it as a worthy second element in the consortium science leg of the Astrobiology triad.

Recommendation

The NASA Specialized Center of Research and Training (NSCORT) program should continue as a distinct approach to localized consortium science. It should continue in parallel with the NASA Astrobiology Institute and should neither be altered in an attempt to fit the NAI mold, nor merged with the NAI.

The research and analysis effort in the Astrobiology program is currently focused on the Exobiology program, which in many ways is the intellectual precursor of the Astrobiology program. The general merits of competitive research and analysis programs have been discussed in other National Research Council (NRC) reports,[3] and in Astrobiology they have an added benefit of extending research beyond NAI member consortia. Research and analysis is a key second leg of the triad of science and technology activities that foster this new research area, and it could be expanded modestly to the point at which it is comparable in size with the other components of the program.

COEL commends NASA for recognizing the long-term and continuing high value of research and analysis programs within and related to NASA Astrobiology. These and comparable programs are essential to the continued scientific vigor of astrobiology through the introduction of new ideas and researchers to the program.

COEL offers no advice on whether the Exobiology and Evolutionary Biology programs should be merged, except to point out that some programmatic advantage exists in maintaining the identity of the different disciplines through well-focused research and analysis programs.

Recommendation

NASA should ensure a balance of astrobiological research activity among its research and analysis programs (i.e., the current Exobiology and planned Evolutionary Biology programs), its technology programs (i.e., the Astrobiology Science and Technology Instrument Development program and the Astrobiology Science and Technology for Exploring Planets program), and the NASA Astrobiology Institute. A well-balanced triad of science and technology efforts expressed through these programs will ensure the long-term vigor of astrobiological research.

Just as NASA's Planetary Instrument Definition and Development Program (PIDDP) within the Solar System Exploration program has served to generate new ideas for flight instruments, so should the Astrobiology program contain a component for the development of new technologies relevant to the field. While the NAI is playing an important role in mission definition through its focus groups, a crucial additional component is a technology-development program for astrobiological instrumentation that might fly in space or be used to analyze samples and environments here on Earth.

Recommendations

- Although the Astrobiology program's present level of involvement in flight missions is appropriate, NASA is cautioned against attempting to force the NASA Astrobiology Institute or other elements of Astrobiology into an artificially focused role of trying to design specific "astrobiology missions." While individual NAI investigators are encouraged to propose instrument concepts or whole Discovery-class (or equivalent) missions, NASA should be careful not to bias the usual peer-review selection process for instruments and missions by specially labeling proposals proffered by NAI investigators.
- NASA should continue the two astrobiology technology programs, Astrobiology Science and Technology Instrument Development, and Astrobiology Science and Technology for Exploring Planets, and in addition the Planetary Instrument Definition and Development Program (in the Solar System Exploration program) and the Extrasolar Planets Advanced Missions Concepts program (in the Astronomical Search for Origins program) as part of the efforts to detect life in this and other planetary systems.

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 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.

ASTROBIOLOGY AND OTHER PUBLIC AND PRIVATE PROGRAMS

Other federal agencies besides NASA have played important and distinctive roles in the fostering of astrobiology. The National Science Foundation's (NSF's) Life in Extreme Environments (LExEn) program was vital in bringing talented biologists and physical scientists together to explore important problems in astrobiology outside the NAI itself. Moreover, the National Institutes of Health (NIH) is the wellspring from which comes much of the biological talent that NASA desires.

The Department of Energy (DOE) has a uniquely effective program for sequencing the genomes of microorganisms, many of which are of relevance to astrobiological research. NASA should strengthen its connection with the DOE to take advantage of the latter's uniquely productive and broad gene-sequencing program. Similarly, the U.S. Department of Agriculture (USDA) has devoted considerable attention to sequencing the genomes of economically important plants and animals. These data are potentially important to astrobiologists for the information they may contain about long-term climate excursions. NASA should engage the USDA in the development of a program to enable astrobiologists to both interpret and use this record. As a basic rule, access of astrobiologists to genome-sequencing opportunities at other government agencies should be designed so as not to discourage or exclude access to other sequencing capabilities, including those in private industry.

Recommendation

In view of the diverse activities in basic science relevant to astrobiology conducted by other federal agencies, NASA should engage the National Science Foundation, Department of Energy, National Institutes of Health, and the U.S. Department of Agriculture in detailed studies of the desirability of, and the means for establishing, bilateral and multilateral programs in astrobiology.

Perhaps the most romantic venture in astrobiology is the search for extraterrestrial intelligence (SETI). This effort has had a checkered reception by scientists and federal lawmakers, with the result that the current efforts are almost entirely privately funded. The SETI Institute in Mountain View, California, the nexus of such efforts in the United States, has accomplished in a spectacular way the founding of a science institute and the procurement of stable private funding to carry on the search. Because world-class scientists lead the SETI Institute, it is a carefully designed effort and worthy of notice by the scientific community and relevant federal agencies.

The leadership of the SETI Institute has forged a unique endeavor out of private and public funds, maintained a high standard of scientific research through its peer-reviewed research activities, and articulated clearly and authoritatively the rationale for approaches to a comprehensive search for extraterrestrial intelligence.

INTERNATIONAL ACTIVITIES IN ASTROBIOLOGY

International efforts in astrobiology have lagged behind those in the United States but are now beginning to gain momentum. While Europe has long had vigorous exobiology research efforts, it was the creation of the NAI that spurred the development of astrobiological institutes and consortia overseas. Notable among these are a large research center in Spain and consortia in the United Kingdom, Australia, and across the European Union. The efforts of a handful of visionary scientists abroad and in the United States, working with the NAI as a catalyst, enabled these to be initiated. For joint endeavors in astrobiology between the United States and other countries to be fruitful, work will have to be undertaken by NASA to ease the strictures of technology transfer regulations.

COEL applauds the efforts of Spanish astrobiologists in creating a world-class astrobiology center, the Centro de Astrobiología (CAB), from the ground up. NASA and the NAI deserve credit for doing their part in fostering the growth of the CAB through encouragement and the creation of associate membership status for the CAB in the NAI.

The committee encourages NASA and the NAI to continue to seed efforts in astrobiology worldwide through the free exchange of scientific information, experimental techniques, and computational results. Association or affiliation with the NAI ought to be used as a tool to encourage international efforts in this regard, but it should be approached with care so as not to give the impression that the United States is in any sense pressuring other countries.

Finally, the committee notes that the International Traffic in Arms Regulations (ITAR) will continue to make it difficult for scientists to fully interact on astrobiology projects internationally. The changes to ITAR that came into force in April 2002 may ease this situation by making it clearer that fundamental research collaboration does not require an ITAR license and that the exchange of most forms of technical information in the public domain can proceed without impediment with nationals of NATO and a few other allied countries. Some problems remain, especially collaboration with foreign scientists and students from non-NATO countries, so it is important for NASA to continue to monitor the situation and to help ensure that ITAR does not have a suffocating effect on the free exchange of the results of space and biological sciences research.

CONCLUSION

The foundational questions that astrobiology addresses will not be answered in the short term. But as a coordinated, focused effort involving consortium- and individual principal investigator-driven science, as well as technology development, NASA's Astrobiology program is well poised to catalyze fundamentally important discoveries concerning the origin of life, its distribution in the cosmos, and the long-term fate of life on Earth.

In the list below, COEL summarizes the overall problems that NASA's Astrobiology program should address in the near future to ensure its own health:

- *Definition of astrobiology and its goals*. The widespread perception that astrobiology as both an intellectual endeavor and a NASA program is ill-defined continues to impair its interaction with related scientific disciplines.
- *Evaluation of the impact of NAI on astrobiology*. With one or two exceptions, the PIs of the current nodes, as well as the NAI director, argued that it was premature to assess how the NAI has affected astrobiology in ways that a standard research and analysis program could not have. This question will be asked with increasing urgency in the coming years, and before long the NAI must undertake a serious self-assessment to answer it.
- *Review/retirement of existing programs*. While the desire to maintain funding for excellent nodes is understandably strong, the mission of the NAI demands that new researchers and new institutions be brought into the NAI to expand the emerging field of astrobiology. A full recompetition at the end of each 5-year cycle, in which old and new consortia compete with each other, is the best way to accomplish this.
- *Insularity of the NAI*. The natural tendency for NAI consortia to see their scientific "universe" as being within the NAI must continue to be resisted. The NAI should be a catalyst for interdisciplinary research in astrobiology among a much larger set of researchers than those who are members of NAI nodes.
- *The "astro" in astrobiology*. Astronomy remains the key fundamental discipline that has yet to have a full impact on astrobiology. Efforts to better integrate astronomical research into the Astrobiology program require careful planning, as well as recognition that astronomical studies relating to the search for origins themselves constitute a discipline that is so active and expansive as to merit consideration of its own virtual institute, modeled on the NAI.

NOTES AND REFERENCES

1. For clarity, COEL distinguishes between *Astrobiology*—the NASA program—and *astrobiology*—a broader area of scientific inquiry defined by some of its practitioners as a new field—of which NASA's program is a part.
2. See the preface for the full charge given to the committee.
3. See, for example, Space Studies Board, National Research Council, *Supporting Research and Data Analysis in NASA's Science Programs,* National Academy Press, Washington, D.C., 1998.

1

The Roadmaps

BACKGROUND OF NASA'S 1998-1999 ASTROBIOLOGY ROADMAP

The word *astrobiology* was used in a published text as far back as 1953[1] but was superseded by the term *exobiology*, which came to represent the NASA effort to understand the origin of life and to search for life elsewhere. In 1995, then-Associate Administrator for Space Science Wesley Huntress, in trying to infuse the biological sciences into NASA's Space Science activities, used the term *Astrobiology* to connote a proposed new multidisciplinary program in the space and biological sciences. The program would be in large measure (but not exclusively) an intellectual outgrowth of the NASA Exobiology and Astronomical Search for Origins research and analysis programs, within which important progress had been made already on specific questions regarding the origin and ubiquity of life in the cosmos.

In 1996, then-NASA Administrator Daniel Goldin recognized and sought to capitalize on the immense public interest generated by the 1996 report of putative fossil organisms in the martian meteorite ALH84001,[2] and by the discovery of planets orbiting nearby stars like the Sun.[3] With the help of NASA's Ames Research Center and the late Gerald Soffen, who was project scientist for the Viking missions to Mars in the 1970s, NASA began the definition of the new program in Astrobiology, broadly construed as the investigation of the origin, distribution, and future of life in the universe.[4]

In 1997, the agency announced its intention to create a geographically distributed institute for the study of astrobiology, to provide general research funding under this rubric, and to use the institute as an experiment in the use of new communications technology to enable scientists to work intimately on collaborative research regardless of geographical limitations. Eleven initial nodes were selected, each headed by a lead university, research institute, or NASA center. The Ames Research Center serves as the central administration for what became known as the NASA Astrobiology Institute, or the NAI. In 2001, four additional nodes were selected, bringing the total to 15. Because the NAI is such a central part of the NASA Astrobiology program, the Committee on the Origins and Evolution of Life (COEL) devotes a separate chapter to its evaluation (see Chapter 2).

Subsequent to the formation of the NAI in 1998, NASA began the process of developing an Astrobiology Roadmap. The stated purpose of this document was to guide research not only in the NAI but in general research and analysis (R&A) programs related to astrobiology, and to develop a complementary technology program for space-based experiments.

CONTENT OF THE ASTROBIOLOGY ROADMAP

While the detailed events that transpired during the development of the Astrobiology Roadmap are an interesting exercise in scientific sociology, they are not immediately germane to the task given to COEL and so their retelling is left to others. The output of the roadmapping effort was a series of subject areas motivated by the following questions, which were developed by NASA and the external scientists who comprised the Roadmap Team.[5] The roadmap begins with three overarching questions, whose ultimate answers lie far in the future but which motivate the research:

1. How does life begin and evolve?
2. Does life exist elsewhere in the universe?
3. What is life's future on Earth and beyond?

These questions, in turn, motivate a set of 10 more detailed "goals" for the scientific research to be conducted within the context of the Astrobiology program. Possible research projects to address these goals have a more detailed set of objectives, but the Astrobiology Roadmap itself offers a set of 17 generic objectives on which, arguably, significant progress can be made in the near-term future. Those objectives, which sample well a more detailed set of objectives formulated by scientific researchers, are listed verbatim in Table 1.1.

The 10 goals developed in the roadmap process are summarized below, as a narrative set of questions:

1. Understand how life arose on Earth. The origin of life on Earth represents the starting point for assessing the degree of commonality of life in the cosmos. Where did the raw materials for life on Earth come from? How were the elements manufactured in previous generations of stars, and in what sorts of molecular arrangements were these materials found in the nascent disk of gas and dust from which our planetary system formed? How and from where was this material delivered to Earth? What were the environments in which life evolved from nonliving chemical systems? What were the phenotypic features of the first organism? When did life begin on Earth? Is the origin of life a common part of the processes of planetary formation and evolution?

2. Determine the general principles governing the organization of matter into living systems. Complementary to the first goal is the "holy grail" of experimental biologists and chemists who work on life's origins: by just what processes does organic (here meaning "carbon-bearing") matter become organized into self-sustaining, living things, that is, life? Does the organization proceed within organic chemical systems themselves, or is templating within mineralogical or other inorganic systems required? What are the temporal and spatial scales and the levels of starting system complexity required for the origin of life? What sources of energy are required? What other kinds of chemical or physical systems can self-organize into patterns that we might call life? Is liquid water required for life? Is life a phenomenon requiring at least two basic kinds of polymers (molecules composed of repeated fundamental units), one devoted to information, the other to structure and catalysis? Indeed, what is the most general but useful definition of life?

3. Explore how life evolves on the molecular, organismal, and ecosystem levels. The history of life is recorded both in the rocks of Earth and in the genetic information stored in every organism. From these disparate types of records, it is possible to map out an extraordinarily complex history of evolutionary changes in life, punctuated by environmental catastrophes that in part (sometimes nearly in whole) emptied ecosystems. What are the detailed genetic relationships among Earth's organisms? How much has the evolution of life been driven by large-scale transfer of genetic molecules among types of microorganisms? How have the mutability and duplicative nature of the genetic material, coupled with environmental changes, driven the evolution of life? Why are there three major domains of life, when did they arise, and have other domains become extinct? What factors internal and external to life led to the origin of complex cells (eukaryotes), and to multicellular complex organisms? What is the evolutionary origin of human intelligence, how is it coupled to self-awareness, and has it arisen in other organisms?

4. Determine how the terrestrial biosphere has coevolved with Earth. The evolution of life on Earth has proceeded over the course of 4 billion years, during which the planet itself has undergone profound changes to the

TABLE 1.1 Objectives Offered for Astrobiology by the NASA Astrobiology Roadmap

Overarching Questions and Topical Areas	Scientific Goals
1. How does life begin and evolve?	
Sources of organics on Earth	Determine whether the atmosphere of the early Earth, hydrothermal systems or exogenous bodies were significant sources of organic matter.
Origin of life's cellular components	Develop plausible pathways by which ancient counterparts of membrane systems, proteins and nucleic acids were synthesized from simpler precursors and assembled into protocells.
Models for life	Create lab models of replicating, catalytic systems capable of evolution, and metabolism in primitive living systems.
Genomic clues to evolution	Expand and interpret the genomic database of a select group of microorganisms so as to reveal the history of evolution.
Linking planetary and biological evolution	Describe the causes and effects associated with development of Earth's early biosphere and the global environment.
Microbial ecology	Define how single-organism and group physiological processes structure microbial communities, influence their adaptation and evolution, and affect detection on other planets.
2. Does life exist elsewhere in the universe?	
The extremes of life	Identify the environmental limits for life by examining biological adaptations to extremes in conditions.
Past and present life on Mars	Search for evidence of ancient climates, extinct life and potential habitats for extant life on Mars.
Life's precursors and habitats in the outer solar system	Determine the presence of life's chemical precursors and potential habitats for life in the outer solar system.
Natural migration of life	Understand the natural processes by which life can migrate from one planet to another, and quantify the probabilities.
Origin of habitable planets	Determine (theoretically and empirically) the ultimate outcome of the planet-forming process around other stars.
Effects of climate and geology on habitability	Define climatological and geological effects upon the limits of habitable zones around the Sun and other stars to help define the frequency of habitable planets in the universe.
Extrasolar biomarkers	Define an array of astronomically detectable spectroscopic features that indicate habitable conditions and/or the presence of life on an extrasolar planet.
3. What is life's future on Earth and beyond?	
Ecosystem response to rapid environmental change	Determine the resilience of local and global ecosystems to natural and human-induced disturbances.
Earth's future habitability	Model the future habitability of Earth by examining the interactions between the biosphere and the chemistry and radiation balance of the atmosphere.
Bringing life with us beyond Earth	Understand the human-directed processes by which life can migrate from one world to another.
Planetary protection	Refine planetary protection guidelines and develop protection technology for human and robotic missions.

SOURCE: Office of Space Science, National Aeronautics and Space Administration, Astrobiology Roadmap, Ames Research Center, Moffett Field, Calif., 1999, available online at <http://astrobiology.arc.nasa.gov/roadmap/introduction.html>.

atmosphere, oceans, and geology. The atmosphere has evolved from being rich in carbon dioxide to being rich in oxygen; correspondingly, the oceans have evolved from being anoxic to being oxygen-rich. The cycling of Earth's outer layer, or crust, has slowed with time, and buoyant masses of granites—called continents—have come to cover about 40 percent of a surface that initially may have been almost entirely basaltic—and largely submerged. The rate of impacts on the surface of Earth diminished rapidly in the first 10 percent of the history of the planet, then declined more slowly with time. When did conditions allow the first organisms and ecosystems to survive? To what extent has the evolution of life been determined by evolving global conditions and sudden environmental catastrophes versus the long-term changes in the genetic code itself?

5. Establish limits for life in environments that provide analogues for conditions on other worlds. Over the past couple of decades, scientists have found life flourishing in environments previously thought to be uninhabitable—from ocean floor vents at high temperatures and extreme pressures to ecosystems buried beneath a kilometer of basaltic rock. Such extreme environments are potentially the refuge of organisms with primitive qualities, which suggests that these organisms are the modern descendants of ancient life forms. What are the most extreme environments of temperature, pressure, salinity, acidity, desiccation, radiation (both acute and chronic), and other parameters under which organisms can survive? What are the limits under which spores can exist and be successfully revived? Can organisms survive impacts from cometary or asteroidal bodies? Can they survive transport on the fragments of ejected crust to a neighboring world?

6. Determine what makes a planet habitable and how common those worlds are in the universe. The fundamental requirements for life on Earth are an adequate source of thermodynamic-free energy, appropriate sources of carbon and other critical elements, and liquid water. Therefore, the simplest definition of a habitable world would be one that supports the three fundamental requirements. Determining which planets have liquid water today, when and how much liquid water occurred in the past, and whether adequate stores of biogenic elements and energy exist is a daunting problem. In our own solar system, the debates rage on regarding when and where Mars had liquid water, and whether it exists today—a quarter century after the valley networks on that planet were first revealed. Compelling but circumstantial evidence exists for a liquid-water ocean under the icy crust of Europa, maintained by tidal heating; if life exists there, it is a long way from the traditional "habitable zone" defined by orbital distances similar to that of Earth around Sun-like stars. Do Mars and Europa support life now, or has Mars supported life in the past? Does the profoundly cold but organic-rich Titan, the giant moon of Saturn, support at least the early steps toward life's origin? What is the range of possibilities for habitable zones around stars like and unlike the Sun? How do Earth-like planets gain their water and organics, and how many are in planetary systems environments that, over billions of years, resemble that of Earth? Could an Earth-sized body orbiting a star like the Sun at a Mars-like distance support life, and for how long?

7. Determine how to recognize the signature of life on other worlds beyond the solar system. The detection of planets orbiting stars that shine a billion or more times more brightly than the planets themselves is a daunting task; as yet it has been done indirectly, with one exception. Even when large ground- and spaced-based telescopic systems become capable of teasing the light of a planet out from under the glare of its parent star, the challenging task of determining whether such planets are habitable remains unsolved—even if the biosphere that one is looking for is Earth-like. Indeed, distinguishing a planet whose atmosphere contains gases in chemical disequilibrium is not enough, because one must know whether the disequilibrium is caused by biological processes or by rapid evolution of the planet's atmosphere itself. The cases of planets where primitive life has only a toehold, or on which life forms different from Earth's exist, or which have only subsurface life beneath an inhospitable surface such as Europa's, may represent those that are impossible to detect remotely. How could one detect the effects of biospheres on parent planets many light years away? How can one separate rapid abiotic planetary evolution from the biochemical modification of surface and atmosphere? To what extent could one detect the signature of life on planets with atmospheres very different from Earth's, or on planets with no atmospheres at all? Finally, how can the search for signals from extraterrestrial civilizations be designed to provide a useful negative answer in the absence of a history-changing positive result?

8. Determine whether there is (or once was) life elsewhere in our solar system, particularly on Mars and Europa. The first directed search for life in our own solar system, the Viking expeditions to Mars, yielded negative results regarding the presence of life at the landing sites. Debate continues on the claim of evidence for biological activity in the martian meteorite ALH84001 more than 6 years after the initial exciting announcement.[6] What are the most robust sets of life-detection experiments to carry to Mars, or to Europa? What types of robotic exploration capabilities are required to find and access sites at which such tools would be useful? Is it best to search for life directly on the surface of a body (e.g., in situ) or to return a sample to Earth? What are the hazards of contaminating a planet with organisms carried from Earth, or of contaminating Earth with a returned sample? How would one recognize life that had an origin separate from earthly life?

9. Determine how ecosystems respond to environmental change on time scales relevant to human life on Earth. Life on Earth today, while still dominated in numbers by the prokaryotes (archaea and bacteria), may be profoundly challenged by the vigor and power of human industrial activities. The species extinction rate today has been amplified directly and indirectly by human activity, relative to that of the average background seen in the geologic record of the last half-billion years (10 percent) of Earth's history. What does the geologic record tell us of the range of climatic extremes and time scales for change over the last half-billion years? How does the coupled air-ocean-land system on Earth respond to rapid changes in basic properties?

10. Understand the response of terrestrial life to conditions in space and on other planets. Humanity first left Earth to set foot on another world in 1969. For the astronauts who went to the Moon, even the span of a few days on an alien world was a profoundly moving and lonely experience. While the pace of human expansion beyond Earth slowed after that initial burst of activity, robotic emissaries continue to push outward through the solar system to the realm of nearby interstellar space. Ultimately, humankind might try to colonize the nearby planets and the space around them.

ANALYSIS OF THE 1998-1999 ASTROBIOLOGY ROADMAP

Scope

The scope of the Astrobiology Roadmap is exceedingly broad, encompassing research from the astronomical study of star formation to global change research. While there is a temporal, evolutionary sequence that connects these and many other fields of endeavor as a kind of "story" of the origin and evolution of life, astrobiology as a working endeavor is not as intellectually cohesive as it might be. This lack of cohesion manifests itself to different degrees in different research areas. In global climate change, for example, the connection with astrobiology needs to be more carefully and clearly defined. The specific means by which research on the causes and behaviors of global climate change on decadal time scales—a key thrust of the U.S. Global Change Research Program—informs research on overarching question 3 in Table 1.1 is not well articulated in the roadmap. It is easier to see the relevance of studies of longer-term climate changes (e.g., periods of glaciation) and abrupt large-scale climate events (such as those seen toward the end of the last glaciation)[7] to the key questions associated with planetary habitability. Resolving this issue requires a more careful examination of the role of the U.S. Global Change Research Program in astrobiology, a task that should form an important part of the preparation of the next roadmap.

COEL would also like to see a more careful study of the relevance of microgravity research in Earth orbit to NASA's Astrobiology program, since NASA itself makes this connection in a cursory way in the current roadmap. While gravity has influenced biological processes on Earth, the study of extant organisms subject to varying values of the gravitational acceleration (from zero to terrestrial) may not inform us as to how fundamental biological processes might be reinvented elsewhere under vastly different gravitational conditions. Thus, scientific research planned for the International Space Station (ISS) may not be directly relevant to the central goals of NASA's Astrobiology program. While it is true that the ISS is advertised as the stepping-stone to colonizing other worlds and hence to moving life from Earth into space, this is a symbolic and philosophical linkage rather than a scientific one.

COEL does not view as constructive NASA's effort to embrace virtually the totality of physical and life sciences in its roadmap definition of astrobiology. The intellectual center of astrobiology remains in the scientific activities that NASA refers to as evolutionary biology, exobiology, cosmochemistry, and (in part) the astronomical search for origins and planetary sciences. While there should be no impediment to scientists talking across disciplinary boundaries to gain new insights, astrobiology ought not to be oversold as being broader than it really is.

Recommendations

- NASA should more carefully craft its definition of astrobiology as a discipline whose central focus is a selected set of issues directly linked to the origin, evolution, and ubiquity of life in the cosmos.
- An important operational goal of astrobiology is to inform NASA missions with respect to the techniques and targets for the search for life elsewhere, and the search for clues to the steps leading to the origin of life on Earth.
- The core scientific areas within astrobiology ought to be specifically and selectively defined as those that deal with the origin, evolution, and occurrence of life in the cosmos as embraced in NASA's research and analysis programs in the general areas of exobiology, evolutionary biology, planetary origin and evolution, cosmochemistry, and astronomical studies relating to the search for origins.
- Global change should be defined more carefully in the next roadmap with respect to the time scales that are relevant to the astrobiological goals of understanding environments conducive to the origin and evolution of life.
- A critical analysis should be undertaken of the relevance of microgravity research to the central scientific goals of astrobiology.

Advances

Significant scientific advances have occurred in the past 5 years in addressing some of the questions identified in the Astrobiology Roadmap. Examples of a few areas that have borne particular fruit, with examples of references, include the following:

- Analysis of complex organic chemistry in interstellar clouds of gas and dust that give rise to new stars and solar systems;[8]
- Direct study of extrasolar giant planets through transits and spectra;[9]
- Discovery that living organisms, normally found on Earth's surface, can survive at extreme pressure;[10]
- Evidence from geologic features that liquid water once flowed on the surface of the planet Mars;[11]
- Indications from magnetic field geometry that liquid water likely exists today below the icy crust of three of Jupiter's large moons, most notably, Europa;[12]
- Ground-based studies of Titan, indicating both temporal and spatial variability and the presence of organic molecules;[13]
- Chemical-isotopic hints that microbial life on Earth existed 3.9 billion years ago, almost to the period of early heavy cometary bombardment;[14]
- Evidence that liquid water existed in the crust of Earth some 4.3 billion years ago;[15]
- Elucidation of the detailed history of evolution and the phylogenetic relationships among organisms;[16] and
- In vitro evolution experiments that have come close to developing self-replicating systems in the laboratory.[17]

Some of these advances will necessitate modifications to the roadmap to reflect insights that were not available 5 years ago. For example, the roadmap played down the study of extrasolar giant planets as a precursor to the study of extrasolar terrestrial planets, in part because there was no opportunity to determine the physical and atmospheric parameters of an extrasolar giant planet 5 years ago; the opportunity exists now, through study of transits and possibly other techniques. Likewise, the assumption in the roadmap that an aggressive and near-term program of exploration of Europa would make it an important astrobiological target on a decadal time scale (i.e., 1999 to 2009) turned out to be overly optimistic. It appears now that the next mission to Europa will launch well after 2010. Nonetheless, in general, the roadmap was well conceived in identifying the larger questions, without micromanaging at the more detailed level.

After almost 5 years of funded research within the Astrobiology program, enough additional evolution of the field of astrobiology has occurred that a new roadmap will be of value; COEL understands that NASA has begun a new roadmap planning process and applauds that effort.[18]

CONTENT OF THE NASA ORIGINS ROADMAP

The roadmap for NASA's Astronomical Search for Origins program,[19] revised in late-2002, considers all programs that deal with the origin of physical and biological structures in the cosmos, and hence formally includes astrobiology within its themes. The current Origins Roadmap takes as its starting point four goals:[20]

1. To understand how galaxies formed in the early universe,
2. To understand how stars and planetary systems form and evolve,
3. To determine whether habitable or life-bearing planets exist around nearby stars, and
4. To understand how life forms and evolves.

The first of these goals looks at the evolution of chemical and physical systems on galactic and cosmic scales, which includes the production of biogenic elements and their dissemination into regions of formation of later generations of stars and their planets. The intersection here with astrobiology is largely in the question of the occurrence and frequency of habitable extrasolar planets. Our bias is to expect only stars of generation equivalent to that of the Sun (with abundant elements heavier than hydrogen and helium) to possess rocky planets of substantial size. This presumption affects at least the strategy for surveying the Milky Way galaxy for terrestrial-sized planets using gravitational microlensing. Current research on the chemical and physical evolution of our galaxy paints a rather complex picture of the enrichment of heavy elements with time.[21] In consequence, rather detailed and subtle arguments have been made that there could be a gradient of habitability associated with the spatially and temporally variable chemical enrichment of our galaxy.[22] Detailed study of stellar metallicity as a function of the occurrence of planets, of position within the galaxy, and of age is called for to lead to better understanding of both the relationship between habitable planet formation (which includes the issue of a sufficient supply of the raw materials for life) and metallicity, and gradients in metallicity versus time and distance from the galactic center. These issues couple in the question of the ubiquity of the occurrence of life in the cosmos, and hence such studies represent a potentially important area of interaction between astronomical research (and hence the Astronomical Search for Origins program) and astrobiology. Collaborative research on this topic among astrobiologists and stellar and galactic astronomers would help repair the problem of insufficient interactions (see the discussion in Chapter 3).

Goals 2 and 3 of the Origins Roadmap cover the formation of stars and planets and the search for and characterization of habitable planets around other stars. These issues are central to astrobiology as defined by the Astrobiology Roadmap (see overarching question 2 in Table 1.1), but they utilize techniques and approaches (both theory and observation) from astronomical research. Goal 4 concerns issues central to astrobiology, understanding the origin and evolution of life. This goal includes, according to the Origins Roadmap, how matter is organized into living systems and what the limits to life are in different planetary environments, but the latter only with respect to microbial communities. The Origins Roadmap then concludes, referring only to the topics under goal 4, that "Astrobiology is the scientific discipline that will make all of these studies possible."[23]

There is thus an interesting disconnect between the Astrobiology and the Origins Roadmaps. The former includes a broader range of topics as being part of NASA's Astrobiology program than does the latter, encompassing astronomical issues such as organic chemical evolution in space, formation of planets, and the search for habitable planets as important themes in astrobiology. On the other hand, the Origins Roadmap itself comprises a set of four goals that roughly correspond to a logical and connected sequence from galaxies through planetary systems and on to life, but then considers astrobiology as a scientific discipline to concern itself only with the last of these, namely, life itself.

The committee finds this disconnect to be intellectually rather disturbing. Astronomy is a science centrally important to the understanding of the occurrence of life in the cosmos. The detection of planets around other stars, their characterization in terms of habitability, the observation of stars and planets in the act of formation, the investigation of interstellar and interplanetary chemistry, and the context of a galaxy replete with ultraviolet radiation, ionization, and fast particles all are scientific elements strongly identified with astrobiology. Yet, paradoxically, with the exception of astrochemistry, in which work on organic chemistry in molecular clouds and primitive solar system bodies informs the earliest stages of life's origins, astronomers engaged in astrobiologically relevant pursuits do not in the main interact with the Astrobiology program. Few participate in the NAI nodes or attempt to or successfully obtain funding through opportunities tagged by NASA as being part of the Astrobiology program. The bulk of the intellectual contributions that astronomy makes to astrobiology are enabled by other programs, such as the Jet Propulsion Laboratory (JPL) Navigator flight programs, National Science Foundation (NSF) Astronomy program, and NASA R&A grants for astronomical studies of origins. Despite two rounds of NAI selections, there is no NAI node whose principal focus is astronomical research in support of astrobiology goals, although one or two of the nodes laudably include some astronomical research. Chapter 3 analyzes this divide further and proposes specific steps to encourage more intimate interaction between the astronomers on the one hand and the geologists, biologists, chemists, and planetary scientists fully engaged in astrobiology on the other.

Recommendation

In the current respective roadmap processes, careful attention should be paid to the relationship between the Astrobiology and the Astronomical Search for Origins programs in order to identify overlaps, common areas of research, and approaches to enhance the level of interaction in research.

THE 2000 SPACE SCIENCE STRATEGIC PLAN

The Strategic Plan issued by NASA's Office of Space Science in 2000 is an overarching document that implicitly includes both the Astrobiology and the Origins Roadmaps.[24] Because the details of these programs and how they interact are really the purview of the roadmaps themselves, COEL does not make specific comments about the much more general material present in the strategic plan. It would be helpful, however, for the next strategic plan to include a discussion of the relationship between NASA's Astrobiology and Astronomical Search for Origins programs.

ESTABLISHMENT OF A COMMUNITY IN ASTROBIOLOGY

NSF's Ridge Program—which began in 1990 and was intended to focus multidisciplinary investigations to understand the midoceanic ridges and their biology—provided an opportunity for a self-selection process to occur among interested scientists. Those unwilling to extend their interests from their own particular areas of expertise to embrace the larger goals and techniques of the multidisciplinary program drifted away from the effort, leaving behind a core community of broad-based scientists. These in turn established their own journals and degree programs and held special sessions at meetings of established scientific societies.

Astrobiology today has been through a similar experience. Only a subset of individuals from the fields underpinning this endeavor have embraced the larger goals of astrobiology beyond their particular discipline, but they form the core of a very active and exciting new science. Several institutions had established degree or certificate programs in astrobiology with non-NASA funding (e.g., from NSF) before the NAI was even founded. The number of courses, degree programs (which are usually concentrations or minors supplementing degrees in traditional areas), and textbooks in astrobiology is increasing. More than a dozen faculty lines have been established within the NAI nodes. Commercial publishers have established two peer-reviewed journals of astrobiology—*Astrobiology,* published by Mary Ann Liebert, Inc.,[25] and *The International Journal of Astrobiology,* published by Cambridge University Press.[26] Special sessions on astrobiology have taken place at society conferences such as those of the American Chemical Society, the American Geophysical Union, and the American Astronomical Society, and a biennial NAI science meeting and other plenary conferences are also held. All of these signs indicate that astrobiology is beginning to evolve into a distinctive area of research and perhaps will become a new field in much the way that planetology did in the 1960s. As one of the long-term goals of the NASA Astrobiology Roadmap, this apparent emergence must be seen as encouraging. However, ultimately it makes sense to foster the emergence of a new discipline only if the result is to bring new insights to bear on scientific problems, so that the fundamental goal of basic research, to create new knowledge, is achieved.

Given the NAI's relative youth, its principal investigators (PIs) found it difficult to provide a list of new discoveries that would not have been made in the absence of the NAI structure or the Astrobiology program as a whole. COEL sent a letter to each of the PIs requesting their response to this issue, and with only a few exceptions, the response was that the question was premature. Throughout the program, several areas can be identified where focused research on traditional issues continues under the aegis of Astrobiology funding. In other cases, new interdisciplinary collaborations have been forged. The NAI has given a broader focus to work whose genesis was in the disciplinary research and analysis programs, and it has opened up paths of interdisciplinary connections. Some of these connections are merely colleagues from different fields coming together to discuss their individual research; in other cases, specific collaborative experimental or field investigations are being conducted. Further, one cannot come away from the national astrobiology meetings without remarking how well the big questions are being addressed, how easy it is to explain to the informed layperson what the research means, and how readily talented students are attracted to this research area.

In summary, anecdotal evidence has been provided by scientists from a number of institutions centrally involved in astrobiology, through the NAI or NSF-funded programs, that their science is gaining an intellectual identity of its own. The evidence includes more diverse and better students, researchers from different disciplines attacking problems that they never would have approached previously, and state-of-the-art tools to which they might not otherwise have access. The committee does recommend, in Chapter 2, that the NAI nodes themselves conduct detailed, soul-searching reviews (perhaps through the use of nonadvocate panels) of the extent to which their programs have generated genuinely new discoveries that could not have been achieved in the absence of the NAI structure.

The enthusiasm and drive of scientists who have aligned their central research foci toward astrobiology, and in particular those involved in the NAI, made a deep impression on COEL. NASA Headquarters, the Ames Research Center, and key members of the scientific community have done a good job in designing and initiating the institute, in encouraging a broader community of astrobiology researchers, and in developing and implementing training and degree programs.

Recommendation

NASA should undertake a comprehensive review of the scientific and educational results of its Astrobiology program in general, and of the NASA Astrobiology Institute (NAI) in particular, at the end of a decade of activity, in order to assess the longer-term effects of the founding of the new program and the new institute on the research area. This review would include analysis of the significant scientific contributions that have arisen from the program. It should be undertaken no later than 2008, when the NAI is a decade old.

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2

The Structure of the NASA Astrobiology Program

Astrobiology research at NASA is performed programmatically under three rather different structures (see Figure 2.1): the consortium-based science of the NASA Astrobiology Institute (NAI) and the NASA Specialized Center of Research and Training (NSCORT) program; the research and analysis (R&A) programs; and the technology-development programs. Table 2.1 lists the Fiscal Year (FY) 2002 budget figures under each category. While the NAI and the technology-development programs are new, the Exobiology R&A program and the NSCORT program have been ongoing at NASA for many years. It is important to note that while the NAI is the most publicly visible part of the NASA Astrobiology program, it represents less than half of the total funding for the program—and far less than half when one considers relevant research programs in related scientific disciplines. The committee reviews each of the elements of the program in the following sections. Some rebalancing of existing elements is recommended in the final section of the chapter. Then, Chapter 3 discusses the more fundamental issue of enhanced interaction between astrobiology and the planetary and astronomical sciences.

THE NASA ASTROBIOLOGY INSTITUTE

Summary Properties of the Institute

The NASA Astrobiology Institute began operations in 1998. The planned initial budget was approximately $4 million to $6 million, rising to an anticipated annual budget of $18 million in FY 2003. The funds are derived from NASA's Office of Space Science (Code S), with small contributions from the Office of Biological and Physical Research (Code U) and the Office of Earth Science (Code Y).

The director of NASA's Ames Research Center appoints the NAI director, with the concurrence of the relevant enterprise associate administrators at NASA Headquarters. Nobel laureate biologist Barry Blumberg succeeded the first director, Scott Hubbard of the Ames Research Center, in 1999. Blumberg stepped down in April 2002, to be succeeded by a new director. The director has his or her own Science Advisory Council to provide advice on broad issues relating to the NAI. An Executive Council, consisting of the principal investigators (PIs) of the NAI's component parts (nodes), guides the management of the NAI, and the broader astrobiological scientific community defines new research directions though regular workshops that address the entire research area of astrobiology.

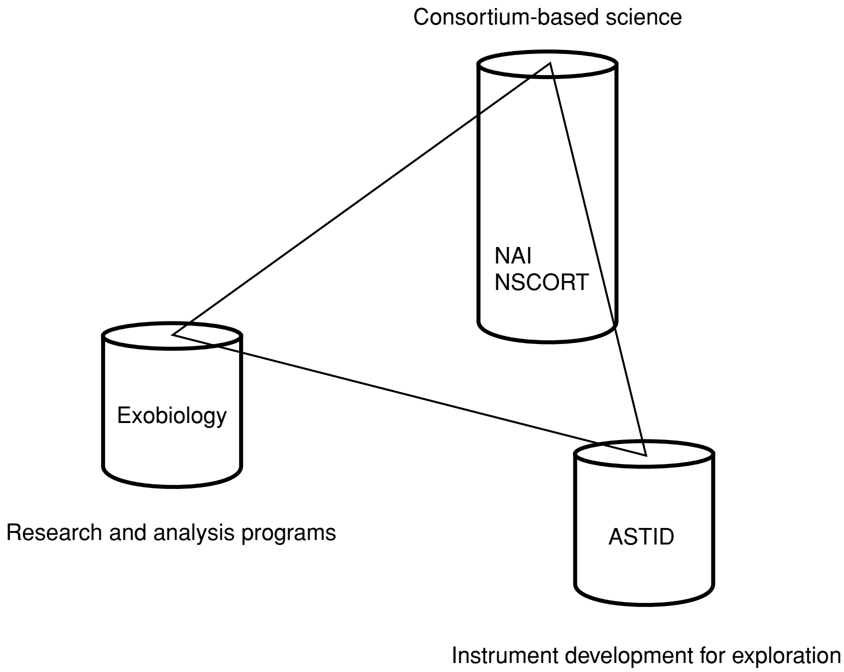

FIGURE 2.1 The three pillars of NASA's Astrobiology program today.

The Organization of the NAI

The members of the NAI are organizations, not individuals (see Table 2.2 for a list of the lead institutions and their demographics). The 15 university and research center teams were selected in two phases as institute members, on the basis of competitive proposals that included both planned research programs and institutional commitments (with nonfederal funds) to astrobiology. NASA supports the nodes through cooperative agreements with Ames Research Center for an initial term of 5 years, with the opportunity to recompete for renewal every 5 years

TABLE 2.1 FY 2002 Funding (in FY 2002 dollars) of Major NASA Astrobiology Program Elements

Program	Funding (in millions of dollars)
Consortium-based	
NAI	18
NSCORT	2
Research and analysis	
Exobiology	8.6
Evolutionary Biology	1.3
Technology development	
ASTID	6
ASTEP	5

NOTE: Only programs specifically tagged as part of the NASA Astrobiology program are included.

TABLE 2.2 Demographics of the 15 NAI Nodes

		Primary Participants				
NAI Nodes	Principal Investigator	At Host Node	At Other NAI Nodes	Other U.S.	International	Totals
Ames Research Center	David Des Marais	27	8	23	7	65
Arizona State University	Jack Farmer	40	3	10	0	53
University of California, Los Angeles	Bruce Runnegar	45	3	4	5	57
Carnegie Institution of Washington	Sean C. Solomon	24	1	11	0	36
University of Colorado	Bruce Jakosky	27	0	2	0	29
Harvard University	Andrew H. Knoll	11	0	20	1	32
Jet Propulsion Laboratory (1)	Kenneth H. Nealson	7	6	41	1	55
Jet Propulsion Laboratory (2)	Victoria S. Meadows	8	3	6	0	17
Johnson Space Center	David McKay	14	2	14	0	30
Marine Biology Laboratory	Mitchell Sogin	15	0	8	5	28
Michigan State University	Michael Thomashow	3	0	5	0	8
Pennsylvania State University	Hiroshi Ohmoto	64	7	33	14	118
University of Rhode Island	Steven D'Hondt	3	0	2	0	5
Scripps Institute	M. Reza Ghadiri	19	0	3	0	22
University of Washington	Peter D. Ward	18	5	4	0	27

SOURCES: NASA Astrobiology Institute, *Annual Science Report: Year 2, July 1999-June 2000*, CD-ROM, Ames Research Center, Moffett Field, Calif., 2001. Data for the following nodes: Jet Propulsion Laboratory (2), Michigan State University, University of Rhode Island, and University of Washington, were taken from their research proposals, posted on the NAI Web site.

within a total planned institute lifetime of at least 20 years. Further detail on the work being done by each of the nodes appears in the NAI's annual report.[1]

Were NAI money to be spread evenly among the approximately 720 researchers (this does not include students) listed by the 15 nodes, the average annual grant would be roughly $25,000. (This is a modest overestimate, as NASA Ames retains a fraction for centralized administrative activities.) In fact, based on discussions with researchers from several NAI nodes, the committee found that the distribution of resources within the NAI is far from uniform, with many researchers receiving little or no NAI support at all, while others rely on it as the primary driver of their program. Conversely, the selected universities made a major commitment to the NAI in their proposals, including faculty positions, cost-sharing on equipment, and other financial commitments that add perhaps 20 to 30 percent to the total amount of the commitment. Nonetheless, it is clear that the NAI will not be the principal source of funding for most researchers in astrobiology, even within the NAI itself. COEL does not recommend a change of course in this regard, because the NAI works as a catalyst of research in astrobiology. Researchers and educators stimulated to pursue astrobiology by involvement in the NAI will, and should, continue to seek funding from a range of public and private sources for their own research programs.

The Role of the NAI

The NAI identifies its purpose as follows:

- Carrying out, supporting, and catalyzing collaborative interdisciplinary research;
- Training the next generation of astrobiology researchers;
- Providing scientific and technical leadership on astrobiology investigations for current and future space missions;
- Exploring new approaches using modern information technology to conduct interdisciplinary and collaborative research among widely distributed investigators; and

- Supporting outreach by providing scientific content for K-12 education programs, teaching undergraduate classes, and communicating directly with the public.

The NAI itself sponsors regular astrobiology workshops, as well as more focused programs in response to research opportunities or NASA requirements. It brings together the astrobiology community to chart the future and provide new ideas to NASA planners. The NAI sponsors the biennial scientific conference in astrobiology, which began in 2000. A Director's Discretionary Fund is used to support innovative research ideas with seed money and to encourage scientists at member organizations to undertake unconventional and risky projects that address fundamental questions in astrobiology. A NASA Astrobiology Postdoctoral Fellow program,[2] administered by the National Research Council, selects talented young astrobiology researchers and supports them directly in order to facilitate work that cuts across departmental and institutional boundaries. These fellows are encouraged to spend time at more than one organization in order to help bind together the members of the institute.

Focus Groups

The NAI is also charged with advising NASA on requirements for new technology or specific flight missions needed to obtain critical data in the space environment related to astrobiological questions. An example is provided by NASA's focus on Mars exploration, including the search for evidence of past (fossilized) life and the possibility of extant ecosystems surviving on Mars today.[3] While the NAI was not directly involved in shaping the architecture of the current Mars program, it created a focus group of interested scientists whose input on site selection was presented in a unified form through unpublished white papers.[4] In addition, a group of the NAI PIs (i.e., the principal investigator of one of the 15 node teams; see Table 2.2) formulated a white paper on the astrobiological value of different types of martian samples in 1999.[5]

Perhaps the most visible of the NAI programs, one conceived and encouraged by Director Blumberg, was the establishment of focus groups to examine specific topical areas relevant to astrobiology. While scientists within the NAI lead the focus groups, membership on a subset of the groups has been openly advertised and is available to all interested scientists. Much of the work of the focus groups is done by e-mail and some by videoconferencing, with occasional face-to-face meetings at convenient times. Active focus groups as of the end of 2001, with their chairs listed, are the following:

- Mars—J. Farmer, Arizona State University;
- Ecogenomics—D. Des Marais, Ames Research Center, and M. Sogin, Marine Biology Laboratory;
- Mission to Early Earth—A. Anbar, University of Rochester, and S. Mojzsis, University of Colorado;
- Evogenomics—S.B. Hedges, Pennsylvania State University, and J. Lake, University of California, Los Angeles;
- Europa—R. Greeley, Arizona State University; and
- Astromaterials—D. McKay, Johnson Space Center.

The committee commends the NAI for creating the focus groups, which have enabled extensive interactions between the NAI and the larger community in astrobiology and related fields. This has particularly been the case for the focus groups that have been openly advertised and made available to all interested participants.

The Quality of Research

The foundational activity of the NAI nodes is intended to be collaborative, cross-disciplinary research on astrobiological problems. Using electronic communications technologies, research teams are supposed to freely interact over large distances, to the extent that laboratory experiments at one facility might be conducted remotely from another institution. This "virtual" aspect of the NAI has not yet been properly implemented. Nonetheless, the research coming from the 15 teams overall is vigorous and in many cases truly cross-disciplinary. The science coming from the NAI teams, judging from the number of publications and quality of the journals publishing the research, is

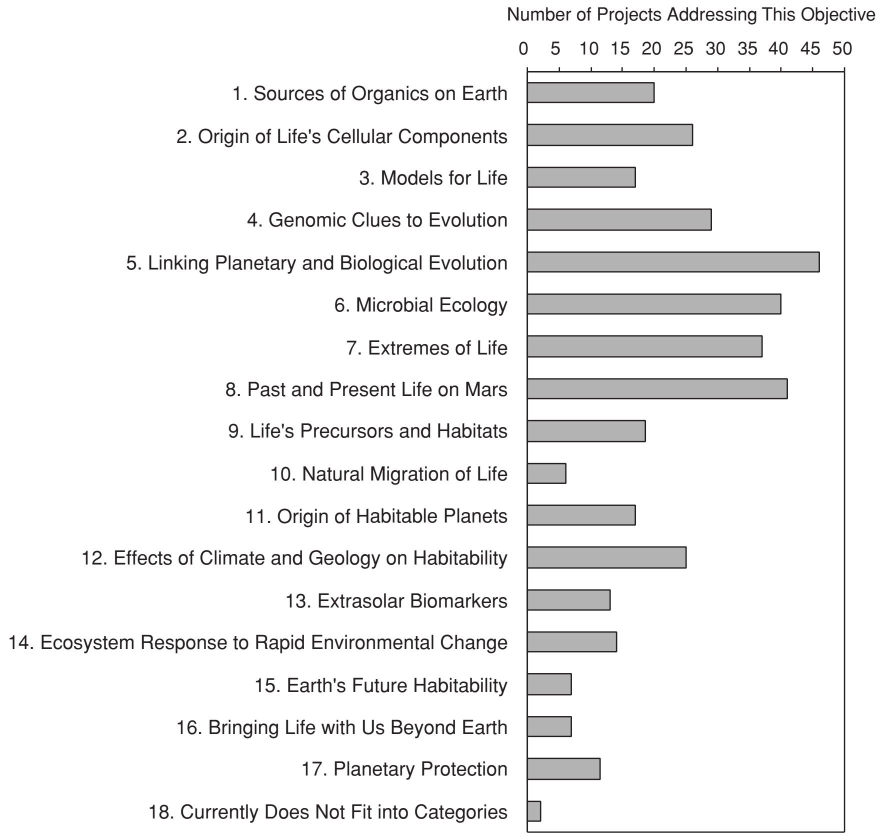

FIGURE 2.2 NASA Astrobiology Institute research project areas in 2001. SOURCE: NASA Astrobiology Institute.

of high quality. (Long-standing journals in the field include *Icarus* and *Origin of Life and Evolution of the Biosphere*; as mentioned in Chapter 1, two new journals publishing in the field are *Astrobiology* and *The International Journal of Astrobiology*.) A detailed summary of the research from 2001 on an institution-by-institution basis appears in the NAI annual report.[6] Figure 2.2 is a chart from the NAI showing the general areas of research.

Student Participation

At the 2001 NAI General Meeting, COEL members conducted an informal discussion with graduate students enrolled at NAI lead institutions that revealed considerable enthusiasm for the program. Students recognized that they were part of a special experiment, and they were energized by the opportunity to conduct research across disciplinary boundaries not crossed by students in traditional programs. It was evident from the discussions and a follow-up survey that students who were resident at the NAI lead institutions felt connected and involved with the NAI, while those at other campuses within the nodes did not feel as much enthusiasm for the workings of the institute. Since that time, an NAI Web site has been established to highlight programs specifically directed at student involvement in NAI activities. The NAI can enhance opportunities for astrobiology students by providing an easily accessible and updated list of internships and fellowships not funded by the NAI and the Astrobiology program. For example, the Planetary Biology Internship, a NASA-funded program, has for a number of years enabled the incorporation of American and foreign graduate students and postdoctoral researchers in NASA-supported laboratories.

One of the major concerns that both groups of students, those at lead (i.e., nodes) and collaborating sites, had was the potential for future employment. It is a specific objective of the NAI to train the next generation of astrobiological researchers. However, it is unknown how many of these students will end up in positions within the current NAI nodes, will move to other universities to found programs in astrobiology, or will go to work in more traditional academic disciplines or in industry.

As positive as the students' experiences appear to be, it is important not to overstate the impact that the NAI has had on the quality of the graduate programs themselves. For example, a number of graduate programs deal with scientific areas central to astrobiology yet are not a part of the NAI, and provide students with top-quality graduate training in research. Strong student satisfaction is evident in those programs as well, according to other studies (e.g., the Sloan survey). Many of these programs are also training grounds for future astrobiologists, and it is important to recognize and foster excellence in all such programs, regardless of whether they are members of the NAI.

Issues

COEL has identified a number of concerns regarding the NAI that it strongly recommends be taken up by the new director and by NASA Headquarters. They include the following:

- Implementation of the virtual institute concept,
- Perception of the NAI membership,
- Barriers to research collaborations, and
- Recompetition for NAI membership.

Each of these issues is dealt with in detail below.

Implementation of the Virtual Institute Concept

Although the NAI has not yet achieved its goal of being a virtual institute, significant progress has been made in the past year through the efforts of the individual PIs. The committee believes that the virtual institute concept still remains a goal central to the NAI. Although the lead institutions in each of the 11 original nodes (and later, those of the 4 newly selected nodes) were equipped early on with high-quality videoconferencing capability, the same was not true of the collaborating institutions within individual nodes. Hence, the lead institutions could videoconference with each other but not with their collaborators in the more numerous, secondary institutions. Videoconferencing therefore became a means to hold monthly meetings of the NAI Executive Committee, but little else.

Likewise, the promise of very-high-bandwidth Internet capability suffusing the entire NAI has not been realized, so that most interactions among researchers occur using the standard Internet capabilities affordable by most universities. Ames Research Center and NAI's director have recognized these shortcomings and are working to correct them, although fully wiring the entire cohort of member institutions with high-bandwidth Internet and videoconferencing service may be beyond the budgetary scope of the current NAI.

COEL recognizes that some might question whether a substantial electronic infrastructure is necessary or even desirable for the conduct of scientific research. The committee offers two responses. First, the original charter of the NAI included the institute's responsibility to test and demonstrate electronic communications technologies as a means to validate or falsify the hypothesis that a geographically distributed network of researchers could be better brought together with such technologies. COEL believes that the NAI has a responsibility to carry through on this mandate. Second, the committee heard the most enthusiasm for advanced electronic networking capability from precisely those NAI researchers who lack it—namely, those who are not at the lead institutions and desire closer interactions with colleagues there. Given this desire for such capability, the committee believes that the NAI should press forward to enable it.

Recommendation

NASA should critically review the electronic communication needs and costs required to make the NASA Astrobiology Institute a virtual institute along the lines of the original vision established by NASA's Ames Research Center and the advisory committees tasked with evaluating the institute concept. Upgrades to accomplish this vision ought to be in place by the time the next round of node selections is made.

Perception of the NAI Membership

The NAI concept has inadvertently cast a shadow on institutions that have hitherto played lead roles in disciplines foundational to astrobiology but which, for various reasons, were not selected for NAI membership. Lead institutions in the NAI are labeled and treated differently by NASA Headquarters, by NASA centers, and by the press, than are other institutions that also have a long and distinguished track record in the space and biological sciences. Many non-NAI universities have made significant investments of their own in research infrastructure, through nonfederal funding that represents value added to the Astrobiology program. The dangers inherent in excessive canonization of NAI's lead institutions is that the field will actually contract rather than expand, as non-NAI institutions with potentially important roles to play in astrobiology see doors closing and hence realign their own research priorities. COEL does not believe that NASA intended this to be the outcome of the formation of the NAI, but it may well turn out to be so.

Recommendation

As a new interdisciplinary scientific endeavor, astrobiology spans a much larger volume of intellectual and capital resources than the NASA Astrobiology Institute itself. In its public materials, NASA should emphasize the broad base of national scientific capability in astrobiology, which is stabilized by three types of programs (consortium science, individual principal investigator research, and technology-development programs) and not just the institute itself.

Barriers to Research Collaborations

While research interactions within the NAI are generally good (excluding the communications problems outlined above), scientific interaction with researchers outside the NAI is much more limited. The perception of many researchers both within and outside the NAI is that the institute represents the centrality, if not the totality, of the research infrastructure in astrobiology. When faced with the need to go outside their own discipline for collaborative help, researchers inside the NAI tend to seek out others within the institute structure itself, even when more appropriate or accomplished collaborators might be found outside the NAI.

Conversely, astrobiology researchers outside the NAI, even well-known or distinguished ones, find that they must breach an extra layer of unfamiliarity or even skepticism in trying to interact with, or participate in, NAI activities. The result is a kind of science enclave embedded within a much larger science community, separated by a low-permeability barrier. This barrier is not healthy for the development of astrobiology as a scientific discipline. COEL wonders as well whether students nurtured within this cocoonlike environment will truly be prepared to interact with the much larger scientific community beyond the NAI.

The NAI itself should encourage collaborations not merely within the institute but with outside investigators and facilities as well.

Recommendation

The administration of the NASA Astrobiology Institute should consider an incentive in which the nodes are rewarded for broadening intellectual involvement in their research beyond the NAI boundaries. In particular, ensuring that the focus groups are open for participation by all interested parties will strengthen their effectiveness in fostering such interactions.

Recompetition

It is important that the NAI have fluidity of programs and nodes that both reward superior work by existing groups and allow for novel ideas and new institutions to participate in this important experiment. Programs of larger scale require a longer time for consummation of work than do smaller-scale programs, but it is important to establish time limits and review processes to refresh the endeavor.

Recommendation

The current NASA Astrobiology Institute nodes should conduct careful, internal, nonadvocate reviews of their own programs to ensure that they continue to fulfill the original intent of the NAI in establishing astrobiology as a field of study. These reviews should honestly and frankly assess the extent to which the NAI model has been responsible for new discoveries and insights that traditional research and analysis programs might not be able to foster. NAI nodes should be required to reapply every 5 years for membership in the NAI. Weaker nodes should be retired so that the NAI has an opportunity to benefit from new ideas and approaches.

THE RESEARCH AND ANALYSIS PROGRAMS

In addition to the NAI, another important component of NASA's Astrobiology activities are the R&A programs devoted to research in exobiology and evolutionary biology.[7] Exobiology is a long-standing program within NASA, and in large measure it provided many of the discoveries that catalyzed astrobiology; the program devoted to evolutionary biology is a new one. R&A programs, far from being a remnant of the "old" way of doing business, are essential to maintaining the scientific vigor of the disciplines captured under the term *astrobiology*. They will continue to be the means by which the majority of newly minted researchers establish their programs, and by which the majority of NASA-funded scientists involved in astrobiology-related topics generate new knowledge and train new students. For most researchers within the NAI itself, R&A programs remain the principal means of garnering research funding.

Research and analysis programs periodically undergo a critical reevaluation of their utility in the context of the current NASA scientific mission. This is healthy, but it must always be done predicated on the basic realization that the programs are competitive.

Exobiology emerged as a grants program at NASA more than 30 years ago, as a way to fund ground-based basic research dealing with the origin of life on Earth and potential environments elsewhere in which life might exist—particularly on Mars. It has since developed into a substantial program supporting the research of some 100 principal investigators, mostly in the United States but with some international collaboration as well. Research grants in the Exobiology program are typically able to support a postdoctoral associate and a graduate student, with small amounts available for travel and supplies. The program has also supported fieldwork, for instance, to collect microfossils and rock specimens related to early life. Because it is important to understand the extent of the scientific accomplishments of this program, which provided a foundation to much of the research in astrobiology, a more detailed examination of the Exobiology program is presented in Box 2.1.

The goals of the research and analysis program in Evolutionary Biology are to determine the following:

- How life and planets coevolve over time,
- How life can become globally stable and persistent,
- The mechanisms for and the likelihood of major steps seen in terrestrial evolution (such as multicellularity) taking place once life arises,
- What the possible detectable signatures of extraterrestrial biospheres (in all stages of evolution) are, and

BOX 2.1 The History and Scope of NASA's Exobiology R&A Program

NASA's Exobiology program was founded in 1965; its charge was to understand the origin, evolution, and distribution of life in the universe. The program has been scientifically successful within this goal and, by sponsoring interdisciplinary research in fields as diverse as astrophysics, geochemistry, and organic chemistry, has provided an extensive body of research on and a basic understanding of prebiotic chemical evolution.

The Exobiology program provided the rationale and research basis for the establishment of the broader program of Astrobiology, to which it still pertains in scope and organization. Following are highlights of some of the research achievements of the program and an examination of its future relevance.

Carbonaceous Meteorites and the Direct Analysis of Molecular Evolution

The carbonaceous chondrites contain both soluble and insoluble organic compounds and provide a unique record for the direct study of prebiotic chemical evolution. For the past 30 years and continuing today, comprehensive molecular analyses of these meteorites have detailed a complex organic suite that contains many compounds similar or identical to those found in the biosphere, as amino acids, carboxylic acids, and sugar alcohols. More recently, a subgroup of meteoritic amino acids were found to contain L-enantiomeric excesses, that is, to be more abundant in the L-chiral form as amino acids of terrestrial proteins.[1]

This was the first unequivocal indication that a purely chemical evolutionary process, as the one believed responsible for the formation of meteorite organics, may also have been at work in chiral selection, a property known since the time of Pasteur to be intimately associated with life. In the long and so far unsettled debate on the origin of terrestrial homochirality—that is, is it a result of evolution or was it inherent to chemical evolution and preceded life?[2]—these findings appear to give weight to the latter hypothesis.

Model Syntheses of Organic Compounds Under Nebular and Planetary Conditions

Two principal mechanisms were suggested for the formation of meteoritic organic compounds. One idea, first put forward by Miller in the Miller-Urey experiment,[3] was that of the production and combination of radicals, induced by light or another form of energy, in a reducing planetary atmosphere. The other idea, proposed by Anders and collaborators, was one of a partial hydrogenation of carbon monoxide by catalytic processes in the solar nebula,[4] similar to the Fischer-Tropsch production of hydrocarbons. Both venues of formation were tested in numerous Exobiology-funded studies and, eventually, molecular and isotopic discrepancies between synthetic product and meteoritic compound showed that neither process had likely been a major source of organics in meteorites. Their formation in carbonaceous meteorites was later elucidated by analyses of stable-isotope ratios in the Murchison meteorite[5] that revealed high stable-isotope ratios for several classes of meteoritic compounds. These findings led to the current interstellar/parent-body hypothesis for the formation of carbonaceous chondrite organics. The hypothesis postulates that the accretion in the solar nebula of icy planetesimals rich in interstellar volatiles lead, upon warming, to a phase of water processes and the production of organics in the variety and complexity found in meteorites.

The Exobiology program has also supported a variety of model syntheses simulating terrestrial environments that only recently have been shown to harbor life and may be considered candidate environments for early life on Earth or, arguably, on other planets. For example, several molecules have been produced under deep-sea hydrothermal vent conditions, including such biologically relevant compounds as pyruvic acid.[6]

With similar rationale, Exobiology has supported the study of extreme terrestrial settings that could be considered analogues for environments on other planets and satellites, especially Mars and Europa. The coldest, driest, most Mars-like places on Earth are found in Antarctica's dry valleys, where the mean temperatures are –20 °C, it never rains, and precipitation is entirely in the form of snow. Here the presence of life inside the surface layers of sandstone rocks and the thick ice-covered lakes provides direct and surprising evidence of how water can persist in an extreme environment and how life can make use of water in a snow-based hydrology. Several studies have used these Antarctica analogues as models of how life would have survived on Mars as it became colder and drier over time.[7]

Early Evolution of Life

A most successful research effort initiated and supported by the Exobiology program was the set of molecular evolution studies conducted by Woese and colleagues, which eventually transformed our understanding of microbial life and diversity on Earth.[8,9] Woese's early studies of key molecular structures that are responsible for translation of nucleic acid's informational molecules into protein led to the discovery of the archaea.

These inquiries described a universal tree of life upon which the coordinates of any cellular-based organism can be mapped in quantitative, objective terms. This paradigm continues to dominate all evolutionary biology and modern molecular ecology, as evidenced by the publication of thousands of manuscripts from hundreds of laboratories throughout the biological disciplines. Studies in this new field of "molecular phylogeny" are now supported by the Exobiology program and other federal agencies, and are expected to have a significant impact on the strategic planning of NASA's future exploration of planetary and small solar system bodies.

Future Relevance to NASA Objectives

The Exobiology R&A program provides the support for basic research that individual principal investigators, with usually only a few collaborators, conceive, formulate, and set forth for peer review. Although funneled through teaching institutions and encouraging community outreach, these grants are unencumbered by obligations other than research. As such, Exobiology-funded studies have been highly productive and often groundbreaking. The program also allows investigators not participating in, or leaving from, larger consortia programs a venue for uninterrupted research.

COEL considers the Exobiology program to represent a key pillar within the broader Astrobiology structure and expects it to remain that way in the future.

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[9]C.R. Woese, O. Kandler, and M.L. Wheelis, "Towards a Natural System of Organisms: Proposal for the Domains Archaea, Bacteria and Eucarya," *Proceedings of the National Academy of Sciences* 87: 4576-4579, 1990.

• What the long-term stability of ecosystems is—including macroscopic and microscopic organisms that may be exported to support long-duration human exploration beyond Earth.

Although the research goals of the Exobiology and Evolutionary Biology activities are central to addressing some of the core questions in astrobiology, NASA's Astrobiology program in total is defined with much broader scope than is either of these programs singly or combined (see Chapter 1). That is, Astrobiology includes the origin of planetary systems and the search for extrasolar planets at one end of an evolutionary temporal sequence, and encompasses the human presence in space at the other. With respect to the two former topics, there are other R&A activities within NASA important to astrobiology. Notable among these are the Origins of Solar Systems and the Cosmochemistry programs. COEL does not advocate the movement of these two programs in particular, or others, into the Astrobiology program at NASA Headquarters, because they support many worthy projects not directly related to the central themes of astrobiology. However, in reckoning the sum total of science responsive to the Astrobiology and Origins Roadmaps and the Office of Space Science Strategic Plan, grants under these programs are relevant.

COEL commends NASA for recognizing the long-term and continuing high value of research and analysis programs within and related to NASA Astrobiology. These and comparable programs are essential to the continued scientific vigor of astrobiology through the introduction of new ideas and researchers to the program.

COEL offers no advice on whether the Exobiology and Evolutionary Biology programs should be merged, except to point out that other research and analysis programs exist that also partially support Astrobiology goals (e.g., Origins of Solar Systems). There is a programmatic tradition in NASA of maintaining the identity of interrelated disciplines through well-focused research and analysis programs, for example in the planetary sciences.

TECHNOLOGY DEVELOPMENT: THE PRIMARY RELATIONSHIP BETWEEN NASA'S FLIGHT PROGRAMS AND ASTROBIOLOGY

To date, the only significant formal interactions between flight programs and elements of NASA's Astrobiology program have been with regard to missions to Mars and, to a much lesser extent, Europa. The NAI has taken a formal position on the utility of various kinds of returned martian samples (so-called grab bags versus documented samples selected for their astrobiological interest), has played a role in landing-site selection for missions under development, and has held workshops and discussions about life detection and planetary protection. Because the state of exploration of Europa is much less advanced, there has been less opportunity for organized elements of the Astrobiology program to influence the mission development process. However, the NAI has organized focus groups on both Mars and Europa, which have provided a useful and generally applauded mechanism for structured discussions on astrobiological themes related to these two bodies.

The Astrobiology Science and Technology Instrument Development (ASTID) program provides an opportunity to fund advanced-concept studies for flight instruments that address astrobiological goals on a wide range of solar system bodies.[8] Such concepts include, for example, the development of advanced sensors that could look on-orbit for signatures of habitable environments in selected locations on Mars. Other concepts funded under ASTID can be found on the NASA Office of Space Science Web site, where titles and PIs of all funded proposals are listed after selection.

Recommendation

Although the Astrobiology program's present level of involvement in flight missions is appropriate, NASA is cautioned against attempting to force the NASA Astrobiology Institute or other elements of Astrobiology into an artificially focused role of trying to design specific "astrobiology missions." While individual NAI investigators are encouraged to propose instrument concepts or whole Discovery-class (or equivalent) missions, NASA should be careful not to bias the usual peer-review selection process for instruments and missions by specially labeling proposals proffered by NAI investigators.

The ASTID program and its new counterpart for the development of advanced instrument concepts for exploring extreme environments on Earth—the Astrobiology Science and Technology for Exploring Planets, or ASTEP, program—represent the third component of a triad of opportunities in NASA Astrobiology. This triad promotes individual peer-reviewed research (R&A), collaborative research of larger scale (NAI and NSCORT), and technology development to take advantage of and to inform these research efforts through novel instrumentation.

The Planetary Instrument Definition and Development Program (PIDDP) provides an important historical lesson, in that a number of instrument concepts that eventually flew on planetary missions were originally developed under PIDDP funding. ASTID provides an opportunity to conceive of and breadboard lightweight or even miniaturized instruments designed to address central science objectives of astrobiology—site selection, analysis of organics, search for life, and so on. After an initial selection of concepts in 2002, a second round will focus on the following topics:

- The handling of samples collected for astrobiological objectives;
- The in situ detection of possible biomarkers such as isotopic and organic measurements; and
- The development of novel access technologies such as drilling into rock or deep drilling into subsurface bedrock, soil, or ice.

Typical ASTID awards range from $30,000 to $300,000 per year, for a maximum of 3 years. This is enough to test breadboard concepts but not to produce flight hardware (or even intermediate, brassboard, hardware).

Although the ASTID program will consider novel instrumentation for use in the laboratory or in terrestrial environments, this is not the central intent of the program. NASA instituted the ASTEP program to address at least some of these parallel goals. Insofar as other federal agencies also fund terrestrial and laboratory-instrument development, COEL agrees with the priority set by NASA that put ASTID in place first, but is pleased that ASTEP is now under way as well.

COEL also notes that another program, referred to as the Extrasolar Planets Advanced Missions Concepts (EPAMC) program, exists at NASA and covers the development of ideas for novel missions to detect and characterize extrasolar planets. In this opportunity, proposals were solicited for the following activities:

- Missions that can provide a deep survey for Earth-like planets around nearby stars, as well as a broad survey for more massive planets around more distant stars, and determine the masses of any Earth-like planets that are found;
- Missions that can provide either scientific or technical support to the scientific aims of the Terrestrial Planet Finder (TPF) mission (a top priority of the most recent astronomy and astrophysics decadal survey[9]); and
- Development and/or validation activities (either ground-based or through low-cost space flight) that will provide significant technology in support of the TPF mission science goals.

The EPAMC program selected six proposals for a 6-month preliminary study; four of these will receive an additional 6 months of funding. Approximate yearlong average funding is $200,000 per concept.

Together with the competed Discovery and Midex mission lines, the ASTID, recently initiated ASTEP, PIDDP, and EPAMC programs provide a range of opportunities to propose instrument and mission concepts in support of astrobiology.

Recommendation

NASA should continue the two astrobiology technology programs, Astrobiology Science and Technology Instrument Development, and Astrobiology Science and Technology for Exploring Planets, and in addition the Planetary Instrument Definition and Development Program (in the Solar System Exploration program) and the Extrasolar Planets Advanced Missions Concepts program (in the Astronomical Search for Origins program) as part of the efforts to detect life in this and other planetary systems.

NASA SPECIALIZED CENTERS OF RESEARCH AND TRAINING

The NASA Specialized Center of Research and Training (NSCORT) program represents a kind of consortium science, distinct from that of the NAI, in which collaborating investigators are co-located at the same or adjacent institutions. While NASA originally funded NSCORT activities in a variety of life science disciplines, only two dedicated to exobiology remain, at the University of California, San Diego (UCSD) and Rensselaer Polytechnic Institute. These centers underwent a thorough review in 2001, with a very positive report issued by the review committee (chaired by Sean Solomon of the Carnegie Institution of Washington). Of particular note is the emphasis on graduate education at these programs. The much older UCSD program, in existence for over a decade, has produced a large number of doctorates in areas central to astrobiology, and many of these people are now active in their own right within this research area.

In addition to having been in existence much longer than at NAI (i.e., at least at UCSD), the NSCORT program provides an important alternative approach to consortium science from that practiced by the NAI. While the NAI constitutes an experiment in the use of electronic technology to implement collaborative science among widely dispersed institutions, the NSCORT activities have no such requirement. Their mission instead is to focus on graduate training, a job they have done well. The vigor of astrobiology is such that the two types of consortia complement each other. For these reasons, the committee finds the NSCORT program to be highly worthy of continuation.

Recommendation

The NASA Specialized Center of Research and Training (NSCORT) program should continue as a distinct approach to localized consortium science. It should continue in parallel with the NASA Astrobiology Institute and should neither be altered in an attempt to fit the NAI mold, nor merged with the NAI.

SOME FINE-TUNING OF THE PROGRAM: A QUESTION OF BALANCE

The Astrobiology program as presently constituted is moving toward a desirable state of balance among programs of consortium science, individual PI science, and technology development directed toward future exploration of terrestrial and planetary environments. This is the correct direction of evolution. However, while the consortium-science and technology-development programs are ramping up in funding amounts, the R&A portion has begun to lag behind. While COEL sees no danger in the immediate future, the long-term scientific vigor of the Astrobiology program and its ability to retain researchers newly minted in astrobiology will be undermined if this trend continues. A small investment by NASA, certainly less than $10 million, would rectify this emerging weakness.

Recommendation

NASA should ensure a balance of astrobiological research activity among its research and analysis programs (i.e., the current Exobiology and planned Evolutionary Biology programs), its technology programs (i.e., the Astrobiology Science and Technology Instrument Development program and the Astrobiology Science and Technology for Exploring Planets program), and the NASA Astrobiology Institute. A well-balanced triad of science and technology efforts expressed through these programs will ensure the long-term vigor of astrobiological research.

Figure 2.3 illustrates the committee's suggestion for how NASA's Astrobiology program might look as a triad of consortium science, traditional or individual principal investigator research, and technology development toward future exploration opportunities. The recommendation on NSCORT is reflected in its separate callout in the figure, within the consortium-based science category.

Finally, COEL calls attention to a potential weakness in a key discipline of astrobiology that might be rectified with the help of the NAI. Although the NAI histogram of research projects areas in Figure 2.2 shows a significant number of projects related to the origin of organics on Earth and the origin of life's cellular components, the actual

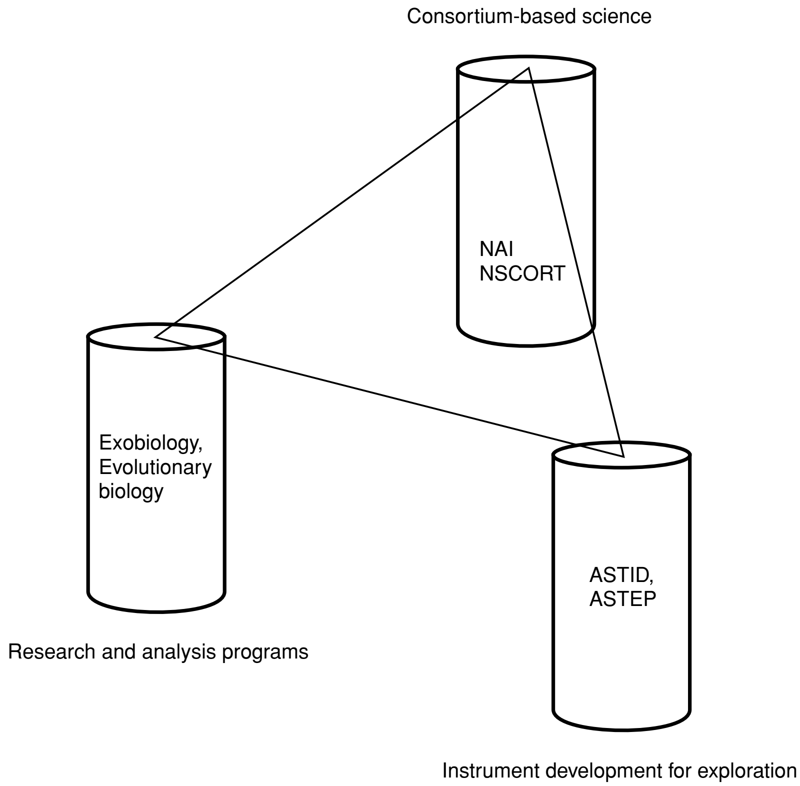

FIGURE 2.3 A balanced, long-term program in astrobiology.

number of laboratories and young researchers involved in prebiotic chemistry is small. While it is true that new approaches (e.g., hot-vent chemistry) are actively supported by the NAI, the demographics of the origin-of-life community indicate that many major researchers in the field devoted to prebiotic chemistry have retired or are not active any more. While it is likely that faculty positions will continue to be opened in the future for those devoted to RNA-related research—phylogenetic studies and biogeochemistry, for instance—the continuation and development of U.S.-based laboratories devoted to prebiotic chemistry probably merit more attention from the NAI.

NOTES AND REFERENCES

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5. The white paper is available directly from Jack Farmer and Ronald Greeley of Arizona State University.
6. More details are available online at <http://www.nai.arc.nasa.gov>.
7. For clarity, COEL uses the terms *exobiology* and *Exobiology* to distinguish between, respectively, a broad area of scientific study and the NASA program.
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3

Toward More Interaction Between the NASA Astrobiology Institute and the Planetary and Astronomical Sciences

Two space science activities, planetary science and the astronomical search for origins, have made and continue to make strong intellectual contributions to astrobiology. Yet both of these disciplines, especially the latter, are underrepresented in the Astrobiology program in general and in the NASA Astrobiology Institute (NAI) in particular. In this chapter the committee explores this imbalance and makes recommendations for its rectification.

PLANETARY SCIENCES AND ASTROBIOLOGY

Intellectually and programmatically balanced research programs within NASA have the greatest potential for successful scientific output. The planetary science community, working within the context of NASA's Solar System Exploration program, has achieved this balance after some decades of evolution. In the first decade of the existence of planetary science as a distinct discipline (through about 1970), planetary scientists focused largely on supporting the primary NASA effort in human exploration of the Moon. While other missions were conceived and executed (e.g., the Mariner missions to Mars and Venus), most of the resources were expended on the Ranger, Lunar Orbiter, and Surveyor spacecraft sent to the Moon. Much was learned about our nearest neighbor in space, with perhaps the most spectacular results being the development of the impact origin of the Moon and the realization that impact processes have played a fundamental role in planetary evolution.[1] However, the narrow intellectual focus of NASA's planetary science activities made them vulnerable to the rise and fall of the Apollo program, and lunar studies fell victim to the end of human lunar exploration.

In planetary science's second decade (through 1980), the Solar System Exploration program broadened somewhat, but large resources were expended on the one goal of searching for life on Mars. While technologically successful, the Viking missions of the mid-1970s cast a scientific pall on the exploration of Mars until the mid-1990s, and in the late 1970s the agency found itself with a few large missions modeled, in scale at least, after Viking.[2] From 1980 through 1990, planetary science largely relied on these large missions, and consequent delays, failures, or cancellation damaged the intellectual vigor of the field.

COEL argues that the situation today in planetary science is spectacularly different, and much healthier. NASA's Solar System Exploration program includes a mix of flight programs, which run from Discovery missions (e.g., Mars Pathfinder, Near-Earth Asteroid Rendezvous, and Stardust) through to flagship missions (e.g., Galileo and Cassini), and provides a varied tapestry of flight-preparation times, risks, and rewards. Notable among these has been the spectacular exploration of the outer solar system, commencing with the Pioneer 10 and 11 missions, through the Voyager discoveries about the satellite systems of the giant planets, and culminating in the Galileo discoveries about Europa and the promise of Cassini discoveries at Saturn. Laboratory studies have blossomed as well, because techniques developed to analyze the Apollo lunar samples have been applied to the large numbers of meteorite samples found, serendipitously, through Antarctic exploration. Among these samples are pieces of Mars and the Moon, and laboratory studies inspired the goal of directly collecting small-body samples that is being realized through the ongoing Stardust mission. These direct samplings of primitive and evolved material in the solar system, including organic phases, are being directly applied as well to the astronomical study of planetary origins.

For over a decade, the astronomical studies have provided increasingly detailed information on planetary systems in formation (from space-based platforms such as the Hubble Space Telescope [HST] and ground-based systems such as the twin 10-m Keck telescopes). But perhaps most extraordinarily, the detection and now the characterization of extrasolar planets has created a new intellectual realm within planetary science, and also has produced profound synergies between observational planetary astronomy and its parental roots in large telescopic observations of the cosmos. Giant planets are being detected indirectly and, in a few cases, observed directly to allow analyses of their bulk and atmospheric properties. Flight opportunities ranging in scale from Explorer (microlensing) through Discovery (Kepler-transits) to flagship (the Space Interferometry Mission [SIM]) missions cannot truly be classified as astronomical or planetological because they are informed by both. Theoretical understanding of planets gleaned from flight missions within the solar system is being applied successfully to extrasolar planets, today in the realm of the giants, but eventually to terrestrial planets as well.

Indeed, for these reasons the planetary science activities today are so intellectually robust that the sudden cancellation in 2002 of two outer planet missions (to Europa and Pluto) will cause much less disruption in the program than it would have in the 1980s or 1990s.

Astrobiology has strong intellectual links with the planetary sciences that go well beyond the exploration of two objects (Mars and Europa) to the investigation of diverse environments within which organic evolution has transpired and extended to the origin of life itself. Several of the node principal investigators in the NAI are either planetary scientists or individuals with a strong interest in the planetary sciences. A number of planetary scientists are involved in other Astrobiology program elements, such as the Exobiology research and analysis program and the Astrobiology Science and Technology Instrument Development program.

However, COEL believes that the relationship between astrobiology and the planetary sciences could be better. The recent effort to produce a decadal strategy for planetary science[3] exhumed deep suspicions within a significant portion of the planetary community that astrobiology would dominate solar system exploration to the exclusion of a balanced flight program, and that it would displace scientific priorities in planetary exploration not having to do with the search for life. In part, this suspicion dates back to the 1970s with the strong Viking emphasis on finding life on Mars at the expense of potential geophysical and geochemical explorations of the red planet. Today, however, planetary science is so intellectually strong and broad that such concerns are unfounded, if NASA continues to recognize the value and strength of a broad planetary program.

COEL believes that the broad planetology and astrobiology communities jointly have a responsibility to go beyond shallow and polarizing characterizations of the two research areas to a much more extensive intellectual and research relationship. This may require formal efforts to bring larger numbers of scientists together to explore the intellectual connections more deeply than they have been explored to date.

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.

Recommendation

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.

ASTRONOMICAL SEARCH FOR ORIGINS AND ASTROBIOLOGY

Astronomical Search for Origins, as a NASA program, comprises study of the formation and early evolution of galaxies, stars, and planets. It has also come to include the detection and characterization of extrasolar giant planets, leading eventually to the detection and characterization of extrasolar planets the size and nature of Earth. The advent of space telescopes and large ground-based telescopes have enabled fundamental advances in these areas. Key results include, for example, the following:

- Origin and evolution of galaxies, production of the biogenic elements, history of star formation rates, temporal and spatial changes in stellar metallicity, relationships between metallicity and planet formation and habitability;[4]
- The relationship between star formation and the frequency of planet-forming disks;[5]
- The frequency of formation of giant planets and terrestrial planets;[6]
- Properties of extrasolar giant planets and their evolution via orbital migration;[7]
- Stability of planetary orbits and spin states as affected by gravitational perturbations from other planets and from natural satellites over the history of planetary systems;[8]
- Elucidation of practical techniques for the detection and characterization of extrasolar habitable planets;[9] and
- Understanding the chemical composition of molecular clouds, protostellar disks, and comets.[10]

Research relating to the astronomical search for origins is incredibly fertile today, and one would be hard-pressed to decide whether the most exciting results are being obtained on the largest (cosmological) or smallest (planetary systems) scales. It is not an exaggeration to argue that the Copernican revolution is in fact being completed today in the elucidation of the structure and fate of the cosmos, and in the determination of the frequency with which planetary systems form and the nature of the worlds thus built. The astronomical search for origins is also a programmatically healthy research area in the sense that discoveries are accomplished with a mix of ground- and space-based facilities, which in turn involve projects both small (inexpensive) and large (expensive) in scope.

Millimeter-wavelength telescopes of 10- to 12-m diameter or greater are crucial in establishing the chemical composition of comets, planetary atmospheres, and interstellar gas.[11] Small ground-based optical telescopes 1 m or less in aperture accomplished the first discoveries of planets around other stars and then their first characterization by transits. These achievements required precise spectroscopic and photometric techniques developed in the laboratory. The iodine gas absorption cells serving as a reference for the stellar wavelength shifts induced by orbiting planets, and the precise photometry enabled by modern electronic detectors, transformed these modest telescopes into major planet-detection and -characterization facilities.[12] Much larger optical telescopes, with a mirror aperture of 6 m or larger and equipped with advanced adaptive optics capabilities, are required to examine the broader class of extrasolar planets that are not in the unusual orbital orientation necessary to make studies of transit possible.

Such facilities, supported outside NASA with other federal, private, or state funds, represent a substantial monetary contribution to the research area of astrobiology, on a level of hundreds of millions of dollars in infrastructure. At the same time, existing or approved large-scale projects such as HST, the James Webb Space Telescope (JWST), and SIM take such observations much farther in terms of precision and sensitivity. (The latter mission is one component of NASA's so-called Navigator program, focusing on the detection and characterization of extrasolar planets.) With HST, it has been possible not only to infer the size of an extrasolar giant planet by means of transit photometry, but also to measure the atmospheric composition of the object.[13] JWST will take the transit capability even farther. Moreover, SIM will enable detection and characterization of planets down to bodies a few times the mass and/or size of Earth.

There are natural intellectual connections between studies in the general areas of the astronomical search for origins and astrobiology. First, life as we understand it is a planetary phenomenon, and we seek its existence on appropriate planets in orbit around other stars. Second, life is the culmination of chemical evolution that has transpired on cosmic time scales. Hence, the origin of the nonhydrogenic chemical elements including carbon in stellar and galactic evolutionary processes leads naturally to organic chemistry in a variety of astrophysical environments, and thence to the origin and evolution of carbon-based life in the free-energy-rich environment of planet Earth. Indeed, in the NASA Astrobiology Roadmap, the astronomical search for origins and the astronomical techniques used to study them play strong roles.

Paradoxically, this is not the case programmatically within the Astrobiology program. Little astronomically oriented research is conducted within the framework of the current Exobiology and Evolutionary Biology R&A programs. Rather, this research fits more naturally within the Origins of Solar Systems R&A program. The latter activity is comparable in size to the Exobiology program, and is administered under the Office of Space Science but not from within the Astrobiology program. The technological-development programs (ASTID and ASTEP) are devoted to techniques aimed at observing planets within the solar system or ecosystems on Earth, while the separate Astronomical Search for Origins program focuses on developing new techniques for characterizing extrasolar planets. The NAI itself has not been able to successfully centralize research teams devoted to the astronomical search for origins in a meaningful way, with the exception of the node led by the University of Washington, which was selected in the second round. Where NAI nodes have included astronomical studies related to the search for origins as part of their research, this could be better integrated into and be a more important part of the overall NAI effort. Part of the difficulty in doing so arises because little common ground exists between the techniques and facilities that astronomers use to detect and characterize extrasolar planets and those familiar to biologists. Further, there is a suspicion among a portion of the astronomical community that the usual difficulty of assembling a peer-review panel for NAI membership that truly spans discipline breadth among biology, geology, and astronomy may have served to rule out worthy proposals based on novel astronomical approaches to astrobiological issues in the last competition for NAI membership.

ENHANCING INTERACTION BETWEEN ASTROBIOLOGY AND THE ASTRONOMICAL SEARCH FOR ORIGINS

COEL sees a danger in attempting a forced realignment of the NAI toward the astronomical search for origins. The natural center of gravity of the research at the NAI and its 15 nodes is not in astronomical studies relating to origins, and it would be detrimental to the flow of research to do anything beyond collegial encouragement and free exchange of ideas between astronomers and other disciplines in the NAI. However, the fertility of current activities in the general area of the astronomical search for origins is exceedingly high. Moreover, public excitement has been high over the discovery of new planets and what this foretells for the eventual discovery of Earth-like planets. That research should not be forced into a different intellectual context simply for the sake of creating an appearance of completeness in NASA's Astrobiology program itself.

COEL offers two suggestions for increasing the volume and value of interactions between scientists active in the general areas of the astronomical search for origins and astrobiology. The first is to encourage the NAI and major astronomical institutions to initiate joint study efforts, ranging from conferences to long-term focus groups, that will enable more researchers in both areas to talk, mutually educate themselves, and "cross over" between the disciplines. The Space Telescope Science Institute's conference Astrophysics of Life (May 2002) is an excellent start to such an endeavor. It could be continued by initiating formal discussions, along the NAI's Mars and Europa focus group models, exploring topics in, for example, "astrobiology and the astronomical search for origins." The NAI and major astronomical institutions, recognizing the parity in research efforts between the two and avoiding the impression that the NAI is trying to reinvent the astronomical wheel, should initiate such focus groups jointly.

The second suggestion, which is longer term, devolves from the fact that the NAI itself was intended to be an experiment in the creation and operation of a virtual institute, whose outcome, if successful, would be the propagation of such a structure to other promising fields of scientific endeavor. Astronomical studies relating to the search for origins could be the next activity ripe for a consortium-based institution—a NASA Origins Institute (NOI) promoting research of scale, which is informed by and informs the large-scale ground- and space-based programs now under way. The breadth of astronomical origins from the creation of galaxies to the formation and early evolution of planets is a strength in this regard. It would contribute to the potential intellectual scope of such a new institute and to the level of competition that would be anticipated in the call for proposals for it. Arguing for this approach is the current lack of consortium-based research opportunities in astronomical studies related to origins on a scale larger than the individual R&A grants (typically $100,000 per year) and smaller than the flight missions (typically $100 million or larger in total development cost, spanning several years or more). Finally, the roadmap makes clear the intellectual and technical linkages among different problems and activities in the Astronomical Search for Origins program. An NOI would allow NASA to reap the benefits of these linkages by encouraging and funding collaboration among multiple institutions with differing expertise in the full range of studies relating to the astronomical search for origins.

COEL recognizes the natural overlaps between the NAI and an NOI, particularly in the area of organic chemistry and the origin of life. In the main, the areas and techniques employed in NAI and NOI research would be complementary, not redundant. Creation of an NOI would be an acknowledgment of both the success of the NAI and the need to maximize the scientific opportunities inherent in the astronomical search for origins. It would also extend the experiment of the virtual institute concept to address the important issue of interactions between institutes. Could the NAI and an NOI foster additional and more meaningful interactions between the corresponding fields?

Recommendations

- 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.

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4

The Roles of Other Federal Agencies with Respect to Astrobiology

NASA has led in funding research directed toward its mission "to boldly go" into and to explore the frontier of space. For astrobiology, NASA has certainly been the leader in efforts to understand how life originates (including prebiotic chemistry), astrochemistry (including meteorite analysis), the early evolution of life on Earth, and biosignatures. Nevertheless, many other federal agencies are interested in the origin, evolution, and destiny of life in the universe, including the National Science Foundation (NSF), which does not have an explicit mission beyond the furthering of basic science and technology, and other "mission agencies."

NATIONAL SCIENCE FOUNDATION

The "basic science" efforts of the NASA program find a parallel in the basic science research of the NSF. It is impossible to review all of the contributions made by NSF-funded research that support the NASA mission. The NSF is frequently cited as a research agency that gets a large "bang for the buck" from the long-term scientific, technological, and economic impact of the research that it funds. The NSF funds many principal investigator-initiated projects that describe organic and inorganic chemical reactivity, for example, directly relevant to origins. Its funded research in geology and planetary science carries out analogous roles in these areas. The NSF is the principal federal funding source for general studies in biology that are not directly related to the nation's biomedical research needs.

In some cases, the NSF has initiated programs relevant to astrobiology themes; perhaps the best example was its Life in Extreme Environments (LExEn) program.[1] Work funded under this program directly relates to goals described in the Astrobiology Roadmap, including the nature of habitable environments. LExEn was distinguished in selecting teams from a wide variety of the disciplines underpinning astrobiology, and it funded a number of important research efforts that are complementary to and not duplicative of work being undertaken in the NAI. Unfortunately, after several successful rounds of funding, the NSF decided to terminate LExEn, for reasons that were never made clear to COEL during its multiple discussions with NSF personnel.

While the NSF espouses a strong desire to collaborate with NASA, the different "personalities" of the two agencies often make long-term relationships difficult. NASA is very much a "mission-oriented" agency, often funding programs that take an exploratory approach to scientific problems—which is less the case at the NSF. For example, evolutionary biology at the NSF is very much "hypothesis driven" and, thus, "discovery-based" proposals fare more poorly than they do at NASA.

COEL understands that the NSF is constructing a new program whose scientific focus is the phylogenetic tree of life. This too follows interests of NASA, which has funded much of the basic research in this area. Carl Woese, for example, whose research created rationalized microbial taxonomy and underlies all current discussions of the history of life on Earth, was primarily funded by NASA (with some additional private funding) and not by the NSF (see Box 2.1 in Chapter 2). At this juncture, it is unclear to what extent such a program will parallel or interface with NASA's Astrobiology program, but COEL urges NASA and the NSF to discuss ways to take advantage of complementary research funded by the two agencies in this area.

The NSF can do things that NASA cannot do, including create initiatives in education through its Industry Graduate Research Traineeship (IGRT) program. For Earth-based research related to life in extreme terrestrial environments, the NSF owns much of the infrastructure, including ships and submersibles. This infrastructure, coupled with the National Oceanic and Atmospheric Administration's (NOAA's) operational satellite systems, enables a large class of astrobiological research. NOAA already works closely with NASA.

Recommendation

In view of the diverse activities in basic science relevant to astrobiology that the National Science Foundation conducts, NASA should engage the NSF in detailed studies of the desirability of and the means by which the two agencies can create joint programs in astrobiology.

DEPARTMENT OF ENERGY

From the perspective of its own missions, the Department of Energy (DOE) addresses issues of interest to astrobiology. Fossil fuels do, of course, come from past life. The search for fossil fuels has generated a rich understanding of geology, geochemistry, and paleontology that contributes to much of NASA's Astrobiology research.

More directly, the DOE recognized the importance of genome sequencing well before other mission agencies did (notably, the National Institutes of Health). DOE's Joint Genomics Institute has the capacity to sequence some 25 million nucleotides of DNA per day.[2] NASA astrobiologists contribute to the scientific direction of this laboratory, and the sequence data from it contribute to our understanding of the phylogenetic tree of life. The DOE also initiated, about a decade ago, a program to study life in the subsurface. While directed toward issues relating to nuclear waste disposal, this work has made scientific contributions in the research area of astrobiology.

While greater reliance on the DOE's sequencing program has the potential to increase the scientific output of NASA's Astrobiology program, some cases have been reported of delays in obtaining sequence data from the DOE on selected projects that may not have had high priority within the DOE. Increased reliance should not be construed to mean that NASA ought to discourage sequencing efforts in other types of laboratories, including those at universities and in private industry.

Recommendation

NASA should strengthen its connection with the Department of Energy to take advantage of the DOE's uniquely productive and broad gene-sequencing program. Creative ways should be developed to help astrobiologists obtain key genetic sequences, in order to complement those produced (and released) for other rationales, so as to further the goals of the Astrobiology program. This collaboration should be designed in such a way, however, as not to discourage or exclude the use of other capabilities, including those in private industry, to sequence organisms.

NATIONAL INSTITUTES OF HEALTH

As the agency responsible for the enhancement of human health, the National Institutes of Health (NIH) generates an enormous volume of research relating to life in all forms, including microbial life (especially from microbes involved in infectious disease), viruses, model systems for developmental biology (relevant to events on

Earth approximately 1 billion years ago) and "higher" life (especially mammalian biology). It is difficult to imagine a field of astrobiology without the contributions of NIH-funded research.

In particular, the NIH has the resources to mount massive programs that are far beyond the budget of NASA's Astrobiology activities. For example, NIH's Structural Genomics program, which involves a major functional commitment, will advance our understanding of the evolution of proteins. NIH also supports major programs in evolutionary biology, including work on molecular evolution of prokaryotes and protists.

At the same time, the NIH is regarded (with some justification) as being conservative in its selection of research topics to fund. NIH reviewing panels emphasize reductionist approaches over the historical approaches that NASA has advanced, and they discourage "discovery research." Asking "big questions" is not generally viewed as a way to strengthen an NIH proposal. Perhaps for these reasons, the NIH has overlooked many of the insights into biology that might be gained from historical, discovery-oriented, and nonreductionist approaches, and the nation's biomedical research mission has lagged as a result.

For these reasons, the NIH will benefit from the research being done by NASA's Astrobiology program. The correlation between the timing of events in the paleontological, geological, and molecular/genomic records is providing insights into the role of individual proteins in modern life forms, including genes involved in disease. The understanding of the evolution of organisms is having an impact on our understanding of adaptation of infectious diseases to antibiotics, cancer to therapies, and organisms to environment.

Recommendation

NASA should engage the National Institutes of Health in a dialogue to explore the desirability and feasibility of the two agencies creating and funding specific collaborative programs in astrobiology.

U.S. DEPARTMENT OF AGRICULTURE

The U.S. Department of Agriculture (USDA), from its mission perspective, also engages in research relevant to astrobiology. The genomes of plants, commercially important animals, and microbial and animal "pests" provide a wealth of information about the past. Within this information is captured the response of the ancestral organisms to historical changes in the physical and biological environment, including mass extinctions and major climate changes that fall within the purview of the Astrobiology Roadmap. The USDA does not, of course, view the data that it collects in this light. Here, interaction between the two agencies is likely to generate synergisms contemplated by neither.

Recommendation

In view of the potential value for the study of long-term climatic excursions recorded in the genomic record in plant and animal stock held by the U.S. Department of Agriculture, NASA should engage the USDA in the development of a program to enable astrobiologists both to use and to interpret this record.

NOTES AND REFERENCES

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2. More information is available online at <http://www.science.doe.gov/ober/microbial.html> and <http://www.ornl.gov/microbialgenomes/>.

5

International Partners

NASA AND NAI CONCEPTUALIZATION OF THE INTERNATIONAL RELATIONSHIP

From the beginning of the development of the NASA Astrobiology program, international involvement was anticipated and desired in view of the strong space science and exobiology research activities going on overseas, particularly in Western Europe. Involvement of foreign nationals was not a specific criterion in the selection of the 15 U.S. nodes for the NASA Astrobiology Institute (NAI), however. As shown in Table 2.2 in Chapter 2, some successful proposals included foreign involvement, while others did not.

To foster the growth of programs in astrobiology beyond the United States, the NAI set up an international associate membership program soon after its own creation. This program allowed astrobiology research programs elsewhere in the world to affiliate themselves with the NAI. It was thought that this not only would broaden the scope of the research and researchers involved in astrobiology but also might encourage funding of astrobiology programs by other countries. To initiate this program, the NAI named Spain's Centro de Astrobiología (CAB), which already had obtained government funding for astrobiology, as an acting associate member in 1999.

Subsequent to the establishment of this relationship, which was formalized in 2000, the NAI developed a procedure for evaluating additional associate memberships. International proposers to the NAI are requested to outline the following:

- The organizational nature of the entity (i.e., government agency, private institution, nonprofit organization, and so on);
- The themes of the scientific work being undertaken or proposed and the potential synergy with NAI objectives; and
- The specific areas in which near-term exchanges and/or partnerships will be productive and areas for long-term cultivation of interactions.

The application package is evaluated in a noncompetitive fashion, that is, on an individual basis. Those entities with stable sources of funding and a vigorous research and teaching program are invited to become associate members of the NAI, and the director of the entity becomes a member of the NAI Executive Council, functioning essentially as one of the NAI principal investigators. Entities that do not meet the criteria or do not wish to have such a formal relationship are invited to become affiliates of the NAI. Such affiliates are encouraged to interact with NAI researchers but do not have formal governance or advisory responsibilities within the NAI.

To date, only the CAB and, more recently, the Australian Centre for Astrobiology have achieved a strong source of stable government funding and attained associate status. Affiliate members of the NAI are as follows:

- The United Kingdom Astrobiology Forum and Network,
- The Groupement de Recherche en Exobiologie, and
- The European Exo/Astrobiology Network Association.

Other major astrobiological groups include the Russian Astrobiology Center.

There is insufficient space in this report to do justice to the diverse astrobiological activities currently under way outside the United States. To illustrate this diversity, COEL highlights below the activities of three representative groups—CAB, the United Kingdom Astrobiology Forum and Network, and the European Exo/Astrobiology Network Association. More information about the groups mentioned above but not described here can be found at their respective Web sites.[1–3]

CENTRO DE ASTROBIOLOGÍA

CAB is the most successful example of the galvanizing effect that the creation of the NAI has had on astrobiology in other countries.[4] Its founding through private and public funds in Spain was greatly aided by the example set by the founding of the NAI and the promise of affiliate membership in the NAI. Located on a military base outside Madrid, CAB is a rapidly expanding institute that integrates biologists, geologists, astronomers, planetologists, and physicists in a strongly collaborative research environment. Ongoing work includes computer modeling of physical processes related to the origin of life and planetary habitability, gene sequencing of organisms with small genomes, geological fieldwork, explorations of a hyperacidic river—Spain's Rio Tinto—with robotic submersibles, and the creation of a telescopic network to search for planetary transits.

CAB's technological and scientific activity may be classified in these groups:

- Observation and modeling (in astrophysics, planetary sciences, biology, and ecology), with analysis of phenomena related to astrobiology and creation of models that generate a scientific explanation for them;
- Theory, applied to fields that are the focus of theoretical research at CAB (hydrodynamics, emergence, critical phenomena of equilibrium, self-organized criticality,[5] fragmentation and fractal characteristics, fractal science networks); and
- Supporting technologies for CAB work (bioinformatics, specific-purpose computers, advanced communications systems, and telematics and robotics), through which the connection between scientific research and forefront technologies produce an advantageous alignment.

In early 2002, a completely new building specifically designed by and for CAB was completed on the edge of the base where CAB is located (the base's gates can be realigned to afford public access for conferences and other events). The new facility provides for open interactions between scientists of different disciplines while also affording ample space for laboratory and computational facilities. This vastly improved space will enhance educational and postdoctoral programs at CAB. As a result of a detailed presentation to COEL by CAB's director and a personal visit to the center by one committee member, COEL finds CAB to be a model for any future "bricks and mortar" institute dedicated to astrobiology.

Although CAB is self-contained, it is not isolated. The new building is wired with next-generation Internet capabilities and is intended to support remote laboratory operations, as well as comodeling on distributed computational systems. CAB is also not isolated in the sense that its purpose beyond astrobiological research is to infuse Spain and its industries with new stimuli for technological development. One of CAB's main objectives is the development of a local industry network, supplemented by high-quality popularization of science, with benefit to Spanish society on all levels. Besides the education and postdoctoral research at CAB (which will be linked with the local industrial infrastructure), CAB has a strong program of outreach, directed to kindergarten through secondary education and to adult education. In a different kind of interactive exercise, CAB in 2000 held a joint field excursion with NAI researchers at the Rio Tinto in Spain, which was well attended.

CAB is a model that will not be replicable everywhere. The ingredients for success at CAB began with the remarkable vision and entrepreneurial capabilities of its director, Juan Perez-Mercader. They included as well a special moment in time when the government of Spain and the national industries were aligned toward the enhancement of Spanish technological development in the context of the European Union. In addition, the encouragement of NASA and the NAI, both symbolic and practical, in the form of CAB's being the pathfinder for international associate membership in the NAI, lent validity and credibility to the endeavor essential for the provision of space and funds from governmental and industry sources.

COEL applauds the leadership of CAB for its extraordinary accomplishment in starting and bringing to fruition a "ground-up" astrobiology center, and for the consequent articulation of the value of astrobiology as a science and as a lever for technology development within Europe. NASA and the NAI also deserve recognition for doing their part in fostering the growth of CAB through encouragement and the creation of associate membership status in the NAI.

U.K. ASTROBIOLOGY FORUM AND NETWORK

The United Kingdom Astrobiology Forum and Network (UKAFN) represent a different kind of international astrobiology effort.[6] The U.K. Astrobiology Forum, a committee of the British National Space Centre, was established in 1998 to encourage and promote the science of astrobiology within the United Kingdom.[7] The eight members of this group are leaders in promoting astrobiology research in the United Kingdom. The forum became an affiliate member of the NAI in October 2000. The U.K. Astrobiology Network (the second component of this combination) is a larger and more informal network of astrobiologists in various fields, set up to promote communication among those involved in the science of astrobiology in the United Kingdom.[8]

The founding of the UKAFN was stimulated both by the creation and early activities of the NAI and by the strong interest in astrobiology-related research in the United Kingdom. Unlike CAB, however, the UKAFN does not constitute a formal institute that is directly funded by governmental or industry sources. It is an association and a network of groups and facilities doing government- and industry-funded research in areas that encompass astrobiology as defined by NASA's Astrobiology Roadmap. Thus, associate membership in the NAI is not appropriate, because there is no central principal investigator within either the forum or the network who controls a source of central funds and therefore could represent the interests of all of the U.K. researchers in the program. Affiliate membership provides a more informal means of interaction and creates a kind of "organizational hyperlink" that encourages frequent communication.

EUROPEAN EXO/ASTROBIOLOGY NETWORK ASSOCIATION

The objectives of the European Exo/Astrobiology Network Association (EANA) are these:[9]

- To bring together European researchers connected with exo/astrobiology programs and foster cooperation and interactions, including those through (but not limited to) a Web site database;
- To attract young scientists to the field;
- To promote exo/astrobiology activities in various European countries and seek financial support;
- To interface with European governmental entities such as the European Space Agency, European Science Foundation, and European Commission, and extend contacts to non-European institutions; and
- To popularize astrobiology.

EANA was formalized in May 2001 during the first European Workshop on Exo/Astrobiology, held in Frascati, Italy. The association is administered through an executive council of 24 members.

THE SHAPE OF INTERNATIONAL INTERACTIONS WITH THE NAI

Astrobiology is a good recent example of the United States leading the rest of the world into a new discipline area and new forms of research. In addition to those described above, other international partnerships with the NAI are being defined (e.g., with Russia) or have already been defined (e.g., with Australia and France). Each one of these interactions will be different, because research is organized and funded differently in the respective countries. Opportunities for multinational consortia, which seem most promising in Europe as the countries of the European Union more tightly integrate in terms of financial and political institutions, could lead to astrobiology projects on much larger scales than are seen today. To date, Japan has not been involved significantly in NAI consortia nor, to COEL's knowledge, been approached to establish an affiliate membership. A resourceful, extremely well-organized research community in Japan includes many researchers actively involved in areas pertaining to astrobiology, and the NAI might direct its attention to establishing linkages.

The committee encourages NASA and the NAI to continue to seed efforts in astrobiology worldwide through the free exchange of scientific information, experimental techniques, and computational results. Association or affiliation with the NAI ought to be used as a tool to encourage international efforts in this regard, but it should be approached with care so as not to give the impression that the United States is pressuring other countries.

One way to ensure that astrobiology becomes a truly international endeavor is to realign the structure of the NAI so that foreign affiliate members become, instead, the nodes of an international astrobiology institute, with the NAI as one member among many. It may be premature to make such a change at the present time when the international programs are just getting started, but it should be considered by all concerned as those programs mature.

Finally, the committee notes that the International Traffic in Arms Regulations (ITAR) will continue to make it difficult for scientists to fully interact on astrobiology projects internationally. ITAR will prevent foreign nationals from collaborating with the NAI or with NASA in general on astrobiology instrumentation intended for flight or on laboratory techniques that have application to international terrorism issues, without formal and specific Memorandums of Understanding for each instrument or technique.[10]

The changes to ITAR that came into force in April 2002 may ease this situation by making it clearer that fundamental research collaboration does not require an ITAR license and that the exchange of most forms of technical information in the public domain can proceed without impediment with nationals of NATO and a few other allied countries. Some problems remain, especially collaboration with foreign scientists and students from non-NATO countries, so it is important for NASA to continue to monitor the situation and to help ensure that ITAR does not have a suffocating effect on the free exchange of space and biological sciences research.

NOTES AND REFERENCES

1. More information about the Australian Centre for Astrobiology is available online at <http://aca.mq.edu.au/>.
2. More details about exo/astrobiological activities in France are available online at <http://www.lisa.univ-paris12.fr/GDRexobio/astrobio.html>.
3. For more details about the Russian Astrobiology Center, see, for example, the Web site <http://biospace.nw.ru/ astrobiology/index.html>.
4. For more details about CAB, see the Web site <http://www.cab.inta.es>.
5. J. Perez-Mercader, "Scaling Phenomena and the Emergence of Complexity in Astrobiology," pp. 337-360 in *Astrobiology: The Quest for the Conditions of Life,* G. Horneck and C. Baumstark-Khan, eds., Springer, Berlin, 2002.
6. More information is available online at <http://astrobiology.rl.ac.uk/>.
7. For more details, see the Web site <http://astrobiology.rl.ac.uk/forum/Welcome.html>.
8. For more details, see the Web site <http://astrobiology.rl.ac.uk/members.html>.
9. For more details, see the Web site <http://www.graz-astrobiology.oeaw.ac.at/eana.html>.
10. See, for example, the State Department Web site containing updates to ITAR, at <http://www.pmdtc.org/>.

6

SETI and Astrobiology

NASA AND SETI

The search for intelligent life on worlds beyond Earth represents the most romantic and publicly accessible aspect of the search for life, yet is perhaps the most problematic. No as yet known remote-sensing technique can detect the presence of intelligent versus complex life forms, other than by listening for electromagnetic forms of communication leaking from or deliberately sent from another world.[1] Human civilization has put chlorofluorocarbons in the stratosphere, which are demonstrably the product of a technological civilization but require high spectral resolution to detect. Further, the damaging effects on the stratospheric ozone layer of these compounds imply that a civilization would do this only for a minuscule amount of time, several decades, making detection of such compounds very unlikely.

Early attempts in the 1950s and 1960s to detect radio signals from another civilization yielded no positive results. Proponents of the search understood the need to build tunable receivers that could scan enormous numbers of very narrow frequency bands at high speed, but the ability to do so was technologically limited until the 1980s, when inexpensive computing capability and receiver technologies matured. In the early 1990s, NASA involved itself in the search through a project known as the High-Resolution Microwave Survey (HRMS), which planned to utilize two complementary search modes: an all-sky survey element (the responsibility of the Jet Propulsion Laboratory) and a targeted search element (the responsibility of the Ames Research Center). Both elements involved state-of-the-art digital spectrum analyzers and signal-processing equipment to carry out the observations and data-processing activities automatically, and the use of large radio telescopes such as those in NASA's Deep Space Network, the National Astronomy and Ionosphere Center's Arecibo Observatory in Puerto Rico, and others.

THE SETI INSTITUTE

In 1993, Congress terminated support for the HRMS project after a floor debate on the question of extraterrestrial life. Scientists from the Ames Research Center's targeted-search team then regrouped through a Silicon Valley-based not-for-profit organization, the SETI (Search for Extraterrestrial Intelligence) Institute, which had been founded some 8 years before.[2] Scientists and engineers from the SETI Institute formed the core of the targeted-search team.

As a non-profit organization, the SETI Institute was in a unique position to acquire the targeted-search equipment, representing about $58 million of taxpayer investment, and to use it for the search for extraterrestrial intelligence. Private fund-raising efforts increased the SETI Institute's expenditures from $2 million per year early in its existence to about $6 million per year at the time the HRMS project was canceled. To implement NASA's targeted search, the SETI Institute first secured an agreement with NASA for a long-term loan of the partially built Targeted Search System. Then it raised private funds to complete the expansion of the system and to conduct the planned observations, which have been under way since 1995 under the name "Project Phoenix."

Project Phoenix does not scan the whole sky. Rather, it scrutinizes the vicinities of about a thousand nearby stars (i.e., within 200 light-years) with properties like those of the Sun. Phoenix looks for signals between 1 and 3 GHz. Exceedingly narrow band signals are assumed to be the "signature" of an intelligent transmission. The spectrum searched by Phoenix is broken into very narrow, 1-Hz-wide channels, so 2 billion channels are examined for each target star. An automatic detection algorithm, one of the major software inventions of the SETI Institute, enables long-term observation with only occasional human intervention. Observations are currently being made during two 3-week sessions each year using the 1,000-foot radio telescope at Arecibo. With about half of the target-list stars searched, no positive results have been found. However, the volume of the Milky Way searched by Project Phoenix is vanishingly small, especially when compared with, for example, what microlensing surveys will cover in the search for planets of the mass of Earth.

A new project, the Allen Telescope Array, will cover a much larger volume of space and a much larger frequency domain. It is a telescope system designed and built specifically for the search for extraterrestrial intelligence, to be sited at a University of California observing station in northern California, with private donations totaling more than $12 million. Interestingly, the Allen Telescope Array is pioneering a variety of concepts to be employed in the proposed Square Kilometer Array, a project highly rated in the most recent astronomy decadal survey.[3]

ASSESSMENT OF THE SETI INSTITUTE

On its face, the SETI Institute appears to be a model for science that is driven entirely by private donations with a particular result in mind. In fact, however, the SETI Institute does receive federal research grants for a variety of projects in the general area of astrobiology. It does so because the institute serves as an organizational structure for a number of scientists who work at the Ames Research Center but do not have civil service positions. Approximately 35 investigators hold NASA grants or cooperative agreements through the SETI Institute that fund individual principal investigator-based research programs. Thus, the SETI Institute is in fact two different entities: a soft-money institution for research over a range of areas of astrobiology, largely funded with federal money, and a donor-financed effort to develop technologies to search for intelligent life throughout a significant fraction of the Milky Way.

The SETI Institute has done an excellent job in developing programs in both arenas, which synergistically provide scientific breadth, vigor, and the resources for conducting a search that the federal government opted out of a decade ago. The SETI Institute's leadership consists of scientists of the highest reputation—Frank Drake, Jill Tarter, and Christopher Chyba—who have personally invested their careers in the science of astrobiology. Students working at the SETI Institute from the Bay Area and elsewhere contribute their own intellectual energy and have produced high-quality research projects that in some cases lead to Ph.D. dissertations. Overall, the scientific quality of the programs and their output are high.

COEL doubts that the SETI Institute is a model that could be replicated elsewhere. It has always had strong involvement from a few select Silicon Valley pioneers who have themselves contributed substantial intellectual and capital resources, thereby providing the momentum for the institute to pursue its long-range goals. But the committee sees the SETI Institute as an important national resource in astrobiology, primarily through its ability to privately fund a high-risk venture with a potentially historic payoff.

Further, COEL sees no merit in debating the validity of a search whose negative results arguably tell us little about the ubiquity of life. The debate has no merit because the foundational motivation for the search is the popular aspiration to communicate with other forms of intelligence as much like or unlike us as we care to imagine. It would be dissembling, to say the least, to discourage such a search (especially one enabled by private funding) at the same time that astrobiology as a whole taps in to the same emotions and aspirations to excite the public about the general search for life's origins, evolution, and cosmic ubiquity.

The leadership of the SETI Institute has forged a unique endeavor out of private and public funds, maintained a high standard of scientific research through its peer-reviewed research activities, and articulated clearly and authoritatively the rationale for approaches to a comprehensive search for extraterrestrial intelligence.

NOTES AND REFERENCES

1. J. Tarter, "The Search for Extraterrestrial Intelligence (SETI)," *Annual Review of Astronomy and Astrophysics* 39: 511-548, 2001.
2. For more details about the SETI Institute, see its Web site <http://www.seti.org>.
3. Board on Physics and Astronomy/Space Studies Board, National Research Council, *Astronomy and Astrophysics in the New Millennium,* National Academy Press, Washington, D.C., 2001.

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Conclusion

Remarkable progress has been made in the past 5 years in organizing the Astrobiology program at NASA, thereby fostering the emergence of an interdisciplinary field with new research opportunities. NASA scientists and managers deserve much of the credit for carrying the idea forward and successfully implementing a broad and active program in an era of tight budgets. It would be a mistake to imagine, however, that the program was created out of "whole cloth." Instead, NASA's Astrobiology program is an outgrowth of the nation's investment over several decades in scientific research in a variety of fields underpinning astrobiology. Without the roughly half-century of novel ideas and exciting discoveries from biology, chemistry, geology, planetary science, astronomy, and other related fields, the Astrobiology program could not have been conceived of, let alone funded, as a significant federal initiative.

There is a hope or even an expectation among the general public interested in astrobiology that key answers will or should come soon. COEL is of the opinion that the results and insights coming from astrobiological research will turn out to be different from what could have been accomplished before the establishment of this program and its flagship institute, the NASA Astrobiology Institute. Every so often an extraordinary insight or discovery will emerge that will not only change the direction of astrobiology but also illuminate in hindsight how the unification of different techniques and approaches under astrobiology has encouraged progress. But the process will take time.

For this reason, COEL counsels patience. More than four centuries ago, decades before Galileo turned the telescope on the sky for the first time, the Italian philosopher-scientist Giordano Bruno wrote: "There are countless suns and countless earths all rotating around their suns in exactly the same way as the seven planets of our system. We see only the suns because they are the largest bodies and are luminous, but their planets remain invisible to us because they are smaller and non-luminous."[1]

Less than 40 years later, Galileo first turned a telescope on the heavens to reveal worlds moving around other worlds: the Galilean satellites of Jupiter. Yet it would be four centuries before techniques inaccessible to Galileo, based on physical principles likely unimaginable to him, were brought to bear to detect and study planets around other stars. While we hope that, in the much more frenetic pace of discoveries that characterize the present century compared with the 16th, we do not have to wait 400 years for the answers to how life began on Earth, or to how ubiquitous or rare are inhabited Earths in the heavens, one cannot predict when or whether success will come.

Bruno also wrote: "The countless worlds in the universe are no worse and no less inhabited than our Earth." Thus he articulated a vision for astrobiology, but today we seek other, more profound ones. As astrobiology develops, we expect shifts in paradigms that will require new approaches and different combinations of disciplines to be applied to the age-old questions of our origin and our relationship to the cosmos within which we exist.

REFERENCE

1. G. Bruno, *De L'infinito Universo e Mondi*, 1584.