NASA SPECIALIZED CENTER OF RESEARCH AND TRAINING (NSCORT) IN EXOBIOLOGY

2004 FINAL REPORT

THE CHEMISTRY OF EARLY SELF-REPLICATING SYSTEMS
(NASA NAG 5-12849)

NSCORT/EXOBIOLOGY - A CONSORTIUM OF:

THE UNIVERSITY OF CALIFORNIA, SAN DIEGO
THE SALK INSTITUTE FOR BIOLOGICAL STUDIES
THE SCRIPPS RESEARCH INSTITUTE
LA JOLLA, CALIFORNIA

NSCORT / EXOBIOLOGY
University of California, San Diego
La Jolla, California

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(NASA NAG 5-12849)
February 1, 2003 through December 31, 2004

Respectfully submitted by:

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Summary of Activities

Program

The NASA Specialized Center of Research and Training in Exobiology (NSCORT/Exobiology) is a program within the University of California, San Diego, California Space Institute (Dr. Wolfgang Berger, Director). It has been funded by two 5-year Federal Demonstration Project Grants from NASA; and currently (February 1, 2003-December 31, 2004) received supplemental funding to support our research; completion of the NAG 5-4546 Final Report for past 5 years, seminars, public lectures, and support for program administrative office. The program's specific aims have been:

1. The support and training of Postdoctoral, Graduate, and Undergraduate Fellows in Exobiology.
2. The support of research by the Principal Investigators and Fellows in the field of Exobiology.
3. Outreach programs emphasizing the dissemination and exchange of information concerning Exobiology within the scientific community, primary, secondary and college students, and the general public.
4. Public Lectures, Discussion Seminars, Seminars and Fellows Journals Club.
5. Host of the 2003 Public Lectures "Celebrating 50 Years of Prebiotic Chemistry" held at the University of California, San Diego in La Jolla, California on June 10, 2003.
6. Host of the 1999 meeting of the International Society for the Study of the Origin of Life (ISSOL) held at the University of California, San Diego in La Jolla, California, from Sunday, July 11 through Friday, July 16, 1999.

Administration

The NASA Specialized Center of Research and Training (NSCORT) in Exobiology is a consortium of scientists at three institutions in the La Jolla area of San Diego, California. The administrative recipient of the NASA grant is the California Space Institute, Scripps Institution of Oceanography, University of California, San Diego (UCSD). The program partners - The Salk Institute for Biological Studies (SALK), and The Scripps Research Institute (TSRI) - receive their assigned funds to support research and training in Exobiology through the central NSCORT office at UCSD (see Organizational Flow Chart, Ref. 1).

NSCORT funds currently (2003-04) support a full-time Program Administrator (Lois Lane). UCSD provides 0.5 FTE support to the California Space Institute Business Office/SIO in support of this grant at no charge to NASA.

Academic and administrative policy, as well as competitive selection of Fellowship recipients, is determined by a Committee of NSCORT Principal Investigators, in cooperation with the Program Administrator.

The *Review Committee,* for evaluation of the NSCORT/Exobiology program, met in La Jolla with the NSCORT laboratories on November 6, 1998 (previously reported). The Committee members were: Thomas Cavalier-Smith, Benton Clark, David DesMarais, Donald DeVincenzi, Michael Meyer, Alex Rich, John Rummel and Alan Schwartz. Because of budget cuts, there were no more meetings of the Review Committee during the present grant period.

The *Astrobiology NSCORT Review Panel* was chartered by the Office of Space Science, NASA Headquarters, to review the performance of the Astrobiology NSCORT's and to analyze the likely effects and impacts of different options for the future of the Astrobiology NSCORT program. On January 23, 2002, the panel visited the NSCORT/Exobiology at the University of California, San Diego for an evaluation of the program (see Ref. 2). The Committee members were:

Sean Solomon	Carnegie Institution of Washington
Max Bernstein	NASA Ames Research Center
Colleen Cavanaugh	Harvard University
Julius Dasch	NASA Headquarters
David Deamer	University of California, Santa Cruz
Carl Pilcher	NASA Headquarters
James Pratt	Portland State University
Michael Meyer	NASA Headquarters
Wolfgang Berger	University of California, San Diego

The group of six *Affiliates* who have agreed to participate in the NSCORT in order to broaden our coverage of research areas that are important to Exobiology are:

Albert Eschenmoser (ETH, Zurich and TSRI); Marina Fomenkova (UCSD); Antonio Lazcano (University of Mexico); Julius Rebek (TSRI); J. William Schopf (UCLA) and Kevin Zahnle (NASA Ames).

PI Meetings: The PI's met regularly throughout the grant period to discuss various NSCORT activities. From 1997-2002 there were thirteen PI Meetings.

2003 Public Lectures - "Celebrating 50 Years of Prebiotic Chemistry"

On June 10, 2003, a symposium "Celebrating 50 Years of Prebiotic Chemistry" (see honoring the 50th Anniversary of the 1953 publication of the Miller Experiment in SCIENCE) was held at the University of California, San Diego. This event was organized and hosted by the NASA Specialized Center of Research and Training in Exobiology. It was sponsored by NASA, the Dean of Physical Sciences and the Department of Chemistry and Biochemistry at the University of California, San Diego (UCSD). (See Publications submitted with this report; and Refs. 4, 7 and 8.)

The following events were held:

For the symposium, public lectures and a reception (see Ref. XX) were held at UCSD on June 10, 2003 in honor of the 50th Anniversary of the Miller Experiment. The speakers were the NSCORT/Exobiology Principal Investigators Dr. Jeffrey L. Bada and Dr. Gerald F. Joyce and the moderator, Dr. Leslie Orgel.

A evening discussion seminar and dinner was held at UCSD with invited scientists, NSCORT investigators, NASA Headquarters Officials and the Chancellor and Officials of the University of California, San Diego.

Stanley Miller has had a long history of support from the NASA Exobiology Section. This event commemorated the anniversary of his classic experiment and was a small recognition of his contributions to the field.

1999 International Society for the Study of the Origin of Life (ISSOL'99) Meeting

The 1999 meeting of the International Society for the Study of the Origin of Life (ISSOL '99) was hosted by the NSCORT/Exobiology at the University of California, San Diego in La Jolla, California, from Sunday, July 11 through Friday, July 16, 1999 (previously reported). Both the research and the training objectives of the NSCORT/Exobiology were well met by support of this important triennial meeting. This meeting was a great success and NASA's sponsorship was recognized and appreciated.

Research

During 1997-2003 , research in Exobiology, supported by NASA, has been conducted in the laboratories of the Principal Investigators and in the NSCORT/Exobiology laboratory. Personnel involved have included staff and technicians, Affiliates and Visiting Scientists, local and extramural colleagues, as well as NSCORT Fellows and Principal Investigators. No actual support was given for this period due to lack of funds.

Areas of Research:

- **The accretion of organic material on the primitive Earth:**
  Dr. Jeffrey Bada, Marine Research Division, SIO, UCSD (NSCORT Director)
  A search is being made of sea water, polar ice, lunar soils and meteorites from Mars for extraterrestrial organic compounds. The amount and nature of these compounds will indicate the importance of extraterrestrial input on the primitive Earth.

- **The formation, concentration and growth of RNA precursor molecules:**
  Dr. Gustaf Arrhenius, Marine Research Division, SIO, UCSD
  The oldest chemofossils so far identified on Earth consist of graphitized organic matter found in turbidite deposits in 3.8 Ga early Archean metasedimentary rocks in southern West Greenland (Isua formation; Rosing 1999). We find that other, more extensive graphite deposits in the Isua formation occur in iron carbonate bearing rocks, earlier thought to be of sedimentary origin. These deposits are now fond to be a product of metasomatism, the graphite here is generated by internal reduction of carbonate ion by Fe(II) in the iron carbonate (siderite) and is consequently of inorganic origin, unrelated to early life.

  Our program aims at further development and application of methods for discrimination between inorganic and biogenic carbon in these most ancient sediments and in elucidating the chemical environment of the earliest known life on Earth.
  The other segment of our research concerns experimental modeling of natural processes leading to the spontaneous formation of aldehyde phosphates, nucleosides and nucleotides. We find that in all reactions investigated catalytic activation is required. This can effectively be achieved by surface active minerals that also effectuate the necessary pre-concentration from the extremely dilute solutions of source molecules that would be expected in a prebiotic environment. An ultimate problem, now under investigation, concerns the initial source of the information in the form of sequence specificity, required to confer biofunctionality to RNA - like molecules.

- **The early evolution of organisms can be traced on the basis of their amino acid sequences. In general, the more closely related are two creatures, the more similar the sequences of their proteins:**
  Dr. Russell Doolittle, Center for Molecular Genetics, UCSD
  Amino acid sequence comparison is conducted with the aid of computers and data banks. The protein sequences themselves are mostly translated from DNA sequences being determined in big genome sequence projects.

- **The chemical reactions of nucleotide bases with other possible primitive Earth compounds:**
  Dr. Stanley Miller, Chemistry Department, UCSD
  The compounds formed from nucleotide bases reacting with the products of prebiotic processes are being investigated. They are potential precursors to the genetic material of the RNA world, which is believed to have existed on the primitive Earth before the DNA world.

- **The catalysis of nucleic acid replication by mineral surfaces:**
  Dr. Leslie Orgel, Chemical Evolution Laboratory, SALK
  We are interested in discovering self-replicating polymers simpler than RNA At the present time we are working with various kinds of peptides. Simple catalysts (including mineral surfaces) that might increase the efficiency of this type of reaction are being investigated.

- **The evolution of instructed protein synthesis in the context of a genetic system based on RNA genomes and RNA catalysts:**

  Dr. Gerald Joyce, Department of Molecular Biology, TSRI
  Evolution is an essential aspect of life. Population of RNA molecules are being made to evolve under laboratory conditions in order to demonstrate the capabilities of RNA as a catalyst.

Fellowships

Subsequent to advertisements for NSCORT/Exobiology Fellowships in the journal *Nature*, the NSCORT/Exobiology home page (http://exobio.ucsd.edu), and distribution of announcements through personal contacts, 98 applications for Fellowships have been received as of January 2002. (See Ref. 3 for complete list of fellows.)

NSCORT/Exobiology Fellows (1997-2004)

	Postdoctorals	Graduate Students	Undergraduates
Fellows*	13	8	27
Adjunct Fellows	5	8	3
Total	18	16	30
Completed	18	15	30

During this grant period, two NSCORT fellows (James Cleaves and Andrew Aubrey) remain in the Bada lab.

*The principal difference between Fellows and Adjunct Fellows is the NASA grant budget category from which the support funds are derived. Separate titles are designated because of overhead implications.

1. **Examples of facilitation by NSCORT/Exobiology of in-house research and education. NSCORT/Exobiology contributes support and sponsorship for:**

   - Journal Club meetings organized by the NSCORT Fellows.
   - Evening Discussion Seminar for NSCORT PIs, Fellows and Affiliates.
   - Seminars and Discussions by invited local, national and international scientists (2003-04).

Minik Rosing	Geologisk Museum, Denmark
Walter Fontana	Santa Fe Institute, Santa Fe, New Mexico
David Harker	University of California, San Diego
Daniel Glavin	Max Planck Insitute
Daniel Mosquera	University of Coruna, Spain
William Hartmann	Planetary Science Institute, Tucson, Arizona
Daniel Fernandez	University of Coruna, Spain
Peter Willis	Jet Propulsion Laboratory, Pasadena, CA

   - National and international visiting scientists to engage in collaborative research.

Paul Braterman	University of North Texas
Pascale Ehrenfreund	Leiden Observatory, The Netherlands
John Eisch	Binghamton University
Dilip Kondepudi	Wake Forest University
Antonio Lazcano	University of Mexico
Marie Christine Maurel	Institut Jacques Monod, France
Michel Maurette	Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse, France
De-Ming Liu	Nanjing Institute of Geology and Palaeontology, People's Republic of China
Cheryl Rosa	University of Alaska, Fairbanks

2. **Examples of NSCORT/Exobiology Outreach**

   a) **WWW Site at http://exobio.ucsd.edu.** This Site contains descriptions of the NSCORT mission, Fellowship program descriptions and applications instructions, and descriptions of the research work currently in the laboratories of each of the NSCORT PI's and short Selected Publications lists and contact information. There are also links to other related sites, at NASA and elsewhere.

b) **Robert D. Tschirgi Memorial Public Lectures at UCSD:** Lecturer, Dr. Thomas Cech, April 17, 1998; Lecturer, Dr. Freeman Dyson, July 13, 1999; Lecturer, Dr. Christian de Duve, April 5, 2001.

"Celebrating 50 Years of Prebiotic Chemistry" – Two Public Lectures: Lecturers, Dr. Jeffrey Bada and Dr. Gerald Joyce, June 10, 2003. (see Ref. 4)

James R. Arnold Public Lecture at UCSD: Lecturer, Dr. William K. Hartmann, May 7, 2004. (see Ref. 5)

3. Examples of facilitation by NSCORT/Exobiology of material to the general public

Interviews with NSCORT/Exobiology scientists, descriptions of research, and other NSCORT/Exobiology associated activities, appeared in local, national and international media throughout 1997-2004.

Media - Broadcast

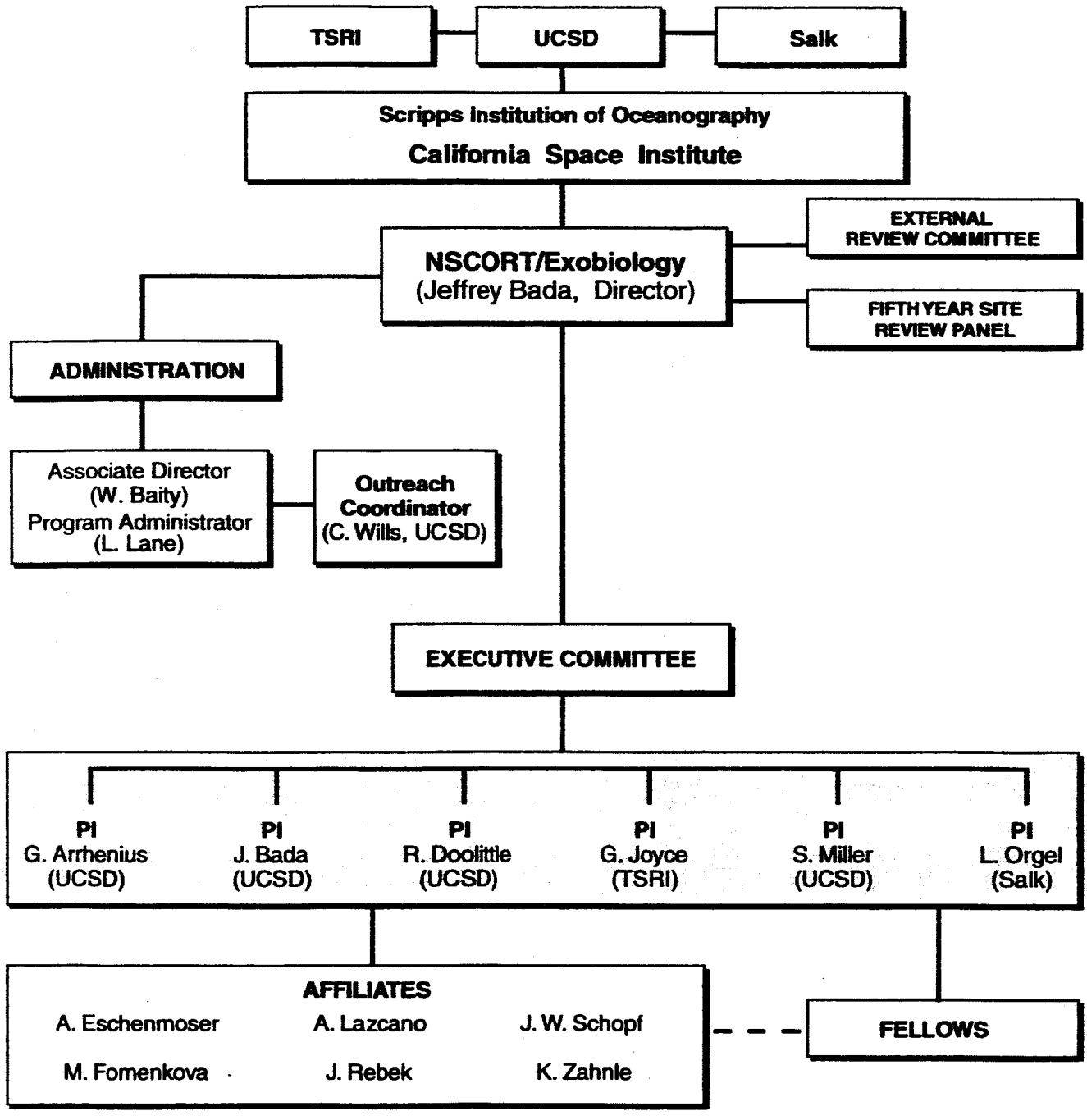
- Pulse of the Planet interview with J. Bada, "Whales Aging" – 3 Programs, February 2002.
- BBC Life Spans interview with J. Bada, " Longevity of Bow Head Whales" , April 14, 2004.
- UCSD TV – NSCORT/Exobiology productions in collaboration with UCSD-TV, 1998-2004 (see Ref. 6).

Media - Electronic

- News release embargoed by Science: "Recooking the Recipe for Prebiotic Soup: Scripps Professor Revisits the Miller Experiment and the Original of Life". Fiftieth anniversary of famous experiment commemorated with June 10, 2003 public symposium at the University of California, San Diego, (J. Bada) May 1, 2003 (see Ref. 7).
- Astrobiology Magazine interview with Stanley L. Miller: "Primordial Recipe: Spark and Stir". Celebrates Stanley Miller's milestone publication, May 14, 2003 (see Ref. 8).

References

NSCORT/Exobiology
Organizational Flow Chart, 1997-2001



Notes:

NSCORT -- NASA Specialized Center of Research and Training
UCSD -- University of California, San Diego
TSRI -- The Scripps Research Institute
Salk -- The Salk Institute for Biological Studies
PI -- Principal Investigator

Report of the Astrobiology NSCORT Review Panel

18 February 2002

Introduction

The field of astrobiology addresses several grand themes, ranging from how life began and evolved on the Earth, and the nature and distribution of life elsewhere, to the more challenging issue of life's future on Earth and beyond. While strongly anchored in the fields of biology and organic chemistry, the subject at the same time involves questions of the origin and evolution of planets in our solar system and around other stars and the factors that govern the habitability and non-habitability of planetary and satellite environments. A subfield of astrobiology, termed exobiology, addresses the origin, evolution, and distribution of non-terrestrial life, although in current usage the word exobiology is increasingly replaced by the broader term.

As the lead federal agency sponsoring research in astrobiology, NASA sponsors several programs in this area. There are research and analysis programs in astrobiology, under which individual investigators or small teams propose work on focused scientific questions. There are also two new technology programs designed to encourage the development of instruments for laboratory-based and in situ analysis in support of astrobiological exploration of the solar system. In 1998 the agency launched the NASA Astrobiology Institute (NAI), an experiment in the operation of a "virtual institute" made up of multi-institutional, multidisciplinary, geographically far-flung teams of scientists addressing broader questions. For about a decade, the agency has also supported NASA Specialized Centers of Research and Training (or NSCORTs) in astrobiology. These centers are university-based consortia emphasizing the synergy between research and training of students and postdoctoral scientists as well as the dissemination of knowledge to the general public and professional educators.

The first such NSCORT, a consortium of scientists at the University of California at San Diego (UCSD), the Salk Institute for Biological Studies, and The Scripps Research Institute, was initiated in January 1992 (as the NSCORT in Exobiology). That NSCORT, administered by the California Space Institute at UCSD, was renewed for a second 5-year period in 1997. In 1998, a second NSCORT in astrobiology was initiated at the New York Center for Studies on the Origins of Life, a consortium of scientists at the Rensselaer Polytechnic Institute (RPI), the State University of New York at Albany, and the College of St. Rose. Both NSCORTs (hereinafter designated by their respective administrative lead institution) are nearing the end of the periods of support awarded as a result of the last peer review of each of the team's proposals.

Panel Charter

In September 2001 an Astrobiology NSCORT Review Panel was chartered by the Office of Space Science, NASA Headquarters, to review the performance of the Astrobiology NSCORTs and to analyze the likely effects and impacts of different options for the future of the Astrobiology NSCORT program. The Review Panel was asked to report its findings to the Solar System Exploration Division through the Division's Senior Astrobiologist.

The Review Panel was specifically asked to evaluate the following:

(a) the degree to which NSCORT scientific productivity is enhanced by the NSCORT structure above that expected from similar individual investigations;

(b) the contributions made by the NSCORTs to training future investigators; and

(c) the contributions made by the NSCORTs to enhancing public understanding of astrobiology.

The Review Panel was also asked to analyze the likely impacts of several options for the future of the NSCORTs. Explicitly listed options included, but were not necessarily to be limited to, the following:

(i) continuation of the Astrobiology NSCORT program with only minor changes through a new competitive selection;

(ii) ending the program and investing the funds in future years in other aspects of astrobiology;

(iii) integrating the NSCORT program with the NASA Astrobiology Institute.

Panel Deliberations

The Review Panel held meetings at each of the Astrobiology NSCORTs. Panel members visited the New York Center for Studies on the Origins of Life on 12-13 November 2001. A visit to the NSCORT administered at UCSD was held on 23-24 January 2002. Considerable documentary material was provided to the Review Panel by the NSCORTs in advance of each visit, including CVs of Principal Investigators (PIs), current students and postdoctoral scientists, and alumni; annual summaries of research progress; and descriptions of education and outreach programs and accomplishments. Additional Review Panel deliberations were accommodated by teleconferences and exchanges of electronic mail.

Evaluation of Current NSCORTs

Research Productivity

To evaluate whether research productivity is enhanced by the NSCORT structure, the Review Panel began by asking whether there appeared to be significant enhancements in the productivity of the individual PIs involved in each program as well as of their respective groups of students and postdoctoral scientists. Toward that end, we attempted to judge not merely the numbers of papers, but more importantly the quality of the work and any increases in interdisciplinary collaborations among the PIs.

UCSD. Although it is always difficult to provide a quantitative estimate of research quality, Prof. Jeffrey Bada, the director of the UCSD program, described one such parameter. He used the Science Citation Index algorithm related to publication in journals that are generally agreed to have significant impact. Before the NSCORT began at UCSD, the average impact score for NSCORT-PI publications in the field of astrobiology was 58. After the first five years, this score rose to 96, and after 5 more years the score had further increased to 162. The Review Panel did not attempt an independent verification of the scores, but we agree that papers from the program

increasingly appeared in high-impact journals and very likely led to increased recognition of this field within the scientific community.

The Review Panel also asked whether involvement in the NSCORT program led to increased collaborative activity among the PIs. Although the UCSD PIs clearly share the common goal of providing an excellent training environment for their students and postdoctoral scientists, there is little evidence of increased research collaboration, at least in terms of papers. Existing collaborations (e.g., Miller and Bada) appeared to continue. One publication did involve all of the PIs, a one-page commentary in *Science* in 1999. We also heard anecdotal comments by the PIs indicating that they have markedly benefited from their involvement in the program. A typical comment was that the NSCORT provided a renewed source of interest and motivation to continue and expand research activities in the field of astrobiology. Another noteworthy comment was that the flow of graduate students and postdoctoral scientists through the program markedly lowered the barriers that tend to form around individual PI laboratories.

Finally, a primary goal of the NSCORT program is to train the next generation of investigators in astrobiology. By attracting highly talented students and exposing them to research programs of leading investigators, the UCSD program has clearly managed to achieve this goal. We were able to identify several significant publications of graduate students, postdoctoral scientists, and their research advisors that were supported by NSCORT funds and appeared in highly competitive journals such as *Science*, *Nature*, and the *Proceedings of the National Academy of Sciences*. Former graduate students and postdoctoral scientists recognized by the Review Panel include Luann Becker, Ronald Breaker, Elizabeth Catlos, Jason Dworkin, Christopher House, Luc Jaeger, Anthony Keefe, Rihe Liu, Stephen Mojzsis, and Terry Sheppard, all of whom are now launched toward academic careers involving continued contributions to astrobiology.

RPI. The effect of NSCORT involvement on the scientific productivity of the PIs in the RPI center is less apparent, but the panel agreed that it is too early to expect a clear effect after less than four years of activity. In contrast to the UCSD program, it is apparent that the RPI NSCORT stimulated an increased level of collaborative activity among the PIs. One innovative route to enhanced interactions is their use of "chalk and talk" sessions in which one PI explains a research topic to the others with no visual aids beyond a blackboard. The research directions of each of the PIs have been significantly changed by their involvement in the NSCORT. New research projects have been undertaken by Delano and Whittet on lunar impact glasses, by Ferris and Roberge on the chemistry of the Titan haze, by Ferris and Gaffey on mineral catalysts, by Whittet and Roberge on the evolution of dust to planets, and by Hagan and Nierzwicki-Bauer on size limits of very small organisms. Not all of these collaborations have yet produced publications, but it was encouraging to see them underway. Most of the publications from the PIs in this center appear in appropriate journals for the specific fields of research, rather than in high-impact journals of broad readership.

Our overall judgement is that the RPI NSCORT is succeeding in its primary goal of training a cadre of excellent graduate students and postdoctoral researchers. The Review Panel observes a continuation of research productivity from the PIs that has not yet been strongly affected by involvement in the NSCORT, but we were impressed by the initiation of the new group of

collaborative projects. Since the inception of the program the overall productivity has varied among the PIs from modest to prolific. We expect, on the basis of ongoing projects and maturing of involved students, that the productivity of the consortium will improve over the next few years. We suggest that the NSCORT director encourage his Co-Is to consider publishing in high-impact journals those research results that have the greatest general interest and significance.

Training

The training component (the "T" in NSCORT) at the centers is one of the most exciting and rewarding aspects of these programs, both by design and by the opportunity for postdocs, graduate students, and undergraduates from disparate fields to interact with each other and with the PIs in a multidisciplinary adventure. While RPI covered a wider range of disciplines, from astrophysics to microbiology, than UCSD, with its emphasis on chemistry and molecular biology, both groups emphasized a multidisciplinary approach to the study of the origin of life. At both RPI and UCSD, the students (both graduate and undergraduate) and postdoctoral scientists raved about the program, bubbling over with excitement and appreciation. Especially noted was their appreciation of the need to learn the "language" of each of the different fields inherent to astrobiology (with RPI students even putting together a dictionary for new recruits) before one could see how the varying disciplines fit together to provide new insights into the quest to unravel the origin of life.

At both centers, the NSCORT grants allowed the continued support of "official" training with courses and student and postdoctoral fellowships on the origin of life. Courses apparently initiated as part of the centers, including "Origins of Life: A Cosmic Perspective" (RPI), "The Origin of Life on Earth and Elsewhere"(UCSD), and a web-based course module entitled "How Could Life Have Arisen on Earth?" (http://chemistry.beloit.edu/Origins/), attract students not only from the NSCORTs but also from the overall student populations at the participating institutions and beyond. Fellowship funding, coupled with the stellar (UCSD; in place 10 years) and growing (RPI; in place 4 years) reputations of origin of life studies, allowed the recruitment of top students and postdocs.

A benefit less tangible, at least perhaps on paper, but heartily attested to by all those interviewed, is the influence and impact of the continued interactions among each center's students and postdoctoral scientists and the remarkable interdisciplinary cross-talk enabled by these NSCORTS. This communication is accomplished via journal clubs, seminar series with internal and outside speakers, meetings among all NSCORT members, and attendance at national and international meetings. The journal club, run by the postdocs and students at both sites and to which PIs are not allowed, serves as a safe haven to learn the language of the varied fields. Here, "dumb" questions can be asked and ideas formulated with one's peers – peers from other fields and labs who would not know each other without the NSCORTs. Furthermore, movement between labs and even between departments is facilitated, providing exposure to a wider variety of techniques and approaches and leading to further interactions. This interdisciplinary education subsequently allowed the participants to feel comfortable asking questions of senior scientists at their institutions, and of scientists from a wide spectrum of fields both at seminars at the respective sites and at outside meetings and symposia. The education and interactions

described by the students and postdocs at both sites more than fulfilled the goals of the NSCORT charge for training and made all of us envious of this extraordinary experience.

The career paths of students and postdocs at the two NSCORT sites can be followed to varying degrees, inasmuch as the programs have been in place for different lengths of time. On the basis of interviews and CVs provided to the Review Panel, it appears that graduate students are accepting exciting postdoctoral positions, both in astrobiology and in more specialized fields. The postdoctoral scientists who have "graduated" from the training programs are moving into academic posts as well as positions in industry (biotechnology) and government. While it was pointed out that it may be difficult to secure a position now as an astrobiologist per se, the postdocs and students were trained so well in their traditional fields that they were able to move on to other openings. Furthermore, even if they were not now engaged in research in astrobiology, many emphasized, both in written comments and interviews, the advantage they felt they had gained from their multidisciplinary NSCORT experience to be able to think broadly and embrace concepts that bridge different fields.

Overall the NSCORTS have served to enhance greatly the education of the next generation of astrobiologists, breaking down the barriers between fields and enhancing multidisciplinary research. The result is a remarkable cohort of young scientists who are creatively addressing questions in the field of astrobiology or who are bringing these abilities to more traditional fields. The breadth and depth of knowledge that the students obtain and the excitement they continue to display for astrobiology research is a direct result of the NSCORTs.

Outreach

The Astrobiology NSCORTs have each developed programs and products that have been uniformly excellent in terms of number, quality, and variety. Examples were numerous and included presentations and lectures for the general public, work with teachers and teacher teams, and assistance by investigators in radio, television, and documentary film productions. Both NSCORTs have developed resources available on internet web pages and engaged in substantial, high-quality outreach. NSCORT investigators have been regularly and widely interviewed and quoted in popular print media.

UCSD. In addition to the collaborative undergraduate course noted above, the NSCORT has produced teaching modules for high school teachers, conducted teacher-training programs, and provided support to individual teachers as summer researchers. Through collaborations with UC television stations, the NSCORT helped produce several hours of television programming and a series of half-hour programs on astrobiology. A book, "The Spark of Life" by Bada and Wills, was aimed at a general but scientifically literate audience and has received considerable attention and acclaim. Additional television and radio programs have included an international array of broadcasters.

RPI. Investigators and students regularly participated in work with teachers and in programs to educate the general public. Of particular note was an extensive series of public radio programs that featured interviews with NSCORT investigators and visiting seminar speakers. Investigators have hosted high school teachers and students in labs and have participated in

developing educational materials along with course materials for undergraduate students. Further, PIs have given keynote addresses to conferences of science teachers and have worked effectively with students in individual local schools.

The Review Panel's only concern with the outreach and public education programs at the two NSCORTs was the apparent lack of a clear strategy for outreach linked to an assessment plan that would gauge impact and significance. Although some evidence was available for the numbers of persons in attendance at public lectures or the size of audiences for broadcasts, it is difficult to judge the outcomes of the outreach efforts in either a quantitative or qualitative manner. The Review Panel advises each center to examine NASA's Implementation Plan for Education and to become familiar with efforts in the Office of Space Science to provide resources and guidance for their efforts to disseminate knowledge. Each center should clearly outline a plan, devise an approach for achieving goals, and take steps to develop applicable measures of success.

Review Panel Findings

On Communication between NSCORTs and NAI

Given the considerable NASA investment in the NAI, there is much that could be gained by providing better scientific and programmatic communication among the NSCORT and NAI consortia and between the NSCORTs and the NAI administrative enterprise. While the Astrobiology NSCORTs and NAI teams have somewhat different organizational structures and overall goals, there are a variety of scientific exchanges and opportunities for students and postdoctoral scientists within the NAI in which NSCORT team members could be encouraged to participate. Examples include NAI video seminars, membership on NAI focus groups, and travel awards for NAI students and postdoctoral scientists to spend time visiting labs at participating institutions. As the field of astrobiology evolves, at times rapidly, the benefits to be gained by removing artificial barriers to quick and effective dissemination of information and learning experiences should be obvious.

On Outreach and Education

At both of the Astrobiology NSCORT sites, there is room for better coordination of outreach and education efforts with other NASA programs. Both of the centers have taken specific steps to educate targeted audiences, including the general public, teachers, and students. These efforts have included the use of broadcast media to create radio and television programming, the development of teaching materials to improve K-12 education, and the creation of courses of general interest to college and university students. Both sites demonstrated the ability to produce programs and materials of high quality through collaboration with educators and through the use of media including modern information technology.

The Astrobiology NSCORTs have not, however, made use of NASA education plans, and as noted above there is a need for an improved definition of outreach and education strategies. Each of the NSCORT consortia has a different research focus, and these centers, working in

coordination with each other and with the NAI, could develop more comprehensive education and outreach approaches at approximately the same level of effort as that currently expended. Specifically, each center should clearly identify their outreach and education audiences and should develop plans congruent with NASA's overall education plan. There should be a mechanism for sharing these strategies among NSCORT and NAI teams. Further, centers can and should coordinate the development of educational materials for K-12 students, teachers, and general higher-education audiences. This coordination could take the form of creation of a variety of teaching "modules" available among the sites and centers. Finally, the centers should pay careful attention to making teaching materials and resources available on well-managed internet web sites, because these web sites will be an increasingly important medium for education and outreach in the future.

On the Continuation of the Astrobiology NSCORT Concept

The Review Panel concluded that the Astrobiology NSCORTs have furthered NASA's goals beyond what could have been expected from the efforts of effective individuals working independently. Such specialized centers of scientific excellence, with an emphasis on training and outreach, have proven to yield a high return on the investment of NASA funds. They continue to be, and are likely to remain, crucial to NASA's aims of facilitating the recruitment and training of scientists and educators interested in the origin of life and related scientific endeavors.

The Review Panel attempted to ascertain those aspects of the current Astrobiology NSCORT programs that seem to make them effective. The close proximity of the principals to one another allows an ease of communication and cooperation that, while not impossible, is severely curtailed in a more geographically diffuse group. The number of PIs in the two NSCORTs is similar (6-7), and each group felt that such a team size has been an important factor in maintaining a cohesive program. The knowledge, intellectual curiosity and flexibility, and capacity for communication among the young NSCORT scientists seem to have been enhanced by their opportunities to meet and talk, not only at team meetings, but also with one another, and with visiting scientists, in the absence of the senior scientists. With such self-motivated students, having venues (e.g., journal clubs, student symposia) in which they can take on leading roles and engage in mutual education contributes to their development of attributes that make these individuals exceedingly valuable members of the scientific community. For similar reasons, it appears to be advantageous if the principal investigators meet regularly for an intellectual exchange aimed at facilitating collaborations and generally cultivating an interdisciplinary outlook.

In summary, it is the considered finding of the Review Panel that the Astrobiology NSCORT program should be continued through a new competitive selection.

NSCORT/EXOBIOLOGY

1992-2003 POSTDOCTORAL FELLOWS AND ADJUNCT* FELLOWS

Name	Period	PI	Present Position
Bohler, Christof	2/94-5/95	Orgel	Res Sci, Gass Fermn. Zurich, Switzerland
Botta, Oliver	3/99-2/02	Bada	Postdoc, Bada lab
Breaker, Ronald (Adj.)	92-95	Joyce	Assoc Prof, Yale University
Broo, Kerstin (Adj.)	6/98-7/00	Joyce	ResAssoc ,Biomed Ctr, Uppsala Univ, Sweden
Chakrabarti, Ajoy (Adj.)	2/93-1/96	Joyce	AssocDir, External Bus Integra Sol, Plainsboro, NJ
Cleaves, James Henderson	11/01-present	Miller/Bada	Postdoc, Miller & Bada labs
Gao, Kui	3/99-2/00	Orgel	Sr Sci, Infectious Disease Lab, Salk Institute, CA
Glavin, Daniel	10/01-2/02	Bada	Postdoc, UC Santa Barbara, CA
Griffith, Michael	1/92-7/93	Ghadiri/Joyce	Isis Pharmaceuticals, Carlsbad, CA
Guntha, Sreenivasulu	1/99-12/00	Eschenmoser	Sr Res Sci, Albany Molecular, Alany, NY
Jaeger, Luc	7/93-7/95	Joyce	Asst. Prof., UC Santa Barbara, CA
Keefe, Anthony	1/93-4/95	Miller	Res.Fel., Harvard Med. Schl, Boston, MA
Kozlov, Igor	5/97-5/99	Orgel	Scientist, Illumina, San Dieog, CA
Krishnamurthy, Ram	12/94-12/96	Arrhenius	Asst Prof, Scripps Research Institute, LA, CA
Kuhns, Scott	1/00-1/02	Joyce	Scientist, Cancer Vax Corp, Carlsbad, CA
Lee, Ton	1/93-12/94	Arrhenius	Fisherman Pharm Corp., Taiwan
Lehman, Niles (Adj.)	9/96	Joyce	Asst Prof, Portland State U, Oregon
Lepland, Aivo (Adj.)	97-01	Arrhenius	Res Sci, Norweigan Geological Survey, Norway
Liao-Arrhenius, Meichia (Adj.)	8/97-9/98	Arrhenius	Adjt Faculty/Lecturer, SD Miramar College, CA
Lyons, James	12/96-12/98	Miller	Astro Postdoc Fel, UCLA, Los Angeles, CA
McDonald, Gene	9/92-8/94	Bada	Res Sci, Jet Propulsion Lab, Pasadena, CA
Mecozzi, Sandro	4/97-3/99	Rebek	Asst Prof, University of Wisconsin, Madison
Miyakawa, Shin (Adj.)	1/99-8/00	Miller	Postdoc, Rensselaer Polytechnic, Troy, NY
Muth, Heinz Peter (Adj.)	92-93	Orgel	Patent Attorney, Germany
Ordoukhanian, Phillip (Adj.)	97-01	Joyce	Dir, Scripps Res Inst Sequencing Core Fac, TSRI
Pitsch, Stefan	2/95-10/95	Arrhenius	Asst Prof, Ecole Polytech Fed Lausanne, Swiss
Reader, John	6/98-5/00	Joyce	Res Assoc, Scripps Research Inst., La Jolla, CA
Rojas, Ana	1/00-12/01	Doolittle	Burnham Institute, La Jolla, CA
Schmidt, Jurgen	2/95-2//97	Orgel	Los Alamos National Lab, NM
Sheppard, Terry	11/95-10/97	Joyce	Asst Prof, Northwestern University
Walda, Kevin (Adj.)	2/94-3/96	Bada	Director, Analytical Facility, UCSD/SIO, CA
Wen, Ke	1/99-1/01	Orgel	Postdoc, Chem&Biochem, UCSD, La Jolla, CA
Wright, Martin	11/93-10/95	Joyce	Pr Sci, Compound Therapeutics, Cambridge, MA
Xu, Yong	4/97-3/98	Arrhenius	Senior Scientist, Atlant University

*The principal difference between Fellows and Adjunct Fellows is the NASA grant budget category from which the support funds are derived. Separate titles are designated because of overhead implications.

1992-2003 GRADUATE STUDENT FELLOWS AND ADJUNCT FELLOWS; UNDERGRADUATE AND ADJUNCT FELLOWS

Name	Period	PI	Present Position
Aubrey, Andrew (Adj.)	01-present	Bada	Graduate ,UCSD,La Jolla, CA
Becker, Luann (Adj.)	94-95	Bada	Ass Prof, UCSB, Santa Barbara, CA
Bernson, Deborah (U. Fel)	Summer 98	Doolittle	Graduate, Cal State, San Marcos, CA
Borquez, Eduardo (U. Fel)	Summer 98-99	Miller	Med. Student, Harvard Medical School
Brinton, Karen	9/92-9/98	Bada	Jet Propulsion Laboratory, Pasadena, CA
Bruick, Richard (Adj.)	93-98	Joyce	AsstProf, UT Southwestern Med Ctr, Texas
Catalina, Maria (U. Fel)	Summer 97	Arrhenius	GUESS Admin, San Diego, CA
Catlos, Elizabeth (U. Fel)	Summer 94	Bada	Asst Prof, Oklahoma State U, Stillwater, OK
Czodrowski, Paul (U. Fel)	Summer'2000	Doolittle	Graduate, Tech U of Munich, Germany
Cleaves, J. Henderson	7/97-10/01	Miller	Postdoc, Miller & Bada labs, UCSD
Dai, Xiao-Chang (Adj.)	12/98	Joyce	California Institute of Technology, CA
Dion, Vincent (U. Fel)	Summer 99-00	Miller	Undergrad, U. of Guelph, Ontario,, Canada
Dworkin, Jason	7/92-8/96	Miller	Res Sci, NASA Ames, Moffet Field, CA
Eppler, Aaron (U. Fel)	Summer 95	Bada	Graduate School
Glavin, Daniel	6/98-9/01	Bada	Postdoc, UC Santa Barbara, CA
Hamilton, Healy (U. Fel)	Summer 95	Bada	PhD 2001; Cal. Acad. Science
Handy, Jacob (U. Fel)	Summer 97-98	Doolittle	Patent Attorney, Gray Cary Ware, La Jolla,CA
House, Christopher (U. Fel)	Summer 93-94	Miller	PhD 2000; Faculty, Penn State U, PA
Kminek, Gerhard (Adj.)	98-3/03	Bada	Adv Concepts Team, European Space Agency
Lang, Greg (U. Fel)	Summer 2000	Bada	Graduate, Millersville U., Lancaster, PA
Larralde, Rosa (U. Fel)	Summer 94	Miller	Graduate, Harvard University
Levy, Matthew	7/96-6/98	Miller	Graduate, U. of Texas at Austin, TX
Liu, Rihe	7/93-12/96	Orgel	Asst Prof, U. N. Carolina at Chapel Hill, NC
Lloyd, Pat (U. Fel)	Summer 93	Bada	Graduate School
Maughan, Quinn (U. Adj.)	98-00	Miller	Tech Writer, Beckman Coulter, Fullerton, CA
McGauley, Michael (U. Fel)	Summer 99	Bada	Graduate, University of Miami, FL
McGinness, Kathleen (Adj.)	99-01	Joyce	Postdoc, MIT, Boston , MA
McAllister, Ryan (U. Fel)	Summer 99	Doolittle	Graduate, University of Illinois, IL
Metzgar, David	10/97-9/01	Wills	Res Assoc, Scripps Res Institute, LaJolla, CA
Mojzsis, Stephen	10/95-9/97	Arrhenius	Asst Prof, U. Colorado, Boulder, CO
Nelson, Kevin	7/96-6/98	Miller	Med Scholar, U. Illinois Urbana-Champaign
Rhew, Robert (U. Fel)	Summer 94	Bada	PhD, 2001; Faculty, Univ. Calif. Berkeley, CA
Robertson, Michael (U. Fel)	Summer 92	Miller	PhD 2002; Postdoc, Univ.Calif. Santa Cruz
Scott, Laura (U. Fel)	Summer 96	Bada	Graduate School
Thomas, Elizabeth (U.Fel)	Summer 98	Wills	Graduate, Cold Sp ring Harbor; Wigler lab
van Zuilen, Mark	7/98-3/03	Arrhenius	Postdoc, CRPG-CNRS, France
Wang, Sharon	9/92-11/97	Bada	Sol Dev, IBM Life Sciences, San Jose, CA
Woiwode, Thomas (U. Fel)	Summer 92-93	Bada	Medical School
Zhang, Shibin (U. Fel)	Summer 94-95	Arrhenius	IBM, San Jose, CA
Zubieta, Chloe (U. Fel)	Summer 97	Arrhenius	Eur Mol Biol Lab, Grenoble, France

1992-2001 NSCORT/Exobiology Summer Undergraduate Fellows

Name	PI Laboratory	Summer
Pagel, Matthew	Wills	2001
Zauscher, Melanie	Bada	2001
Breitbart, Mya	Arrhenius	2000
Czodrowski, Paul (see Graduate List)	Doolittle	2000
Dion, Vincent (see Graduate List)	Miller	2000
Lang, Greg (see Graduate List)	Bada	2000
Pagel, Matthew	Wills	2000
Finarelli, John (NPBI Fellow)	Arrhenius	2000
Dion, Vincent (see Graduate List)	Miller	1999
Kimble, Ryan	Wills	1999
McAllister, Ryan (see Graduate List)	Doolittle	1999
McGauley, Michael (see Graduate List)	Bada	1999
Safier, Jennifer	Bada	1999, 1998
Airo, Alessandro	Orgel	1998
Bebié, Joakim	Arrhenius	1998
Bernsen, Deborah (see Graduate List)	Doolittle	1998
Borquez, Eduardo (see Graduate List)	Miller	1998
Casini, Carolina	Bada	1998
Handy, Jacob (see Graduate List)	Doolittle	1998, 1997
Thomas, Elizabeth (see Graduate List)	Wills	1998
Catalina, María (see Graduate List)	Arrhenius	1997
Estévez, Carlos	Miller	1997
Glavin, Daniel (see Graduate List)	Bada	1997, 1996
Makevich, John	Bada	1997
Ormsbee, Alice	Miller	1997
Zubieta, Chloe	Arrhenius	1997
Maughan, Quinn (see Graduate List)	Miller	1996
Nelson, Kevin (see Graduate List)	Miller	1996, 1995
Scott, Laura	Bada	1996
Dacks, Joel	Miller	1995
Eppler, Aaron (see Graduate List)	Bada	1995
Hamilton, Healy (see Graduate List)	Bada	1995
Khalsa, Guru	Miller	1995
Levy, Matthew (see Graduate List)	Miller	1995, 1994
Zhang, Shibin (see Graduate List)	Arrhenius	1995, 1994
Catlos, Elizabeth (see Graduate List)	Bada	1994

1997-2001 NSCORT/Exobiology Summer Undergraduate Fellows

Name	PI Laboratory	Summer
House, Christopher (see Graduate List)	Miller	1994, 1993
Larralde, Rosa (see Graduate List)	Miller	1994Rhew,
Robert (see Graduate List)	Bada	1994
Balasingam, Kishan	Arrhenius	1993
Lloyd, Pat (see Graduate List)	Bada	1993
Woiwode, Thomas (see Graduate List)	Bada	1993, 1992
Cozzatti, Jean-Paul	Miller	1992
Foster, Krishna	Thiemens	1992
Frutos, Annabelle	Arrhenius	1992
Mojzsis, Stephen (see Graduate List)	Arrhenius	1992
Rice, Abraham	Miller	1992
Ring, Ken	Arrhenius	1992
Robertson, Michael (see Graduate List)	Miller	1992
Warden-Owen, Lisa	Arrhenius	1992

CELEBRATING 50 YEARS OF PREBIOTIC CHEMISTRY

PUBLIC LECTURES

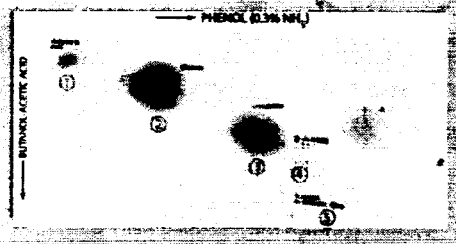
Moderator:

Dr. Leslie Orgel
The Salk Institute
for Biological Studies

Sponsored by:
The NASA Specialized Center of Research & Training (NSCORT) in Exobiology
The Dean of Physical Sciences, and the Department of Chemistry & Biochemistry at the University of California, San Diego (UCSD)
National Aeronautics & Space Administration

Tuesday, 10 June 2003
Public Lectures at 3:00 pm
Reception following lectures

Robinson Building Complex Auditorium
Graduate School of International Relations & Pacific Studies (IR/PS)
Thurgood Marshall College
University of California, San Diego



Title:

"Revisiting the Miller Experiment 50 years later"

Speaker:

Dr. Jeffrey L. Bada
Director, NSCORT/Exobiology
University of California, San Diego

Jeffrey Bada, a Professor at the Scripps Institution of Oceanography, University of California at San Diego, has had a sustained interest in the origin of life for more than 30 years. His first paper, published in 1968 with his mentor, Stanley L. Miller, was on the racemization kinetics of amino acids. He has since explored a number of topics relevant to the origin of life, such as the importance of extraterrestrial sources of organic compounds on the early Earth, the biogeochemistry of amino acids, the origin of homochirality and the use of state-of-the-art analytical methods for the *in situ* detection of extraterrestrial life. He is the co-author, with Christopher Wills, of *"The Spark of Life: Darwin and the Primeval Soup"*.

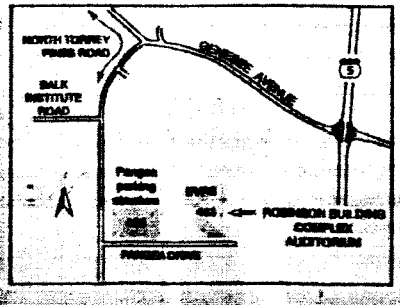
Title:

"The Antiquity of RNA-Based Evolution"

Speaker:

Dr. Gerald F. Joyce
Departments of
Chemistry & Molecular Biology
The Scripps Research Institute

Gerald Joyce is a Professor in the Departments of Chemistry and Molecular Biology and an Investigator of the Skaggs Institute for Chemical Biology at The Scripps Research Institute. His research concerns the test-tube evolution of RNA enzymes. His lecture will concern the role of RNA-based Darwinian evolution in the early history of life on Earth.



DIRECTIONS (to UCSD Pangea Parking Structure and Robinson Auditorium, IR/PS): Interstate 5 (North or South); WEST off Genesee Avenue; LEFT on North Torrey Pines Road; LEFT on Pangea Drive
PARKING (Purchase $3 permit):
Follow directional signs for Prebiotic Chemistry Public Lecture; purchase $3 parking permit from parking attendant and park in the Pangea Parking Structure. Park and follow directional signs to Robinson Auditorium (Bldg. #463 on UCSD Campus map: http://maps.ucsd.edu/CampusMap.pdf). Parking attendant will assist you.

For information, contact (858) 534-1891
or visit the NSCORT/Exobiology website at http://exobio.ucsd.edu

JAMES R. ARNOLD

James R. Arnold is Harold C. Urey Professor of Chemistry (emeritus) at the University of California, San Diego (UCSD). He received his degrees in chemistry from Princeton University. As a graduate student there, he worked on the Manhattan (atomic bomb) Project. He began his research career at the University of Chicago working under Prof. Willard Libby in the development of Carbon-14 dating. He was brought to the University of California, San Diego by Dr. Roger Revelle in 1958 as one of the first faculty members for the then new UCSD campus. He was the founding chairman of the UCSD Department of Chemistry. His research over the last several decades has mainly been in the area of space and planetary science, including participation in NASA's Apollo missions to the moon, and studies of lunar samples returned by those missions. He was the first director of the University of California's California Space Institute. He is a member of the U.S. National Academy of Sciences, and of the American Academy of Arts and Sciences. He has received a number of medals and awards. Asteroid 2143 is named for him "Jimarnold".

His participation in the Apollo program of manned exploration of the moon led him, along with Gerald O'Neill, Freeman Dyson, and other space scientists, to think about the future of human exploration and settlement of the moon, Mars, and other solar system objects. In 1979 he published a paper calling attention to the possible existence of substantial deposits of ice in the lunar polar regions.

His current interests are mainly in the area of increasing access to the space frontier, in particular by lowering costs while maintaining or improving reliability. The link between this goal and the education of a new generation of space leaders is very close.

The California Space Institute presents the 3rd

James R. Arnold Lecture

Co-hosted by NSCORT

EXPLORING MARS WITH SPACESHIP AND PAINTBRUSH

(WHAT WE'VE LEARNED ABOUT THE RED PLANET - AND WHY)

Presented by

William K. Hartmann

Senior Scientist
Planetary Science Institute
Tucson, Arizona

May 7, 2004 4:00 PM

Institute of the Americas, UCSD
(University of California, San Diego)
Copley International Conference Center

Reception to follow in the Plaza of the Institute of the Americas

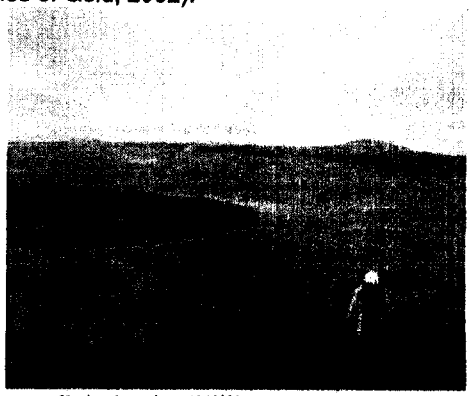
The public is cordially invited
The event is free
$3.00 parking permit is required to park at UCSD

http://calspace.ucsd.edu/JimArnoldLecture.htm

WILLIAM K. HARTMANN

Dr. William K. Hartmann is known internationally for planetary research as well as his writing and painting. He served on NASA's Mars Global Surveyor imaging team (1997-present) as well as the Mariner 9 Mars mapping team (1971-1973).

With Dr. Donald R. Davis of PSI, he is credited with originating the modern theory of the origin of the moon (1975) and he has also worked on asteroid properties and the origin and evolution of planets. Asteroid number 3341 is named after him in recognition of his planetary research. His astronomical paintings have been in many books, magazines, and exhibitions. He was the first winner of the Carl Sagan Medal of the American Astronomical Society for communicating planetary science to the public (1997), was elected a Fellow of the American Association for Advancement of Science (2001), and is a co-winner of the Rucorn-Florensky Medal of the European Geophysical Society for work on cratering (2002). He has published numerous popular science books, including *A Traveler's Guide to Mars (2003)*. He has also published two novels, one about Mars (*Mars Underground*, 1997) and one about the southwest (*Cities of Gold*, 2002).



Painting by William K. Hartmann

Exobiology on UCSD/TV

Rich Wargo,
Science Editor, UCSD/TV

Over the past several years, the NSCORT Exobiology program has made excellent use of the unique outreach opportunity afforded by the two UC television stations operated from the UCSD campus. The NSCORT's Chris Wills sits on our advisory board.

Together, the stations provide coverage to over 7 million households nationwide, and with the inclusion of UCSDTV's simultaneous webstreaming (www.ucsd.tv - "video on demand") the programs have reached global audiences. Further depth is achieved by UCSD-TV's on-demand video archive, providing further access to the programs.

The programs produced serve a variety of audiences and interests, from highly technical presentations for special interest audiences, to programs designed for high school through adult audiences with treatments and presentations about the activities and research interests of the NSCORT Exobiology program.

The various NSCORT collaborations with the UC stations have supported over ten hours of original television programming featuring NASA supported researchers and other noted investigators in the field of the origins of life. They have included Michael Carr, Chris McKay, Ken Nealson, David Koerner, David McKay, , Jeff Bada, Chris Wills, Russell Doolittle Dan Glavin and Freeman Dyson,. These programs have each enjoyed up to fifty repeat broadcasts, enhancing access to the programs.

Future production features a series of half-hour programs which address current issues and approaches in exobiology as represented by the activities of the cadre of young researchers in the NSCORT Exobiology program. Currently featured in these programs which are in production are NSCORT Fellows Dan Glavin, Oliver Botta, Gerhard Kminek, Jim Cleaves and John Reader.

NSCORT Exobiology productions in collaboration with UCSD-TV

-The Robert D. Tschirgi Memorial Lecture: Crawling Out of the RNA World
Thomas Cech

-ISSOL 1999 Plenary Address: Gravity is Cool: Why Our Universe is Hospitable to Life
Freeman Dyson

- The Search for the Origin of Life: The Habitability of Early Mars
Michael Carr

- The Search for the Origin of Life: Survival of Life Beyond its Planet of Origin
Chris McKay

- The Search for the Origin of Life: Survival and Evolution of Life in Space
Ken Nealson

- The Search for the Origin of Life: The Evolution of Early Solar-System Analogs
David Koerner

-The Search for the Origin of Life: Evidence for Mineralized Bacteria in the Nakhla Meteorite
David McKay

-The Search for the Origin of Life: Amino Acids in the Nakhla Meteorite
Dan Glavin

-UCSD Conversations: Bada:
Jeff Bada explains a new theory of the origin of life

-UCSD Conversations: Mars Rocks:
Danny Glavin of Scripps Institution of Oceanography on the search for evidence of life on Mars

-UCSD Conversations: Exobiology Summer Camp:
A look at an summer undergraduate study program in exobiology

-UCSD Conversations: The Spark of Life:
Chemist Jeff Bada and Biologist Chris Wills discuss their new book "Spark of Life"

- The Birch Aquarium Presents: The Spark of Life: Darwin and the Primeval Soup

New research shows that life probably arose on Earth almost four billion years ago, at a time when the planet's surface was pounded by huge waves and tides, and periodically devastated by volcanic eruptions. Join the authors of "Spark of Life", UCSD's Jeffrey Bada and Christopher Wills, as they describe the steps by which living organisms may have first appeared, and how right from the beginning, the forces of evolution were at work.

-Perspectives on Ocean Science: Bring 'em Back Alive: The Search for Life on Mars in the Coming Decades

Exploring the difficulties faced with collecting samples and how we are searching for evidence of life on Mars with Scripps Institution's Jeff Bada.

-OnBeyond: Revisiting the Miller-Urey Experiment

On the fiftieth anniversary of Stanley Miller's watershed experiment, both his first and last graduate students recreate the original experiment and evaluate the results with modern high precision techniques and reflect on the impact of the experiment on science.

-OnBeyond:

Dan Glavin explores the potential for the delivery of organic constituents to earth via micrometeorites.

-50 Years of Prebiotic Chemistry:

Three luminaries in the field of the study of the origins of life, Leslie Orgel, Jeffrey Bada and Gerald Joyce explore developments in the field over the last fifty years and new developments to come in the field.

Programs in Production - 2004

-A Search For Origins: Building Blocks

The origin and delivery of organic compounds essential to life

- A Search For Origins: Replication

Investigations into the chemical pathways that may have enabled replicating systems to arise

Scripps Contacts:
Scripps Contacts: Mario Aguilera or Cindy Clark, 858/534-3624 E-mail: scrippsnews@ucsd.edu

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For Release: May 1, 2003

Recooking the Recipe for Prebiotic Soup: Scripps Professor Revisits the Miller Experiment and the Origin of Life

Fiftieth anniversary of famous experiment commemorated with June 10 public symposium

In the fall of 1952, Stanley Miller, now a chemistry professor emeritus at the University of California, San Diego (UCSD), began simulating primitive earthly conditions in an experiment that produced the basic building blocks of life. When he published the results in Science on May 15 the following year, he kick-started research on the origin of life and transformed modern thinking on a dormant area of science.

Jeffrey Bada, a professor of marine chemistry at Scripps Institution of Oceanography, UCSD, and an expert on origin of life processes, revisits the famous "Miller experiment" in a report published in the May 2 issue of Science.

"Up to Miller's experiment there was a large vacuum in our understanding of how life began on the earth," said Bada, who coauthored the report with Antonio Lazcano, a scientist at the Universidad Nacional AutÃ³noma de MÃ©xico, and is a visiting scholar at UCSD in Miller's laboratory. "Up to that point no one had demonstrated how compounds like amino acids could be synthesized under possible early Earth conditions."

Bada and Lazcano's essay traces the history of the Miller experiment, which originated when the late Nobel Laureate and UCSD Chemistry Professor Harold Urey discussed the idea behind the experiment in a lecture at the University of Chicago. Miller, then a graduate student in the audience, eventually presented Urey the idea of a prebiotic synthesis experiment applying an electric discharge to a mixture of methane, ammonia, water vapor, and hydrogen. Urey eventually agreed to the idea.

Results of the famous Miller experiment, which used the glass apparatus pictured, were published by Science 50 years ago. The lower flask was designed to simulate the oceans and the upper flask the atmosphere. The energy was supplied by sparking between two wire electrodes.

During Miller's experiment, the mixture of gases was circulated through a liquid water solution and continuously zapped with the electric spark, which substituted for lightning. The surprising products of the process were "biochemically significant" compounds such as amino acids, hydroxy acids, and urea. Thus, with Urey's guidance, Miller had produced the basic building blocks of contemporary life forms on Earth.

"In the early 1950s, several groups were attempting organic synthesis under primitive conditions," Bada and Lazcano note in their essay. "But it was the Miller experiment, placed in the Darwinian perspective provided by Oparin's ideas and deeply rooted in the 19th century tradition of synthetic organic chemistry, that almost overnight transformed the study of the origin of life into a respectable field of inquiry."

Bada and Lazcano also note that Miller's study was published only a few weeks after Watson and Crick's landmark paper on the DNA double-helix model and the authors highlight the important link between the two young fields in the years that followed.

- EVENT NOTE: Bada will be giving a public lecture on the 50th anniversary of the Miller experiment at 3 p.m. on Tuesday, June 10, 2003, during "Celebrating 50 Years of Prebiotic Chemistry," a public event at the Robinson Building Complex Auditorium, Graduate School of International Relations & Pacific Studies (IR/PS), Thurgood Marshall College, UCSD campus. The event, which also features Gerald Joyce of the Scripps Research Institute, is sponsored by the NASA Specialized Center of Research and Training (NSCORT) in Exobiology, the UCSD Dean of Physical Sciences, the Department of Chemistry and Biochemistry at UCSD, and the National Aeronautics and Space Administration. For information about the event: 858/534-1891; or visit the NSCORT/Exobiology web site at http://exobio.ucsd.edu. Scripps Institution of Oceanography on the web: http://scripps.ucsd.edu Scripps News on the web: http://scrippsnews.ucsd.edu Scripps Centennial on the web: http://scripps100.ucsd.edu

Scripps Institution of Oceanography, at the University of California, San Diego, is one of the oldest, largest, and most important centers for global science research and graduate training in the world. The National Research Council has ranked Scripps first in faculty quality among oceanography programs nationwide. The scientific scope of the institution has grown since its founding in 1903 to include biological, physical, chemical, geological, geophysical, and atmospheric studies of the earth as a system. Hundreds of research programs covering a wide range of scientific areas are under way today in 65 countries. The institution has a staff of about 1,300, and annual expenditures of approximately $140 million from federal, state, and private sources. Scripps operates one of the largest U.S. academic fleets with four oceanographic research ships and one research platform for worldwide exploration.

Great Debates

Living on Mars

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Primordial Recipe: Spark and Stir

Summary (May 14, 2003): No single experiment, according to Carl Sagan, has done more to convince scientists that life is 'likely abundant in the cosmos' than the work fifty years ago by then graduate student, Stanley Miller. This week celebrates his milestone publication, and *Astrobiology Magazine* interviewed him about his work and reflections today.

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Primordial Recipe: Spark and Stir

by Astrobiology Magazine staffwriter

Fifty years ago on May 15, 1953, a University of Chicago graduate student, Stanley Miller, published a landmark two-page paper in Science magazine. He considered if amino acids could be made from what was known about the early Earth's atmosphere. Could the building blocks of life be cooked up?

Miller began his paper:

> *"The idea that the organic compounds that serve as the basis of life were formed when the earth had an atmosphere of methane, ammonia, water and hydrogen instead of carbon dioxide, nitrogen, oxygen and water was suggested by Oparin and has been given emphasis by Urey and Bernal. In order to test this hypothesis..."*

"... some warm little pond, with all sorts of ammonia and phosphoric salts, light, heat, electricity etc...", Charles Darwin, on the

When Miller first presented his experimental findings to a large seminar, it is reported that at one point, Enrico Fermi politely asked if it was known whether this kind of process could have actually taken place on the primitive Earth. Harold Urey, Stanley's research advisor, immediately replied, saying 'If God did not do it this way, then he missed a good bet'. The seminar

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1859
Wilhelm Tempel discovers diffuse nebula around Pleid star Merope
1879
Thomas Edison demonstrates electric light
1914
US post office 1st used an automobile to collect & deliver mail
1936
HR Ekins of "NY World-Telegram" beats 2 other reporters in a race around the world on commercial flights, by 18« days

ended amid the laughter and, as the attendees filed out, some congratulated Stanley on his results.

pools
Credit:Smithsonian

Although Miller had submitted his paper in mid-December 1952, one reviewer did not believe the results and delayed its publication until May 15th. Later Carl Sagan would do many experiments varying the chemical percentages, but described the Miller-Urey experiments as "the single most significant step in convincing many scientists that life is likely to be abundant in the cosmos."

Early Earth: Flash in a Flask

Even today, only a few definitive things are known about what the Earth might have been like four billion years ago. It is thought that the early sun radiated only 70 percent of its modern power. No free oxygen could be found in Earth's atmosphere. The rocky wasteland lacked life. Absent were viruses, bacteria, plants and animals. Even the temperature itself is uncertain, since three schools of thought today maintain that the Earth could have been alternatively frozen, temperate or steamy.

Charles Darwin imagined life springing from a temperate world, with small ponds or runoff channels. Compared to diluted chemistry in a vast ocean, repeated evaporation and refilling have possible advantages, to find just the right concentrations somewhere so that biochemistry could begin. Glaciers, volcanoes, geysers and cometary debris potentially resupplied this primordial pond with both energy and more complex organic compounds. That is a scenario requiring relatively temperate starting conditions, and more extreme possibilities are also in the mix.

If the early Earth was a cauldron of volcanic activity, then seepage of acidic gases and heating might have circulated vital compounds to the surface. These vents may have been underwater, and precursors to biochemistry like acetic acid may have become reactive in combination with carbon monoxide. Alternatively, if the early Earth lacked any greenhouse of blanketing carbon dioxide, life could still have begun in a ball of ice. When combined with water, even a thin atmosphere of organics (formaldehyde, cyanide and ammonia) can create some building blocks of life (such as the amino acid, glycine). Thawing this 'snowball Earth' could then be triggered by a chance collision with large comets or meteors.

Terrestrial options for early climate. Early earth, snowball, cauldron or temperate?*Credit: NASA*

To test whether a primordial pond or ocean could seed the stuff of life, some experiments were needed. Miller laid out an experimental plan. He filled a flask with methane (natural gas), hydrogen and ammonia. Another flask below provided a miniature pond of water, as the model for an early ocean. Discharging flashes of voltage to simulate lightning provided just the necessary spark for new chemistry to begin. When he left the pot to cook overnight, the odds seemed stacked against coming in the next morning to discover the simulated ocean had turned reddish-yellow. But he was surprised: given a simulated ocean, atmosphere and lightning, then a hydrogen-rich mix of methane and ammonia could be transformed to amino soup.

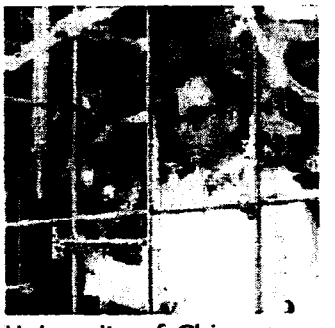
Stanley Miller with his Nobel Laureate supervisor, Harold Urey, demonstrated that 13 of the 21 amino acids necessary for life could be made in a glass flask. Placing water in this atmosphere, sparking a lightning discharge into simple organic molecules like ammonia surprised everyone by producing some of biology's essential building blocks. Indeed the formation of life had begun to take on a distinctly molecular character, as Charles Darwin had foreseen as his classical warm pond of organic soup: (*"... some warm little pond, with all sorts of ammonia and phosphoric salts, light, heat, electricity etc..."*).

Miller found that at least 10 percent of the carbon was converted into a small number of organic compounds and about two percent went into amino acids. Hydrogen, cyanide, and aldehydes were also produced. Glycine was the most abundant amino acid produced.

Flash forward fifty years and many high schools chemistry labs routinely repeat Miller's classic result. Lasers are often substituted for high voltage discharges as an energy source, and this dramatically speeds up the signature yellowing of the primordial oceans.

But as the Earth's early chemistry has become better understood, a catch has arisen. Ironically, while complex biochemistry can spring from simpler building blocks, one missing element--the simplest hydrogen--may have been in short supply four billion years ago. Without it, the reactions don't trigger the right organic chemistry. If the Earth more likely was rich in nitrogen and carbon dioxide-- rather than hydrogen, methane and ammonia--, then any amount of sparking delivers a mere drop of organic byproducts. The primordial soup is too dilute.

Workarounds to get enough concentrated chemistry for self-assembly to arise have reverted to evaporation (such as tidal pools) or a large seeding event from a colliding comet. Both these could quicken the biochemistry enough for life.



University of Chicago graduate student, Stanley Miller, 1953.*Credit: U. Chicago*

Interview with Professor Stanley Miller

To commemorate the fiftieth anniversary for whom most consider the father of primordial chemistry, Professor Stanley Miller, of the University of California, San Diego, the Astrobiology Magazine had the opportunity to get his perspective today.

Astrobiology Magazine (AB): This is the fiftieth anniversary of your original University of Chicago work. Do you have any retrospective thoughts on what was going through your mind at the moment you starting flipping the electrode switch, and how successfully the experiment would carry forward as a classic at that time?

Professor Stanley Miller (SM): I would say curiosity was probably the primary impetus. Upon observing the results for the first time, my focus was devoted more to the "how and why" than the ramifications.

The actual long-term significance of the experiment has been an evolution in and of itself. I believed the results of the experiment would provide valuable insights into the origin of life, but at that time I hadn't really devoted much thought as to the extent of its influence.

The scientific community's immediate response, as well as that of the public media, was a very big surprise.

AB: What is your current opinion on the need for a primitive reducing atmosphere for pre-biotic life to take hold 3.5 to 3.8 billion years ago?

SM: I have not found an alternative to disprove the need for a primitive reducing atmosphere.

AB: Do you believe that material transported on meteors or comets is insufficient to seed life, if such amino acids were successfully transported intact to the surface of the Earth?

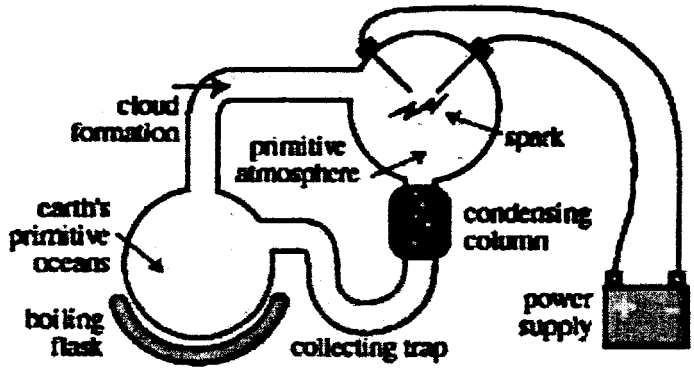
SM: Meteorite and other exogenous contributions become very important only if the earth had a neutral atmosphere. However, if the only sources of organic compounds under such conditions were the very small number of compounds produced with a CO2 rich atmosphere and delivered from outside, the amount may be too low for the origin of life.

AB: Since many astrobiologists are currently examining hydrothermal vents, in search of extremophiles, does the prebiotic chemistry actually get decomposed rather than enhanced by the presence of such ocean venting?

SM: Locating extremophiles is not relevant to the synthesis of organic compounds necessary for life, as the conditions of such ocean venting decomposes rather than enhances prebiotic chemistry.

AB: It has been reported that you had your first results within a matter of weeks, while Urey thought the original electrode experiments might exceed the limits of a 3-year degree program. Was the initial success due to the hint of using a reducing atmosphere or were there other parts of the rapid progress that surprised you?

SM: A reducing atmosphere was definitely the key, resulting first in the water turning red overnight, and after time continuing to change colors as synthesis of organic compounds proceeded. I never had any doubts about the outcome, but I was surprised at the efficiency of the synthesis.



Miller's classic experimental setup, with a simulated ocean, lightning and broth of hydrogen, methane, ammonia and water.

AB: Have you followed the methanogen research at all? It seems that the use of methane as a precursor was very important to the original experiments, and presumably the progress in methanogens provide some prospecting hints for astrobiologists.

SM: Methanogens appear to be a very ancient form of life, but their biology tell us nothing about the origin of the first biological system. I am sure once they evolved they begun contributing to the methane budget of the Archean atmosphere, however my concerns regarding the reducing atmosphere refer to the period before the origin of methanogenes themselves.

AB: Since this is also the fiftieth anniversary of the Watson-Crick publication, how would you characterize the 13 of 20 amino acids that can be synthesized prebiotically with the complexity of living cells manufacturing proteins from DNA? Is there a bridge that time has clarified there?

SM: Different researchers have different opinions about what is a prebiotic synthesis, but I do not think that there is yet a good prebiotic synthesis of arginine, lysine, and histidine, and of other biochemical compounds.

It is possible of course, that not all them were available in the primitive soup, and that some were synthesized by cells once they evolved. This would require the appearance of biosynthetic pathways, and the more complex they are, the more clear it becomes that they could have not appeared until the genome was sufficiently complex to encode for the proper catalysts.

John Oró showed that one could synthesize adenine, one of the nucleobases, with remarkable ease. Of course, we do not know how synthesis of proteins originated, but it is possible that once a catalytic apparatus was in place, some of the more complex amino acids like histidine resulted not from prebiotic synthesis, but from ancient metabolic pathways.

What's Next

There are other hurdles in the progression from simple molecules to complex life that are large research topics. Producing amino acids and nucleotides , and getting them to polymerize into proteins and nucleic acids (typically, RNA), are parts of a vast and ongoing 'origins' discussion. But RNA is a relatively fragile component (compared to DNA, or other biomolecules), and thus again its first appearance remains subject to the particular local conditions of the early Earth. To stabilize or catalyze the first

biomolecules, clay crystals and vesicle reactions may have helped. No one has been able to synthesize RNA without the help of protein catalysts or nucleic acid templates.

Most scientists now believe that microbes can survive interplanetary journeys ensconced in meteors produced by asteroid impacts on planetary bodies containing life, and this observation has changed a number of the statistical assumptions about where and when biomolecules might first be seeded. Swedish chemist Svante Arrhenius first proposed the notion of interplanetary transport in 1903. However, for life to appear elsewhere, by some similar carbon-based pathway, and then arrive later on Earth means some similar primordial soup needed to be sparked someplace else--perhaps in a reducing atmosphere as Miller first showed fifty years ago.

Related Web Pages

Miller's 1953 Science paper [PDF 800 kB]
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Miller-Urey Experiment: Amino Acids from Scratch
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Defining Life
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Note: *Terrestrial Origins: [2003-05-14]*

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*Bada, J.L. , and Lazcano, A. Prebiotic soup: revisiting the Miller experiment. Science 300, 745-746 (2003).

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*Copy submitted with this report.