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

2002 FINAL REPORT

THE CHEMISTRY OF EARLY SELF-REPLICATING SYSTEMS (NAG 5-4546)

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

2002 FINAL REPORT

(NASA NAG 5-4546)

April 1, 1997 through March 31, 2003

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University of California, San Diego
La Jolla, California

2002 FINAL REPORT

THE CHEMISTRY OF EARLY SELF-REPLICATING SYSTEMS
(NASA NAG 5-4546)

Respectfully submitted by:

Jeffrey L. Bada
Principal Investigator
Director, NSCORT/Exobiology

NSCORT/EXOBIOLOGY
CUMULATIVE SUMMARY OF ACTIVITIES
April 1, 1997 through March 31, 2003

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Program

The NASA Specialized Center of Research and Training in Exobiology (NSCORT/Exobiology) is a program within the UCSD California Space Institute (Dr. Wolfgang Berger, Director) currently funded by a second 5 year Federal Demonstration Project Grant from NASA. Its specific aims are:

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. 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, page 29).

NSCORT funds support a half-time Associate Director (William A. Baity) and 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, are determined by a Committee of NSCORT Principal Investigators, in cooperation with the Associate Director.

The *Review Committee*, for evaluation of the NSCORT/Exobiology program, met in La Jolla with the NSCORT laboratories on November 6, 1998 (see Ref. 2., page 30) for Review Committee Report). The Committee members are:

Thomas Cavalier-Smith	University of Oxford
Benton Clark	Lockheed Martin Astronautics
David DesMarais	NASA Ames Research Center
Donald DeVincenzi	NASA Ames Research Center
Michael Meyer	NASA Headquarters
Alex Rich	Massachusetts Institute of Technology
John Rummel	NASA Headquarters
Alan Schwartz	University of Nijmegen

Because of budget cuts, there will be 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 Refs. 3 & 4, pages 36 & 43). 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).

NSCORT PI Meetings: The PI's meet regularly throughout the grant period to discuss various NSCORT activities. Listed below are 1997-2002 dates and agenda items for these meetings.

1997-2002 NSCORT PI MEETINGS

Date	*Agenda Items*
January 21, 1997	Advertising for fellowships; budget allocations; duration of fellowships & eligibility of fellows for a 2nd fellowship; preparation for the 1999 ISSOL Meeting; discuss date for Review Committee Meeting
March 19, 1997	Select Review Committee Members; NSCORT Laboratory occupancy; Outreach; fellowship distribution among PI's, Affiliates; fellowship advertisements; fellowship salaries; fellowship policies; fellowship candidates.
July 18, 1997	Old business; UC/Ames Astrobiology Institute; Tschirgi Memorial Lecture next academic year; progress of fellowship applications; ISSOL Meeting planning; Associate Director candidates; miscellaneous business.
September 30, 1997	Old business; ISSOL Meeting preparation; 1998 18-Month Review Committee Meeting to be held on November 6, 1998; progress of fellowship applications; Biochemical Evolution Course (Chem 122).
November 4, 1997	Discussion of 1999 ISSOL Meeting
March 30, 1998	Old business; 1999 ISSOL Meeting Preparation; 1998 Summer Student applicants; status of fellowship allocations; new fellowships; one-unit undergraduate seminar programs for Winter 1998 and Spring 1999.
July 23, 1998	Old business; new fellowship applicant; status of fellowship allocations; fellows yearly reports; 1999 ISSOL Meeting preparation; Affiliate support; visiting scientists; NSCORT PI laboratory visits for 1998 NSCORT summer students.
October 20, 1998	Discussion of Review Committee Meeting on November 6, 1998; 1999 ISSOL Meeting planning update.

March 11, 1999	Discussion of ISSOL '99 Preparation; review ISSOL '99 Abstracts; set next Review Committee Meeting date and discuss Review Committee Report to NSCORT; new fellowship awards.
December 17, 1999	Post-ISSOL Meeting discussion; discussion of NASA budget, plans beyond NSCORT; proposed fellows visit to NASA Ames.
October 23, 2000	Third Robert Tschirgi Memorial Lecture/speaker, Christian de Duve; fellowship status; status of budget; NSCORT after April 2002 ?; Geobiology Course; One-Day Symposium; Evening Discussion Seminar; Visiting Scientists; 2001 Continuation; web sites.
November 27, 2001	Discussion of proposed January 2002 NASA Review Panel Visit; budget status; proposed allocation to PIs; Orgel report on his November 2001 COEL presentation .
January 18, 2002	Discussion of January 23, 2002 NASA Review Panel Visit.

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. Morning sessions (see Refs. 5 & 6, pages 47 & 48) consisted of 2-3 invited talks on one of the 5 major themes of the 1999 ISSOL meeting, which were followed by contributed talks. Afternoons continued with the contributed talks in two parallel sessions, plus poster sessions. A special "Mars" session in the afternoon on the last day of the meeting was followed by the ISSOL Executive and Open Business meetings. Evening activities included a Welcome Mixer, a Reception at the Stephen Birch Aquarium at UCSD, and a Banquet at the Hilton Torrey Pines. The results of the scientific sessions are summarized at http://exobio.ucsd.edu/issol99/sci_summaries.htm (Ref. 7, page 49).

The ISSOL '99 First Announcement was mailed to the ISSOL Membership in July 1998 (Ref. 8, page 62), and the ISSOL '99 Second Announcement (submitted with 1999 Annual Report) early in December 1998. The *ISSOL '99 Book of Program and Abstracts* was prepared by the NSCORT/Exobiology (submitted with the 1999 Annual Report). Complete meeting information was updated frequently on the ISSOL '99 Meeting page at the NSCORT WWW site: http://exobio.ucsd.edu/issol99.htm/. Questions regarding the meeting were emailed to nscort@ucsd.edu and were answered promptly throughout the registration process.
This meeting was a great success and NASA's sponsorship was recognized and appreciated. See the Local Organizing Committee Report at: http://exobio.ucsd.edu/issol99/loc_report.htm. Both the research and the training objectives of the NSCORT/Exobiology were well met by support of this important triennial meeting.

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.

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.

Honors and Awards

Gustaf Arrhenius	Royal Swedish Academy of Sciences, Hans Pettersson Gold Medal, 1997; Inaugural Lecture, Royal Gothenburg Academy of Arts and Sciences, October 1998; Gyorgy Hevesy Lecture, Hungarian Academy of Sciences, April 2001.
Jeffrey Bada	Member of NASA committee on "Mars sample handling and return protocol", 1997-1998 Member of National Research Council, National Academy of Sciences committee on "Sample return from small solar system bodies", 1997-1998
Gerald Joyce	T.Y. Shen Lectures in Biological Chemistry, MIT, October 1997; Hans Sigrist Prize, University of Bern , December 1997; Cynthia Ann Chan Memorial Lecture, Department of Chemistry, University of California, Berkeley, March 1998 David W. Beach Memorial Lectureship, Purdue University, April 2000 Linnæus Lecturer, Uppsala University, Sweden, February, 2001 Elected, U.S. National Academy of Sciences, May 2001

Leslie Orgel	Chairman, Task Group on Sample Return from Small Solar System Bodies, Space Studies Board, National Research Council, 1997-1998; Visiting Scientist in the laboratory of Prof. P. Luigi Luisi, Eidgenossische Technische Hochschule, Zurich, Switzerland, May 1998; Member of the Astrobiology Oversight Task Force (AOTF) of the Space Science Advisory Committee (SScAC), a standing committee of the NASA Advisory Committee, 1999
Christopher Wills	AAAS Award for Public Understanding of Science and Technology, January 1999 (Previous winners include Carl Sagan and E.O. Wilson) Book "Children of Prometheus" nominated for the the 2000 Aventis Prize, England's premier award for science books. Wright Lecturer on Cosmic Evolution, sponsored by Fondation Wright, Science Center, Boston. Lectured, along with David Deamer, on the biological basis for the origin of life, October 17, 2001.

Fellowships

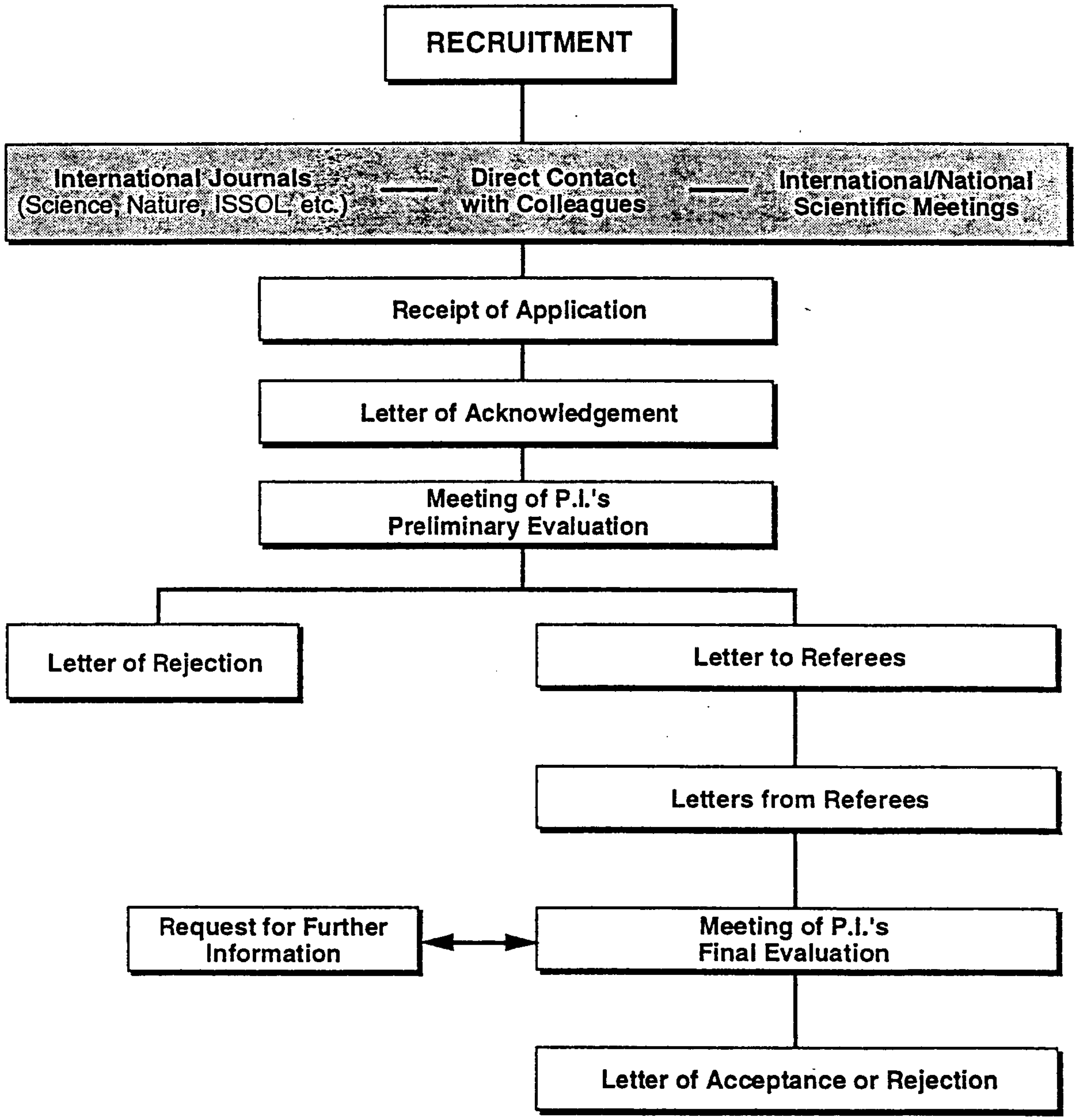
Subsequent to advertisements for NSCORT/Exobiology Fellowships in the journal *Nature*, May 1, 1997 (see Ref. 9, page 64), the NSCORT/Exobiology home page (http://exobio.ucsd.edu), and distribution of announcements through personal contacts, 98 applications for Fellowships have been received as of January 2001 (see Fellowship Selection Process on following page). For list of 1992-2003 Fellows see Ref. 10, page 65).

NSCORT/Exobiology Fellows (1997-2003)

	Postdoctorals	Graduate Students	Undergraduates
Fellows*	13	8	27
Adjunct Fellows	5	8	3
Total	18	16	30
Completed	18	12	30

*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.

NSCORT/Exobiology
Fellowship Selection Process



- Applications summarized on receipt by Associate Director and distributed to P.I.'s
- Initial contact with applicants through Associate Director
- Applicants referred to direct contact with P.I.'s for specific research interests
- Accepted applicants referred to direct contact with P.I.'s for timing/laboratory arrangements
- Accepted applicants referred to Associate Director for administrative/residential arrangements

1997-2003 POSTDOCTORAL FELLOWS AND ADJUNCT FELLOWS

Name	PI Laboratory
Botta, Oliver	Bada/UCSD
Broo, Kerstin (Adj.)	Joyce/TSRI
Cleaves, James Henderson	Miller & Bada/UCSD
Gao, Kui	Orgel/Salk
Guntha, Sreenivasulu	Eschenmoser/TSRI
Ke, Wen	Orgel/Salk
Kozlov, Igor	Orgel/Salk
Kuhns, Scott	Joyce/TSRI
Lepland, Aivo (Adj.)	Arrhenius/UCSD
Liao-Arrhenius, Meichia (Adj.)	Arrhenius/UCSD
Lyons, James	Miller/UCSD
Mecozzi, Sandro	Rebek/TSRI
Miyakawa, Shin (Adj.)	Miller/UCSD
Ordoukhanian, Phillip (Adj.)	Joyce/TSRI
Reader, John	Joyce/TSRI
Rojas, Ana	Doolittle/UCSD
Schmidt, Jurgen	Orgel/Salk
Sheppard, Terry	Joyce/TSRI
Xu, Yong	Arrhenius/UCSD

1997-2003 GRADUATE STUDENT FELLOWS AND ADJUNCT FELLOWS

Name	PI Laboratory
Aubrey, Andrew (Adj.)	Bada/UCSD
Brinton, Karen (Adj.)	Bada/UCSD
Bruick, Richard (Adj.)	Joyce/TSRI
Casini, Carolina (Adj.)	Bada/UCSD
Cleaves, J. Henderson	Miller/UCSD
Dai, Xiao-Chang (Adj.)	Joyce/TSRI
Glavin, Daniel	Bada/UCSD
Handy, Jacob	Doolittle/UCSD
Kminek, Gerhard (Adj.)	Bada/UCSD
Levy, Matthew	Miller/UCSD
McGinness, Kathleen (Adj.)	Joyce/TSRI
Metzgar, David	Wills/UCSD
Mojzsis, Stephen	Arrhenius/UCSD
Nelson, Kevin	Miller/UCSD
van Zuilen, Mark	Arrhenius/UCSD
Wang, Sharon (Adj.)	Bada/UCSD

1997-2001 UNDERGRADUATE FELLOWS AND ADJUNCT FELLOWS

Name	PI Laboratory
Matt Pagel ('01)	Wills/UCSD
Melanie Zauscher ('01)	Bada/UCSD
Breitbart, Mya ('00)	Arrhenius/UCSD
Czodrowski, Paul ('00)	Doolittle/UCSD
Dion, Vincent ('00)	Miller/UCSD
Lang, Greg ('00)	Bada/UCSD
Pagel, Matthew ('00)	Wills/UCSD
Finarelli, John (NPBI* '00)	Arrhenius/UCSD
Dion, Vincent ('99)	Miller/UCSD
Kimble, Ryan ('99)	Wills/UCSD
McAllister, Ryan ('99)	Doolittle/UCSD
McGauley, Michael ('99)	Bada/UCSD
Safier, Jennifer ('99)	Bada/UCSD
Kasmayr, Daniel ('99 Adj.)	Orgel/Salk
Airo, Alessandro ('98)	Orgel/Salk
Bebie, Joakim ('98)	Arrhenius/UCSD
Bernsen, Deborah ('98)	Doolittle/UCSD
Borquez, Eduardo ('98)	Miller/UCSD
Casini, Carolina ('98)	Bada/UCSD
Handy, Jacob ('98)	Doolittle/UCSD
Politis, Panagiotis (NPBI'98)	Orgel/Salk
Safier, Jennifer ('98)	Bada/UCSD
Thomas, Elizabeth ('98)	Wills/UCSD
Catalina, Maria ('97)	Arrhenius/UCSD
Estevez, Carlos ('97)	Miller/UCSD
Glavin, Daniel ('97)	Bada/UCSD
Handy, Jacob ('97)	Doolittle/UCSD
Makevich, John ('97)	Bada/UCSD
Maughan, Quinn ('97 Adj.)	Miller/UCSD
Ormsbee, Alice ('97)	Miller/UCSD

*NASA Planetary Biology Internship (NPBI) Summer Fellows were provided UCSD housing & benefits by the NSCORT/Exobiology.

1. **Examples of facilitation by NSCORT/Exobiology of in-house research and education In addition to providing direct funds for PIs' research, and Fellowships for postdoctoral, graduate and undergraduate students, NSCORT/Exobiology contributes support and sponsorship for:**

- A monthly Journal Club and field trips organized by the NSCORT Fellows.
- The 1997-2001 Summer Student Symposiums organized by the NSCORT Fellows (see Ref. 11, page 69 for 1997-2001 Summer Student Symposium agendas); taped interviews of summer students aired on UCSD TV; and welcome reception for 1998-2001 summer students.
- Evening Discussion Seminars for NSCORT PIs, Fellows and Affiliates.
- Seminars and Discussions by invited local, national and international scientists.

Russell Doolittle	University of California, San Diego
Gerald Joyce	The Scripps Research Institute
Wing-Huen Ip	Max Planck Institute for Aeronomy
John Kerridge	University of California, San Diego
Dilip Kondepudi	Wake Forest University
Antonio Lazcano	University of Mexico
Michel Maurette	Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse
Christopher McKay	NASA Ames Research Center
Stanley Miller	University of California, San Diego
Robert Tschirgi	University of California, San Diego
Luc Jaeger	Institute de Biologie Moleculaire et Cellulaire du CNRS, France
Thomas Cech	University of Colorado, Boulder
David Koerner	University of Pennsylvania, Pennsylvania
Jeffrey Bada	University of California, San Diego
Leslie Orgel	University of California, San Diego
James Lyons	University of California, San Diego
Sally Ride (M. Kessler, R.Fetter, J. Johnson)	University of California, San Diego EarthKAM Program
David Stevenson	California Institute of Technology, Pasadena
Gero Kurat	Naturhistorisches Museum, Vienna
James Ferris	Rensselaer Polytechnic Institute, Troy
Paul Hoffman	Harvard University, Cambridge
Pascale Ehrenfreund	Leiden Observatory, The Netherlands
Bernard H. Foing	ESA Space Science Department, The Netherlands
Piet Herdewijn	Rega Institute, Katholieke Universiteit, Belgium
Ken Nealson	Jet Propulsion Laboratory, Pasadena
Jonathan Lunine	University of Arizona
Harry Noller	University of California, Santa Cruz

- Seminars and Discussions by invited local, national and international scientists.

Adri van Duin	University of Newcastle, United Kingdom
Curt Mileikowsky	Royal Institute of Technology, Stockholm, Sweden
Ray Jayawardhana	University of California, Berkeley
Andreas Quirrenbach	University of California, San Diego
Buford Price	University of California, Berkeley
Adam Burrows	University of Arizona, Tucson, Arizona
Jason Dworkin	NASA Ames Research Center, Moffett Field, California
Jeffrey Wong	Hong Kong University of Science & Technology
Adrian Tuck	NOAA Aeronomy Laboratory, Boulder, Colorado
Gene McDonald	Jet Propulsion Laborator, Pasadena, California
Geoffrey Zubay	Columbia University
Jennifer Blank	University of California, Berkeley
Michael Famulok	University of Bonn, Germany
Luc Jaeger	Institute de Biologie Moleculaire et Cellulaire
Humberto Campins	University of Arizona, Tucson, Arizona
John Valley	University of Wisconsin
Nicolle Zellner	Rensselaer Polytechnic Institute
Margaret Turnbull	University of Arizona, Tucson, Arizona
Ruth Blake	Yale University

- 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

b) Courses in Chemical Evolution (from 1997-2001)

- **Winter 1997 Chem 122:** Biochemical Evolution - S. Miller, L. Orgel, G. Joyce, A. Lazcano (see Ref. 12, page 84)
- **Spring 1997-2001 Chem 173:** Atmospheric Chemistry - J. Lyons
- **Fall 1997, 98, 99 Earth Science 30:** The Oceans - J. Bada

- **Fall 1998 Graduate Seminar:** The Origin(s?) of Life - J. Bada and C. Wills. Seminar will cover historical and current theories about the origin of living organisms on the Earth and elsewhere. Special attention will be paid to the origins of both genetic and energy-utilizing systems, along with the roles of the RNA world and of possible pre-RNA replicating systems. The possibility of life elsewhere in the solar system and in the universe will also be examined, including critical weighing of the evidence for traces of life in the Martian meteorite ALH84001 and the evidence. Open to graduate students and (with permission) advanced undergraduates. Interested faculty and postdoctoral fellows may participate.
- **Winter 1998, 99, 2001 Earth Science 102:** Introduction to Geochemistry – J. Bada and M. Kastner.
- **Winter 1999 One-Unit Undergraduate Seminar:** The Origin of Life on Earth and Elsewhere - J. Bada. Seminar will consider the processes involved in the transformation from an abiotic to a biotic Earth. The chemical and physical environment of the primitive Earth, the types and sources of organic compounds and the steps leading to the origin of life will be evaluated. Other worlds, both in our solar system and beyond, where the origin of life may have also taken place, and how we might detect this life, are discussed.
- **Winter 1999, 2000 SIO 269:** Origin and Evolution of Earth's Atmosphere. M. Wahlen. R. Weiss and G. Arrhenius.
- **Spring 1999 One-Unit Undergraduate Seminar:** Evolution of Early Life on Earth - R. Doolittle. Seminar begins with a discussion of a putative RNA world, moves on to RNA-protein interactions and the invention of translation, then to considerations of the earliest forms of living organisms. The final session will deal with the origin of eukaryotic cells.

2. **Examples of NSCORT/Exobiology Outreach** ***(January 1997-present)***

   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 is now an integrated publications list, to which we will soon attach a search engine. The research activities of the NSCORT Affiliates as well as the Fellows are described in the yearly reports, now included on-line. There are also links to other related sites, at NASA and elsewhere. In Outreach we are broadening our scope across the full K-12 spectrum as well as to the general public with a suite of web pages on the theme of Life in the Universe. This will include backgrounders and current news in Exobiology, a Question and Answer or Ask a Scientist section, bibliographic references and links to NASA's overall Astrobiology program.

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

c) **NSCORT Presentations and sponsorship at Universities and national and international meetings and symposia**

1997

International School of Space Chemistry (L. Becker), March, 1997.

Yale University, Dept. of Geology & Geophysics (J. Bada), March, 1997.

Symposium on the Cosmos, Life and Human Beings, et al., The Graduate University for Advanced Studies, Hayama, Kanagawa, Japan (S. Miller), March 1997.

University of Wisconsin, Madison (J. Bada), April, 1997.

American Chemical Society Spring Meeting Symposium (J. Bada and NSCORT PIs), April, 1997.

National Academy of Sciences, (J. Bada), April, 1997.

Scientific Forum on the Origin of Life, Arken, Gothenburg, Sweden (S. Miller), April 1997.

San Diego Annual Microbiology Conference (S. Mojzsis), May, 1997.

American Chemical Society Meeting, Saratoga Springs, New York (G. Arrhenius), June, 1997.

9th Rencontres de Blois (S. Mojzsis), June, 1997.

Frontiers of Science Conference (J. Bada), July, 1997.

Gordon Research Conference (G. Joyce, R. Doolittle, S. Mojzsis, S. Wang, W. Schopf, M. Fomenkova, K. Zahnle), July, 1997.

SPIE Meeting (J. Bada, G. Arrhenius, S. Mojzsis and L. Becker), July, 1997.

University of Guadalajara,Division of Biological Science, Guadalajara, Mexico (S. Miller), July 1997.

Royal Swedish Academy of Sciences (G. Arrhenius), August, 1997.

University of Gothenburg, Sweden (G. Arrhenius), August, 1997.

17th International Congress of Biochemistry and Molecular Biology, Biological Chemistry Division, American Chemical Society, San Francisco (G. Joyce), August 1997.

7th Annual V. M. Goldschmidt Conference, Tucson, Arizona (S. Mojzsis), August,1997.

4th Cambridge Symposium on Oligonucleotide Chemistry and Biology, Cambridge, UK (G. Joyce) , September 1997.

Geological Society of America Annual Meeting, Salt Lake City (J. Bada) , October 1997.

Foundation for American Communications (J. Bada), October 1997.

UCLA Extension Series: Evolution and the History of Life, University of California, Los Angeles, California (S. Miller), October 1997.

NASA Exobiology Program, PI Symposium, Mountain View, CA (G. Arrhenius, G. Joyce, S. Mojzsis) , November 1997.

NSCORT Presentations and sponsorship at Universities and national and international meetings and symposia *(1997 Continued)*

Hans Sigrist Foundation Symposium, "Frontiers in RNA Chemistry", University of Bern (G. Joyce) , December 1997.

1998

Department of Chemistry, Cal State Northridge (J. Bada), February 18, 1998.

European Union of Geosciences, Strasbourg, France (Arrhenius, Mojzsis, Lepland, van Zuilen), March-April 1998.

Invited lecture, The Twelve Thirty Club of La Jolla (J. Bada), March 25, 1998.

Department of Physics, UCSD (J. Bada), March 12, 1998.

Video Seminar via satellite hook-up, Department of Environmental Sciences, U. Massachusetts, Boston (J. Bada), April 4, 1998.

98th Annual Meeting of the American Society for Microbiology, Atlanta (J. Bada), May 1998.

Keynote Address, Sixth International Conference on Artificial Life, Los Angeles, CA, (G. Joyce), June 1998.

Navartis Foundation discussion meeting, London (J. Bada), June 1998.

Royal Society of London discussion meeting on "Molecular information and prehistory" (J. Bada), June 1998.

Eight International Goldschmidt Conference in Geochemistry, Toulouse, France (Arrhenius, Siegel, Mojzsis), August 1998.

Origins of Biological Homochirality, Serramazzoni, Italy (J. Siegel) October 1998.

Universidad Autónoma de Madrid, Fundación Ramón Areces, Madrid, Spain (S. Miller), June 1998.

Universidad Internacional Menéndez Pelayo, Origen de la Vida ¿En la Tierra Y Otros Planetas?, Valencia, Spain (S. Miller), October 1998.

Department of Chemistry, University of California at Berkeley (J. Bada), November 10, 1998.

Pontifical Academy of Sciences Plenary Session, Vatican City (G. Joyce), October 1998.

Symposium on Fundació "la Caixa"(*The Limits of Life),* Museu de la Ciéncia, Barcelona, Spain (S. Miller), November 1998.

NASA Exobiology Program, PI Symposium, Mountain View, CA (G. Arrhenius, R. Krishnamurthy) , November 1998.

Royal Göteborg Academy of Letters and Sciences (G. Arrhenius), November 98.

International Symposium on Interdisciplinary Research, Stockholm (G. Arrhenius), November 1998.

American Geophysical Union, San Francisco, CA (M. vanZuilen, G. Arrhenius), December 1998.

Cold Spring Harbor Symposium on Biochemistry, Banbury Center, Cold Spring Harbor Laboratory (S. Miller), December 1998.

NSCORT Presentations and sponsorship at Universities and national and international meetings and symposia *(Continued)*

1999

Harvey Mudd College Public Lecture Series, The Claremont Colleges (G. Joyce), February 1999.

CSEOL Symposium/Workshop, UCLA Center for the Study of Evolution & the Origin of Life (S. Miller), February 1999.

Gordon Research Conference on The Origin of Life, Ventura, California (S. Miller), February 1999.

Royal Swedish Academy of Sciences, Stockholm, Sweden (G. Joyce), April 1999.

North Carolina RNA Society, Raleigh, NC (G. Joyce), April 1999.

Session Organizer and Lecturer, Symposium on "Combinatorial Biology" (G. Joyce), 1999.
American Society of Biochemistry and Molecular Biology Annual Meeting, San Francisco, CA (G. Joyce), May 1999.

Surface Analysis '99 symposium, University of Wisconsin-Milwaukee (S. Miller), June 1999.

ISSOL '99 Meeting, University of California, San Diego (G. Arrhenius, E. Borquez, K. Broo, H. Cleaves, C. Estevez, D. Glavin, J. Bada, K. Brinton, R. Doolittle, G. McDonald, S. Miller, K. Gao, C. House, G. Joyce, G. Kminek, I. Kozlov, Q. Maughan, P. Politis, K. E. McGinness, K. Nelson, O. Ordoukhanian, L. Orgel, J. Reader, A. Lepland), July 1999.

Leukemia Society of America Workshop on Therapeutic Nucleic Acids, Philadelphia, PA (G. Joyce), October 1999.

Swedish Space Science Board, Symposium on emergence and early evolution of life, Sigtuna, Sweden (G. Arrhenius), October 1999.

International Symposium on "Frontiers in Bioorganic Chemistry - 2000", Academia Sinica, Taipei, Taiwan (G. Joyce), November 1999.

American Geophysical Union, San Francisco, CA (Arrhenius, Lepland, van Zuilen), December 1999.

2000

Workshop on Life, Millennial World Meeting of University Porfessors, Modena and Rome, Italy (J. Bada, G. Arrhenius, A. Lazcano) September, 2000

National Academy of Sciences, National Research Council, Life Detection Workshop, Washington, D.C. (J. Bada) April 2000.

NSCORT Presentations and sponsorship at Universities and national and international meetings and symposia *(2000 Continued)*

Gold Medal Symposium, University of California, Los Angeles (S. Miller, L. Orgel, J. Cleaves) April 2000.

Euroconference - XIIemes Rencontres de Blois -"Frontiers of Life" ,Chateau de Blois, France (S. Miller, A. Lazcano) , June 25 - July 1, 2000

Astrobiology Science Conference, NASA Ames Research Center (J. Cleaves, K. Nelson, A. Lepland, S. Hiyakawa, G. Arrhenius), April 2000.

Sixth Trieste International Conference on the origin of life, Trieste, Italy (S. Miller, A. Lazcano), June 2000.

First Steps in the Origin of Life in the Universe, Sixth Triest Conference on Chemical Evolution, Trieste, Italy (A. Lazcano), September 2000.

51st International Astronautical Congress Rio de Janeiro, Brazil, (A. Lazcano) October 2-6, 2000.

Leach Lecture, Lorne Conference on Proteins, Lorne, Australia (R. Doolittle), February 6, 2000.

Plenary Lecture at Microbial Genomes 2000, "Searching for the Common Ancestor" (meeting held at the Pasteur Institute, Paris), (R. Doolittle) April 11-15, 2000.

Schyberg Lecture 2000, Lund University, Lund, Sweden (R. Doolittle) May 3, 2000.

American Chemical Society Lecture: "Bring'm Back Alive: Searching for Evidence of Life on Mars During the Coming Decade", San Diego State University, San Diego (J. Bada), November 14, 2000.

Institute of Molecular and Cellular Biology, University of Texas at Austin (G. Joyce) February 10, 2000.

New Swiss Chemical Society Symposium, "Perspectives in Chemistry and Chemical Biology", ETH, Zürich, Switzerland (G. Joyce) March 27-28, 2000.

David W. Beach Memorial Lectureship, Purdue University (G. Joyce) April 17-18, 2000.

Department of Biochemistry, University of Texas Southwestern Medical Center (G. Joyce) May 11, 2000.

Geobiology Meeting, The Agouron Institute, Pasadena, CA (G. Joyce), May 12-14,2000.

Astrobiology Forum, Center for Astrophysics, Harvard University (G. Joyce) September 8, 2000.

Center for Molecular Genetics, University of California, San Diego (G. Joyce), November 6, 2000.

NSCORT Presentations and sponsorship at Universities and national and international meetings and symposia*(Continued)*

2001

Linnæus Lecture, Uppsala University, Sweden (G. Joyce)

AAAS Program of Dialogue on Science, Ethics and Religion Workshop on "What is Life? A Defining Question for Science, Philosophy, and Theology in the 21st Century", Washington, DC (G. Joyce)

American Chemical Society National Meeting, Division of Organic Chemistry, Tetrahedron Prize Symposium, Chicago, IL (G. Joyce)

Public Symposium on, "What is Life?", Astrobiology Institute, University of Colorado, Boulder (G. Joyce)

Pfizer Symposium, "Evolution of Biological Molecules and Synthesis", Department of Chemistry and Chemical Biology, Harvard University (G. Joyce)

d) Sponsorship and support of sessions devoted to Exobiology at national and international conferences

Gordon Research Conference, July 1997

American Chemical Society Spring Meeting-Symposium; "Meteorites: A Window to Chemistry - The Solar System, April 1997.

International Society for the Study of the Origin of Life (ISSOL '99); 12th International Conference on the Origin of Life, July 1999.

Astrobiology Science Conference, NASA Ames Research Center, April 2000.

3. Examples of facilitation by NSCORT/Exobiology of educational programs for high school and college

- Exobiology Demonstration Teaching Module for high school teachers, available for circulation among local secondary schools. Includes bibliographic materials, laboratory apparatus, A/V aids, lecture notes, and student handouts. Presentations by NSCORT Fellows, NSCORT laboratory visits, etc.
- Sponsorship of two teams of Rincon Indian Reservation high school students to the Native American Science Bowl, Shiprock, New Mexico, February 1997-1999.
- High School Teaching Module on Exobiology, La Jolla High School, La Jolla, California, Science Teacher: Stephen Brown. NSCORT/Exobiology Outreach Project World Wide Web Address: http://www.sdcs.k12.ca.us/schools/ljhs/ exobiology/ contents.html
- Carlsbad High School Career Day - April 22, 1997; Presentations by S. Mojzsis
- S. Mojzsis, guided students through the Scripps Undergraduate Research Fellowship from 1994-1997 as an Education & Outreach Effort.

- Heinz-Albert Staubitz Target Film Production, Germany. Filming video for the classroom documenting Stanley Miller's research (1997).
- Stephen Bartram (Rancho Buena Vista High School Science Teacher, Vista California) collaborating with the Gustaf Arrhenius laboratory for Summer 1997 as an American Chemical Society Educational Enrichment Grant Recipient.
- Exhibit of Dr. Miller's electric discharge apparatus, at the Naturalis Museum in Leiden, The Netherlands, January, 1998. I.M. vanWaveren, curator.
- Bakken Museum article by Stanley L. Miller, July 1998
- Perspectives on Science" Program for San Diego county high school science teachers. Howard Hughes Medical Institute supported program at Point Loma Nazarene University, San Diego, CA (G. Joyce) September 28, 1998.
- Development of "Life in the Universe" web site with the California Space Institute - Fall 1998; Bill Baity.
- Miller-Urey apparatus simulation and two video interviews of S. Miller located on: http://calspace.ucsd.edu/marsnow/miller/ (developed by S. Ellis) 1999.
- DNA Learning Center Web-site: http://www.accessexcellence.com/RC/miller.html (S. Miller) May 7, 1999.
- Classic Experiments Web-site (S. Miller), Reply to an average ten inquires per week regarding the Urey-Miller experiment, August 3, 2000. http://calspace.ucsd.edu/marsnow/miller/.
- Joint NASA Ames Astrobiology Academy and NSCORT/Exobiology Symposium for High School Students; 40 high school participants from the San Diego area atUCSD/SIO, July 27, 2001.
- Web-based course module entitled, "How Could Life Have Arisen on Earth?" (http://chemistry.beloit.edu/Origins); written by Paul Jaisen, Stanley Miller, Matthew Levy and Jason Dworkin (see Ref. 4, page 45).

4. 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 1997-00.

***The Spark of Life*, an NSCORT/Exobiology Outreach Project**

The Spark of Life, by Christopher Wills and Jeffrey Bada, was published in the Spring of 2000. It is aimed at a general but scientifically literate audience, and draws on the work of NSCORT members and many other members of the origin-of-life community. The aim was to present a balanced view of how life began on Earth, examining geology, chemistry, molecular biology and other fields.

The central thesis of the book is that the old idea of chemical evolution, a period of gradual increases in the complexity of the chemical environment that was originally proposed by Alexander Oparin, can best be thought of in a Darwinian framework. It seems odd to think of

Darwinian evolution taking place in a world without living organisms, but if we simplify the Darwinian process - in the book we refer to it as "Darwin Lite" - we can see that there could be selection for something as simple as the ability of molecules to interact with each other and build up in complexity, while those that cannot interact are washed away. This would result in the concentration of certain types of molecules to high levels. The start of true Darwinian evolution, which requires self-replicating systems, would be facilitated by the availability of these high concentrations of molecules.

Reaction to the book has generally been favorable, and we expect that it will continue to stimulate discussion. A copy of *The Spark of Life* is submitted with this report.

Media - Broadcast

- Discovery Channel, "Aliens, Are We Alone?", July 6, 1997.
- Heinz-Albert Staubitz, Target Film Production, Germany. Filming video for the classroom documenting S. Miller's research (1997).
- PBS Broadcast - January 11-January 15, 1998 Interview with S. Miller on "Origins - A Science Odyssey".
- UCSD TV - Broadcast of taped interviews with 1997 NSCORT/Exobiology Summer Students, January 20, 1998.
- Beyond Productions Films used footage of Miller performing the electric discharge test for use in a science documentary. July 1998.
- National Film Board of Canada preparing scientific documentary on the origins of life. Interviews with G. Arrhenius, J. Bada, S. Miller and L. Orgel on September 28, 1998.
- Austrialian Science Documentary, July 1998, S. Miller.
- Discovery Channel, July 1998, S. Miller.
- BBC, Interview with G. Arrhenius (May 1999).
- Finland Television, Interview with G. Arrhenius (March 1999).
- World of Wonder documentary (German Television), March 1999, S. Miller.
- Canadian National Film Board of Science (Documentary on Origin of Life), March 1999, S. Miller.
- Origins - The Genesis Factor, January 5, 2000, S. Miller.
- UCSD TV - ISSOL '99 Conference. Talks delivered on July 16, 1999 by David Koerner, Chris McKay and Ken Nealson (January 12 and 16, 2000).
- UCSD TV - Talk by R. Doolittle (January 12 and 16, 2000).
- National Public Radio, All Things Considered, "Essence of Life" Interview with Bada, Miller & Orgel, March 17, 2000.
- Coast to Coast with Art Bell, May 28, 2000 from 11:00 pm-2:00 am PDT. Interview with J. Bada.
- Science International, September 21, 2000, S. Miller.
- French Informational Program, July 2000, S. Miller.
- German Radio WDR, September 27, 2000, S. Miller.
- BBC Radio 9, September 28, 1999, S. Miller.
- NPR News, Kestenabaum, September 20, 2000, S. Miller.
- Film – CBS (KTVT) Dallas, November 2000, S. Miller.
- CBS Interview by Marc Levenson with J. Bada and C. Wills on *The Spark of* Life, October 2000.

Media - Broadcast *(Continued)*

- UCSD Conversations with Pat Ledden. Discussion of *The Spark of Life* with C. Wills and J. Bada, October 17 and 22, 2000 and January 10, 2001.
- Wills and Bada presentation of *Spark of Life* at the Birch Aquarium, University of California, San Diego . Aired on UCSD/TV on January 10 and January 14, 2001.
- UCSD/TV Conversations with Danny Glavin discussing his activities in the Bada lab and the MOD. Aired January 20 and 21, 2001.
- ABC News Radio interview on "The Spark of Life" (J. Bada) February 2001.
- NPR interview regarding paper in *Nature* (J. Bada) December 2001.
- Pulse of the Planet interview, "Whales Aging" – 3 Programs (J. Bada) February 2002.

Media - Printed

- San Diego Union Tribune - "QUEST" articles - A Three part series by Scott LaFee including interviews with NSCORT scientists; (1) dated December 4, 1996, "Original Life" describing research of S. Miller, L. Orgel, G. Joyce, J. Bada. (2) dated December 11, 1996, "A Splice of Life" describing research of G. Joyce and NSCORT Affiliate, J. Rebek. (3) dated December 18, 1996, "Altered Facts" describing research of C. Wills.
- Forskning och Framsteg, **8**, 1997. Livets Vagga (The cradle of life) Joanna Rose; G. Arrhenius.
- Oregonian (OR) January 2, 1997, "1997: A blockbuster year in Science".
- Science, January 3, 1997: "Evidence for life on Earth more than 3850 million years ago"
- Super Interessante (Brazil), February 1, 1997: "Impressoes digitais de priscas eras"
- San Diego Union Tribune & Sacramento Bee - March 19, 1997: M. Fomenkova, was among those making an inventory of numerous chemicals in the Hale-Bopp comet in hopes of learning more about the early solar system. (Two print media)
- Random House Publishing (Book on Sagan), March 17, 1999, R. Doolittle.
- National Geographic, March 1999, R. Doolittle.
- Focus (UK) Popular Science, March 11, 1999, R. Doolittle.
- UCSD Science Report, Vol. 3, Issue 2, April 1999, R. Doolittle.
- Italian Monthly, May 1, 1999, R. Doolittle.
- Comments Carried Worldwide - March 1997: J. Bada and postdoc, L. Becker, discussed their research results on whether a meteorite that fell on Antarctica carried chemical and possible fossil evidence of primitive life on early Mars -- in Newsweek, Associated Press, Science, New York Times, Chicago Tribune, Houston Chronicle, San Francisco Examiner, Chronicle of Higher Education, Chemical and Engineering News, Science News, Scripps-Howard, San Diego Union Tribune and others. (Twelve or more separate print media articles.)

Media - Printed *(Continued)*

- Traces suggesting life on Earth began nearly 400 million years earlier than previously thought was reported in the Los Angeles Times, The San Diego Union Tribune and Science News. (Three print media articles).
- Seattle News Article on "Cooking Up Some Primordial Soup" - March 4, 1997: Interviews with S. Miller, J. Bada and G. Joyce, on searching for life on other worlds.
- The Scientist, March 31, 1997: "Scientists debate RNA's role at beginning of life on Earth".
- Discover. April 1, 1997: "Breakthroughs: earliest life in oldest rocks".
- Philadelphia Inquirer - April 13, 1997: Comments from J. Bada, regarding scientists search for extraterrestrial life.
- Sunday Star-Ledger, Newark, Jersey - April 20, 1997: Comments from J. Bada in article on "Clues to Distant Life Spur Scientists".
- San Diego Union Tribune, April 30, 1997: "Rocks show life started earlier than believed" G. Arrhenius and S. Mojzsis.
- Los Angeles Times - May 15, 1997: "Probing the Chemistry of Creation" L. Orgel, G. Joyce, S. Miller, G. Arrhenius and J. Bada.
- Space News - August 18, 1997: Interview and comments by J. Bada, in "One Year Later, Mars Rock Continues to Spark Debate".
- Simon LeVay interviewed G. Arrhenius, S. Miller, L. Orgel and G. Joyce, December 11, 1997: Writing book on "Biology of Cosmos".
- UCSD Perspectives, Fall 1997, 20-22 - Oldest rocks hint of young life (J. Howard); G.Arrhenius and S. Mojzsis.
- Forskning och Framsteg, **8**, 1997. Livets Vagga (The cradle of life) Joanna Rose; G.Arrhenius research.
- National Geographic Magazine - Rise of Life, March, 1998, 58-81, (R. Monastersky, L. Mazzatenta); on NSCORT PIs' research.
- Miller, S. interviewed by Keay Davidson, San Francisco Examiner for a book: "Carl Sagan - A Life", John Wiley & Sons, (Ed. Emily Loose) on March 13, 1998, published 1999
- European News Editor for New Scientist magazine interviewed S. Miller his team's research on the stability of several compounds, i.e. citosine, guanine, adenine, to see how they behave at 100 C, June 1998.
- S. Miller and J. Cleaves' work on "tholins"., and a report on J. Bada's notion on the source of d-amino acids from bacteria. SCIENCE NEWS , July 11 1998 issue.
- Two articles quoting S. Miller about origin of optical activity and amino acid polymerization. New York Times, July 31, 1999.
- Bada, J. *Chemical & Engineering News*, Dec. 20, 1999 Issue. Claims of signs of life in Martian meteorite still face skepticism.
- Glavin, Bada, Brinton, McDonald, Nakha meteorite Terrestrial contamination: amino acids found in Martian meteorite derived from Nile Delta soil, (1999).
- Bada, J. *Chemical & Engineering News*, Dec. 20, 1999, Mars Organic Detector (MOD) on Mars 2003 Lander will look for amino acids in Martian soil.

Media - Printed *(Continued)*

- Bada, J. *Proc Nat'l Acad Sci*, Aug. 1999 "Amino acids in the Martian meteorite Nakhla" August 9, 1999 Dallas Morning News by Alexandra Witze
- Bada, J. "Science Update" -- Story on "Amino acids in the Martian meteorite Nakhla" July 28, 1999 San Diego Union-Tribune by David E. Graham
- Bada, J. "Did meteorites help with life on Earth?" January 10, 1999 San Diego Union-Tribune by Dennis L. Mammana
- Stargazers Column: "Meteor shower helps clean universe" Plug for J. Bada November 17, 1999 lecture at the Reuben H. Fleet Science Center.
- Bada, J. *National Geographic,* Jan. 2000 "Life Beyond Earth".
- New Scientist, UK, June 29, 2000, S. Miller.
- Lancet, September 20, 2000, S. Miller.
- New York Times article, September 20, 2000, S. Miller.
- Wills, C and Bada, J., *The Spark of Life,* March 2000, book published by Addison Wesley in April 2000. This is a general interest book for outreach in Exobiology.
- Wills, C. and Bada, J. Review of the *The Spark of Life* "In the Primordial Soup" by Tim Flannery, *The New York Review*, November 2, 2000.
- Wills, C. and Bada, J. *The Spark of Life*, Works of Note, *Mercury*, September-October 2000.
- Wills, C. and Bada, J. *The Spark of Life*, Natural Selections Bookshelf, *Natural History*, June 2000.
- Wills, C. and Bada, J. Interview regarding the *The Spark of Life*: Quest, "Authors Strike More Sparks' with Answers," The San Diego Union Tribune, May 3, 2000.
- Wills, C. and Bada, J, Review of the *The Spark of Life*, Science News Books, *Science News*, May 27, 2000.
- Wills, C. and Bada, J., Review of the *The Spark of Life*, "A Dip in the Soup with a Pinch of Salt," Book Reviews, *Nature*, September 28, 2000 (see Ref. 13, page 85).
- Wills, C. and Bada, J., Review of the *The Spark of Life*, "Life Is In the Bag, Or is it?," Book Reviews, *Nature Cell Biology*, October 2000 (see Ref. 14, page 86).
- Wills, C. and Bada, J., Booklist, Review by Gilbert Taylor of the *The Spark of Life*, May 15, 2000.
- Wills, C. and Bada, J., Announcement of the *The Spark of Life*, "Life Here & Beyond," *Sky & Telescope*, December 2000.
- Bada, J., Article about "Cetacean Seniors: Whales that give new meaning to longevity", *Science News*, Vol. 158, October 14, 2000 (see article on website: http://www.sciencenews.org).
- Bada, J. Interview by Neil Morgan regarding "Origin of Life? Science seeks hard answers in San Diego". San Diego Union Tribune, Quest Section, November 30, 2000 (see Ref. 15, page 87).
- Wills, C. and Bada, J., Review of the *The Spark of Life*, "It Takes Two to Tango", *Cell*, Vol. 105, 307-330, May 4, 2001 (Ref. 16, page 89).
- Bada, J. Article about "Old Salts: Eye-opening research suggests bowhead whales may live for centuries" San Diego Union Tribune, Quest Section, January 24, 2001.

Media - Electronic

- Science Line/ScienceNet <http://www.campus.bt.com/CampusWorld/pub/ScienceNet>http://www.campus.bt.com/CampusWorld/pub/ScienceNet . Public science information service; it contains all the questions Dr. Miller's group have answered over the years in an on-line searchable database. Portions reformatted for NSCORT Q&A web page.
- Ransom Publishing Ltd (a UK based educational interactive publisher) - Photograph of S. Miller and citation in the CD ROM, The History of Life , by Steve Rickard, August 17,1998
- Amazon.com: Book reviews, description, about the authors, and buying information for *The Spark of Life: Darwin and the Primeval Soup* (J. Bada and C. Wills). http://www.amazon.com/exec/obidos/ASIN/0738201960 .
- News release web page for *The Spark of Life*: http://www.sio.ucsd.edu/scripps_news/archives.html, April 24, 2000.

Public Presentations

- San Diego Association for Rational Inquiry, "Life on Mars" (L. Becker), February 23, 1997.
- San Diego Science Educators Association 13th Annual Conference (J. Bada) March 14 & 15, 1997.
- Robert Tschirgi Memorial Lecture I by Thomas Cech at UCSD on April 17, 1998. Title: "Crawling Out of the RNA World". TV taped but not broadcast - available upon request.
- Bakken Museum, Netherlands (S. Miller) Summer 1998.
- Sharpe Planetarium, Memphis, Tennessee (S. Miller), May 11, 2000.
- Reuben H. Fleet Science Center (S. Miller), July 20, 2000.
- Robert Tschirgi Memorial Lecture II by Freeman Dyson at UCSD on July 13, 1999. Title: "Gravity is Cool: Or, Why Our Universe is Hospitable to Life". This lecture will be broadcast in 2000 by UCSD-TV and was the public lecture at ISSOL '99.
- Reuben H. Fleet Science Center - "Eyes on the Universe" lecture series, J Bada November 17, 1999 "Life on Mars?" transcripts of the series will appear on CalSpace and NSCORT web sites in 2000.
- Wills, C and Bada, J., *The Spark of Life* book signing by Bada and Wills at the Birch Aquarium at Scripps Institution of Oceanography on Sunday, October 1, 2000.
- Wills, C. and Bada, J. , *The Spark of Life*, Science Breakfast and book signing at the Birch Aquarium at Scripps Institution of Oceanography, December 5, 2000.
- 40/40 Vision Lecture Series in honor of UCSD's 40th Anniversary featuring R. Doolittle on the Revolution of Biology, University of California, San Diego (R. Doolittle), December 6, 2000.
- Barcelona Museum of Science (in progress, 2001).
- 35th Annual Local Authors Exhibit, San Diego Public Library, *The Spark of Life* on exhibit January-February 2001.

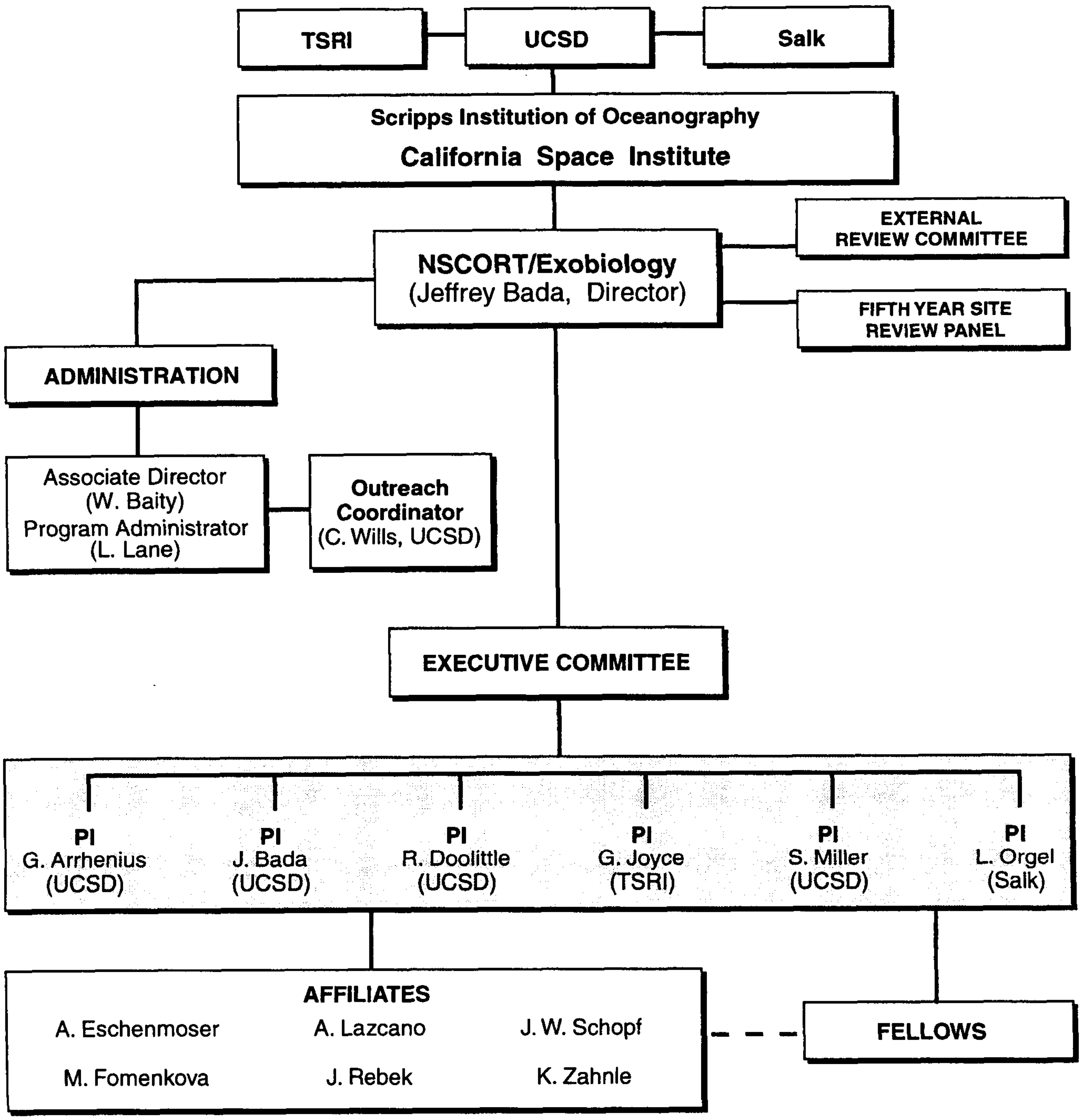
Public Presentations *(Continued)*

- San Diego Chapter of the Mars Society, ComicCon International 2001, San Diego Convention Center, "Going to Mars: Inspiration through Fiction" (Panel member: B. Baity), July 20, 2001 (see Ref. 17, page 91).
- Joint NASA Ames Astrobiology Academy and NSCORT/Exobiology Symposium for High School Students; 40 high school participants from the San Diego area at UCSD/SIO, July 27, 2001

References

1. NSCORT/Exobiology Organizational Flow Chart, 1997-2001 (page 29).
2. 1998 Report of the External Review Committee for NSCORT/Exobiology (page 30)
3. Report of the Astrobiology NSCORT Review Panel, February 18, 2002 (page 36)
4. Summary of Outreach & Education; and Exobiology on UCSD TV, Review Panel Visit. January 23, 2002 (page 43)
5. ISSOL '99 General Schedule (page 47)
6. ISSOL '99 Scientific Program Schedule (page 48)
7. ISSOL '99 Scientific Session Summaries (page 49)
8. ISSOL '99 First Announcement (page 62)
9. Predoctoral and Postdoctoral Fellowships advertisement in *Nature*, May 1, 1997 (page 64)
10. List of 1992-2003 Fellows with Present Position (page 65)
11. 1997-2001 Summer Student Symposiums (page 69)
12. Miller, S. L., "Chem 122 - Biochemical Evolution Lecture Schedule" (page 84)
13. "A dip in the soup with a pinch of salt", *Nature*, Book Reviews (page 85)
14. "Life is in the bag, or is it? *Nature Cell Biology*, Book Reviews (page 86)
15. "Origin of life? Science seeks hard answers in San Diego", San Diego Union Tribune (page 87)
16. "It Takes Two to Tango: Information, Metabolism, and the Origins of Life," *Cell* **105**: 307-330, May 2001. Wills & Bada, *The Spark of Life* Book Reviews (page 89)
17. "Space: The Final Frontier, Mars: The Next Step", The Mars Society of San Diego, an Outreach Project. Baity (page 91)

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

Lockheed Martin Astronautics
P.O. Box 179 Denver, CO 80201-0179
Telephone 303-977-3000

Ref.2

LOCKHEED MARTIN

January 14, 1999

Dr. Jeffrey L. Bada
Director, NSCORT/Exobiology
3266 Sverdrup Hall
Scripps Institution of Oceanography
University of California, San Diego
La Jolla, California 92093-0212B

Dear Jeff,

Enclosed is the Report of the External Review Committee for the NSCORT on Exobiology, based upon the review meeting held Nov. 6, 1998.

With Best Regards,

Benton C. Clark, PhD
Director, Advanced Planetary Studies

Cc: Baity, Lane
Review Committee Members

Report of the External Review Committee for the NSCORT for Exobiology
November, 1998

An intensive day of review was conducted on Nov. 6, 1998 for the NASA Specialized Center of Research and Training (NSCORT) in Exobiology. The meeting was held at the Radisson Hotel, La Jolla, CA, and was hosted by Dr. Jeffrey Bada, Dr. Bill Baity, and Ms Lois Lane. The review format included a rapid overview of NSCORT research objectives by Bada, followed by condensed presentations by the various students and post-doc's conducting research under the five different Principal Investigators, summarizing their findings. A copy of the detailed agenda is attached.

The members of the External Review Committee in attendance were: Clark, Cavalier-Smith, DeVincenzi, Meyer, Rich, Rummel and Schwartz. DesMarais could not attend due to a conflict with the First General Meeting of the Astrobiology Institute, held at NASA/ARC.

General Finding: The overall finding of the External Review Committee is that the NSCORT continues to be highly effective. The level of quality speaks for itself and is extremely high. Several recommendations from previous reviews have been implemented, but some have not and additional recommendations can be made.

1. Research

Finding: The NSCORT research is extremely diverse and highly productive, with an excellent variety of topics within each group. Addition of the research activities of Dr. Russell Doolittle has further broadened the scope to include early evolution at the organism level. This is a welcome move into an area of strong contemporary research, formerly not covered by this NSCORT. The committee notes that all six P.I.'s are international leaders in their areas of expertise. Although this is not an intrinsic requirement of the NSCORT, it is gratifying that significant progress is being facilitated simultaneously across a broad range of fronts.

Recommendation: Continue on this general path. Since no P.I. research topics significantly overlap or duplicate any of the others, and since all seem to materially contribute to the progress of Exobiological research, it is recommended that any planned changes to the P.I. complement or to specific research objectives be implemented only after careful, measured deliberation. Although the External Review Committee has not been previously consulted prior to P.I. re-allocation decisions, such decisions in the future may benefit from coordination with the committee.

2. Synergy

Finding: The research activities attack a number of diverse topics. Few topics, if any, are dependent upon completion of some other topic under another P.I. Primarily for this reason, the synergistic relationships among different research areas are not strong. The positive side of this is that the lack of strong, sequential mutual dependency eliminates potential pitfalls to research productivity and results. The negative side is that synergistic leveraging is not strong here.

Nonetheless, there are indeed potential interconnections that may not be obvious at the current stages of research. With the high quality of work, some cross-flow of methodologies, techniques and/or experiment designs are likely to occur. Perhaps the most significant connectivity is that the six research areas are spread across the range of problems in the origin of life: early inorganic/organic interactions; early organic synthesis; molecular evolution in the first chemically replicating systems; and evolution of the earliest known organisms. This in itself is indicative of an appreciation of the synergisms that must have been part of the origin of life itself. Exposure of the students to this wide range of research problems is bound to help prevent the possible focusing on singular problems in a field that is, at this time at least, highly complex and open.

Recommendation: It is recommended that the NSCORT office document, for the record, those actual collaborations that occur between P.I.'s as well as between students working on specific problems. In addition, it may be worthwhile to construct a graphical aid portraying the specific steps in the origin and evolution of early life on a barren planet, with designation of the research thrusts of the six major P.I. efforts, and how they potentially overlap.

The NSCORT office is encouraged to consider whether joint projects across laboratories, or the time-sequenced sharing of the same students, could be worthwhile endeavors, with the specific aim of broadening training and potentially increasing synergies.

3. Student Fellows (including Post-Doc's)

a) Finding: Approximately a dozen students made presentations of their research. All were outstanding. This was an exceptional window into the quality and capability of the students that are being trained under this NSCORT. It was quite obvious that each of the P.I.'s has done a good job of bringing each student up to a high level of knowledge within their topic of study.

Recommendation: No change.

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b) Finding: In a separate, private session with the students (no P.I.'s present), it was learned that research is not just a main focus, but the overriding activity. Students, as in past years, continue to express feelings of relative isolation. Part of this is due to the time demands of student life.

Recommendation: For those students who naturally gravitate to involvements that extend beyond research tasks, opportunities should be made available. See comments below on Outreach opportunities, and methods of improving the interchange of ideas and experiences between students and laboratories.

4. Education and Training (General)

a) Finding: The summer student program is reported to be extremely successful.

Recommendation: It is recommended that at least one member of the External Review Committee be invited to participate at some level in the next summer program. That person or persons will then report independently and possibly make additional recommendations to the committee.

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b) Finding: Student involvements on a broader scale could be greater. For example, the Journal Club is generally successful but sometimes poorly attended, and there are few opportunities for wider interactions.

Recommendation: Several suggestions are offered:

1) Have another Field Trip to NASA/Ames Research Center.
2) Following any guest symposia, afford students (or a selected subset) the opportunity to participate in dinner with the guest speaker.
3) Open up the Journal Club to all members of NSCORT-supported labs, not just NSCORT fellows.
4) Change time of Journal Club to the evening (e.g., 5:45 pm)
5) Schedule and have students organize reciprocal lab tours, sponsored and hosted by the students in the lab being visited.
6) Encourage students to take course work in other disciplines.
7) Have "Breakfast with the Director", or some other venue at which the NSCORT Director meets at least once each year with the students to hear their gripes, concerns and suggestions. Make this meeting mandatory for the students. If the session is too large, consider breaking it up into 2 or 3 sessions at different times of the year.

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c) Finding: Students generally concentrate on a single research project in one laboratory.

Recommendation: For graduate students (but probably not for post-docs), the NSCORT should consider having explicit exchanges of students between labs. For example, a student could undertake a minor project in one laboratory, and then switch to another laboratory for his/her major project. These rotations will benefit the students, and could benefit the laboratories involved.

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d) Finding: More than two-thirds of the students plan to work in other fields, in most cases related to biotechnology and/or to pharmaceuticals.

Recommendation: Maintain a balance between encouragement to pursue exobiology opportunities, and the larger set of opportunities in other fields. In any event, encourage that any students who choose careers in other fields maintain their interest in exobiology, with the possibility of some participation in developments in the study of the origins and evolution of life.

5. Professional Outreach

Finding: The committee notes that NSCORT's sponsorship of the 1999 ISSOL meeting provides major opportunities for professional outreach.

Recommendation: Because of this unique opportunity, and the avowed major purpose of the NSCORT program to further the program for student training, it is recommended that a serious effort be made to specifically highlight student involvement at this ISSOL meeting. Three possibilities are suggested:

a) Involve students in organizational and logistical aspects of the meeting. This experience will potentially serve them well, especially later in their careers.

b) Assign a student to each major Guest Speaker, to serve as a host and assistant.

c) Have a students-only session (not to include post-docs; not limited to NSCORT students)

All suggestions should be considered. Suggestion c) would be of greatest value in exposing students to all the experiences in preparation and presentation at a major scientific conference. One idea is that Registration Fee's could be waived for students making presentations or otherwise providing assistance to the ISSOL meeting.

A suggestion that students might be considered for leading a session was discarded, due to the difficult responsibility of the chairperson to keep presenters within time limits.

6. Public Outreach

a) Finding: The ISSOL meeting also provides major opportunities for public outreach.

Recommendation: The NSCORT should leverage this effort by arranging certain sessions and guest talks that can have strong public appeal. The organizing committee should also carefully plan and facilitate interactions with the public media. Noteworthy scientific findings should be publicized. The activities of the NSCORT also should be publicized, and these activities should be coordinated with the Public Affairs Office at NASA/Headquarters.

Although the Mars Polar Lander will only be enroute to Mars at the time of the meeting, there will be ample opportunity to discuss this upcoming mission, as well as the major scientific results of the Mars Global Surveyor and Pathfinder, and how their results will impact exo- and astrobiology.

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b) Finding: The student fellows were again polled for their involvement in giving talks to lower-level students and/or the general public. Only three had done so. When asked how many would be willing to do so if asked, nearly a unanimous raising of hands occurred.

Recommendation: Provide a mechanism for opportunities by these energetic workers to spread the word, as well as to serve as training and experience for developing their presentation, organizational, and communications skills. Steve Brown agreed during this meeting to facilitate this opportunity for a large number of the fellows. However, the Associate Director of the NSCORT should monitor this activity to ensure that it is being successfully pursued. The Review Committee feels that this activity could be an important component of the successful completion of the work by students and fellows. In addition, each should understand and become proficient in explaining the relevance and potential benefits of this research to the general public, as well as the reasons behind the interest of NASA in supporting such work.

7. Outreach -- Technology Transfer

Finding: Specific requests have been made in previous reports that the NSCORT advise on the applicability of research to transfer of technology for the benefit of the public. There has been no response in a detailed manner. Applications relevant to human health advancements (pharmaceuticals, etc.) seem obvious.

Recommendation: Although this is not a primary goal of the original NSCORT, it is nonetheless an interest of NASA and the U.S. Government. A modest effort should be placed into simply documenting any current results as well as potential future results on the transfer of information, techniques, data, and/or discoveries made under this work to the use by the private sector to develop marketable items or to the general knowledge which can serve for the betterment of human well-being. If this approach is too intensive, it may be useful to at least inventory the students who have and who are participating in this program, and their resulting professions. Investigators are very well placed to make these connections and to emphasize the potential importance of Origins of Life research to these goals.

8. Meeting Format

Finding: The committee was satisfied with the format of this year's meeting. However, by holding the meeting exclusively in a hotel off-campus, there was no opportunity to visit the laboratories.

Recommendation: Although the reasons were clear (large-scale construction activities on campus), and the meeting was a great success, it is suggested that next year's meeting might adopt a different format. It should be considered whether a visit to laboratories would be practical (e.g., by splitting up into sub-groups and making the visits in the afternoon). Alternating years of these two formats might be appropriate.

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 OUTREACH & EDUCATION

NASA Review Panel Meeting
UCSD - Wednesday, January 23, 2002

Contributions made by the NSCORT / Exobiology to enhancing public understanding of exo/astrobiology include the following examples, taken from among the many listed in "Cumulative Summary of Activities" pp 43-50:

Print Book - "The Spark of Life - Darwin and the Primeval Soup" by C. Wills & J. Bada, Perseus Publishing, 2000. Oxford University Press paperback, 2001.

The general interest journal articles, book reviews, and book chapters cited by the P.I.s in "Publications."

A companion booklet to the "Life in the Universe" web courses described below is planned.

Courses University courses and seminars taught by the P.I.s are described in "Activities" pp 37-38 and include Biochemical Evolution, Atmospheric Chemistry, The Oceans, The Origin(s?) of Life, Introduction to Geochemistry, The Origin of Life on Earth and Elsewhere, Origin and Evolution of Earth's Atmosphere and Evolution of Early Life on Earth. A web-based course module entitled "How Could Life Have Arisen on Earth?" (http://chemistry.beloit.edu/Origins/) was written by Paul Jaisen (Cal State San Marcos), along with Stanley Miller, Matthew Levy, and Jason Dworkin of the NSCORT

A web-based course, "ABCs of Life in the Universe" by W. Berger & W. Baity, designed for secondary school teachers, was offered through UCSD Extension in summer 2001 and winter 2002 (currently). This 8-week course is being re-formatted into two 6-week courses for presentation through UC Riverside and Cal State Long Beach in spring 2002 and these will be available through CalSpace for use anywhere in the country.

Lectures Robert Tschirgi Memorial Public Lecture series:

I. Thomas Cech - "Crawling Out of the RNA World," April 17, 1998.

II. Freeman Dyson - "Gravity is Cool: Or, Why Our Universe is Hospitable to Life," July 13, 1999.

III. Christian de Duve - "Reflections on the Origin and Evolution of Life," April 5, 2001.

WWW Many of the web-based course materials first saw light as annotated fact-sheets and tables of data and figures with interpretative musings and links to other sites, available to the public at the NSCORT web site (exobio.ucsd.edu). These are in a less course-like presentation, minus the quizzes, interaction and course credit. Due to the increasingly difficult environment (viruses and worms), this material is being transferred to a well-supported and more secure CalSpace-hosted site (calspace.ucsd.edu/exobio/).

A CalSpace and California Space Grant student site which originated some of the "Life in the Universe" components was developed in 1999 under the mentorship of W. Baity and a similar team incorporated astrobiology into an update of an NASA/ARC Center for Mars Exploration CD-ROM in 1998. See http://calspace.ucsd.edu/origins and /marsnow.

Other W. Baity and a number of the Fellows have met with the developer of several popular and realistic electronic simulation games, who is developing a "Life in the Universe" game. These games sell in multiples of 100,000: it is safe to say that more people have been exposed to city planning through "Sim City" than in all the city-planning courses ever given. The development complexity and duration are similar to those of a spacecraft instrument- we do not expect a product before 2004.

Presentations by Fellows to NASA/ARC and GSFC Astrobiology Academy visitors, July 27, 2001. We provided an overview of activities to this well-informed group of 40 college students.

Developing classroom (typically grade 5-6) activities as part of the Astronomical Society of the Pacific's Project Astro (on-going).

Many other outreach activities are listed in "Activities" pp 43-50.

TV *(Presented by Richard Wargo, UCSDTV)*
Summary of programs created.
Summary of broadcasts.
Current: interviews with ISSOL research Fellows.

How Could Life Have Arisen on Earth?

Module written by Paul G. Jasien, Stanley L. Miller
Matthew Levy, and Jason Dworkin

Help with Quicktime Movies

Session 1: How could life have arisen on earth?
Introduction

Exploration 1A: What are your initial ideas?
Exploration 1B: What are the requirements of life?

Session 2: Under what conditions did life arise?
The Primordial Environment

Exploration 2A: What are your initial ideas?
Exploration 2B: What processes control the temperature of the earth?
Exploration 2C: Can we make a simple model for the amount of O_2 on the primitive earth?

Session 3: How can the molecules of life be made?
The Building Blocks

Exploration 3A: What are your initial ideas?
Exploration 3B: What do molecules look like in 3-D?
Exploration 3C: Could life have arisen in space?
Exploration 3D: Can we simulate the conditions of the early earth in the laboratory?

Spark Discharge

Exploration 3E: How can we simulate the origin of life on a computer?

Session 4: What do we mean by a "stable" molecule?
A Question of Time

Exploration 4A: What are your initial ideas?
Exploration 4B: What does thermodynamics say about "stability"?
Exploration 4C: Are amino acids "stable"?
Exploration 4D: How can we quantitate the rate of a reaction?

Session 5: Can life have arisen from a poison?
Rate Laws

Exploration 5A: What are your initial ideas?

Variable Concentration Polymerization

Exploration 5B: How can we mathematically represent the reaction rate?
Exploration 5C: What could have happened in a tidal pool?
Exploration 5D: How can the rate law be determined?
Exploration 5E: How can you find the rate law for the formation of adenine?
Exploration 5F: How can we relate rate laws to reaction mechanisms?

Session 6: How can prebiotic reaction rates be increased?
Temperature and Rates

Exploration 6A: What are your initial ideas?

Variable Temperature Polymerization

Exploration 6B: What molecular level model can account for reaction rate changes?
Exploration 6C: Can organisms grow at high temperature?
Exploration 6D: How can certain molecules increase reaction rates?
Exploration 6E: Why doesn't a catalyst get used up?
Exploration 6F: How are reaction rate and equilibrium related?

Reaction Rate and Equilibrium

Session 7: Can we determine when life arose?
Nature's Clock

Exploration 7A: What are your initial ideas?
Exploration 7B: How can we model nuclear decay processes?
Exploration 7C: Can we quantitatively analyze a first order reaction?
Exploration 7D: How can we find the age of rocks?

Session 8: Putting it all together
Case Study

To fund or not to fund? Evidence for signs of life on an extreterrestrial meteorite.

This Origins of Life module has been developed under the direction of the ChemLinks Coalition, headed by Beloit College, and The ModularChem Consortium, headed by the University of California at Berkeley. This material is based upon work supported by the National Science Foundation grants No. DUE-9455918 and DUE-9455924. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation, Beloit College, or the Regents of the University of California.

Origin of Life | ChemConnections

http://chemistry.beloit.edu/Origins/

Exobiology on UCSD/TV

Rich Wargo, 1/22/02
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.

ISSOL '99 General Schedule

I = invited paper; c = contributed paper; P = Poster; Parallel A & B = Parallel Sessions of Contributed Papers

Time	July 11, Sunday	July 12, Monday	July 13, Tuesday	July 14, Wednesday	July 15, Thursday	July 16, Friday
		Session 1	Session 2	Session 3	Session 4	Session 5
7:30	Meeting Registration* and On-Campus Housing Muir Conference Desk 7:30 a.m.-Midnight					
08:30-09:00		Opening Ceremony**				
09:00-10:15		Abiotic Synthesis Invited Papers I1.1) François Raulin I1.2) George Cooper	Origin of Chirality Invited Papers I2.1) Keith Kvenvolden I2.2) John Cronin	Replication/Catalysis Invited Papers I3.1) Guenter von Kiedrowski I3.2) David Bartel	Minimum Genomes Invited Papers I4.1) Karen Nelson I4.2) Eugene Koonin	Exobiology/Astrobiology Invited Papers I5.1) David Koerner I5.2) Chris McKay
10:20-10:40		Coffee break	Coffee break	Coffee break	Coffee break	Coffee break
10:40-11:15		I1.3) Gunter Wächtershäuser	I2.3) Albert Eschenmoser	I3.3) Reza Ghadari	I4.3) Russell Doolittle	I5.3) Ken Nealson
11:15-12:15		Contributed Papers c1.4-c1.7	Contributed Papers c2.4-c2.7	Contributed Papers c3.4-c3.7	Contributed Papers c4.4-c4.7	Contributed Papers c5.4-c5.7
12:30-2:00		Lunch break OLEB Editorial Board Meeting / Faculty Club	Lunch break ISSOL Executive Council Meeting / Faculty Club	Lunch break	Lunch break ISSOL Executive Council Meeting / Faculty Club	Lunch break
		*2 Parallel Sessions*** *of Contributed Papers*	*2 Parallel Sessions*** *of Contributed Papers*		*2 Parallel Sessions*** *of Contributed Papers*	Session 6: Mars Invited Papers I6.2) Michael Carr - 2:15 p.m. I6.2) David Paige - 2:40 p.m. Contributed Papers c6.3-c6.4 - 3:05 p.m.
2:00-4:15		A) Prebiotic Chemistry-1 cA1.1-cA1.9	A) Extraterrestrial Organics cA2.1-cA2.9		A) Replication cA3.1-cA3.9	
2:00-4:15		B) Prebiotic Chemistry-2 cB1.1-cB1.9	B) Paleogeochemistry cB2.1-cB2.9		B) Catalysis cB3.1-cB3.9	
4:30-6:00		Coffee break and Poster Session 1*** Abiotic Synthesis	Coffee break and Poster Sessions 2 & 5*** Origin of Chirality Exobiology/Astrobiology		Coffee break and Poster Sessions 3 & 4*** Replication/Catalysis Minimum Genomes	ISSOL Open Business Meeting 4:00-5:15 p.m. Poster Award
	Welcome Mixer Porter's Pub Student Center 5:30 - 7:00 p.m.	Reception Stephen Birch Aquarium 7:00 - 10:00 p.m.	Reception & Public Talk Freeman Dyson Mandeville Center Main Auditorium 7:30 - 9:00 p.m.	Group Excursion San Diego Wild Animal Park 2:00 - 11:00 p.m.		Banquet & Awards Hilton La Jolla Torrey Pines Reception: 7 p.m. Banquet: 8 - 11:00 p.m.

*Weekday meeting registration at Mandeville Center Main Auditorium: Monday, 8:00 a.m.-5:00 p.m.; Tuesday, 8:30 a.m.-5:00 p.m.; Wednesday, 8:30 a.m.-12:30 p.m.; Thursday & Friday, 8:30 a.m.-5:00 p.m.

**All Sessions will be held in the Mandeville Center at the University of California, San Diego

***Poster set-up time at 5:00 p.m. on July 11 and/or 8:00 a.m. on July 12; at 8:00-9:00 a.m. on July 13 & 15. Poster presenters required to be present at their poster session between 4:30-6:00 p.m.

ISSOL '99 Scientific Program Schedule*

I = invited paper; c = contributed paper; Parallel A & B = Parallel Sessions of Contributed Papers

	Monday 7/12	Tuesday 7/13	Wednesday 7/14	Thursday 7/15	Friday 7/16
8:30-9:00	*Opening Ceremony*				
	Session 1	Session 2	Session 3	Session 4	Session 5
Plenary	***Abiotic Synthesis***	***Origin of Chirality***	***Replication/Catalysis***	***Minimum Genomes***	***Exobiology/Astrobiology***
9:00-9:05	Brack (Chair)	Shimoyama (Chair)	Cairns-Smith (Chair)	Lazcano (Chair)	Horneck (Chair)
	Harada (Co-Chair)	Goldanskii (Co-Chair)	Yamagata (Co-Chair)	Doolittle (Co-Chair)	DeVincenzi (Co-Chair)
	Invited Papers	*Invited Papers*	*Invited Papers*	*Invited Papers*	*Invited Papers*
9:05-9:40	I1.1 Raulin	I2.1 Kvenvolden	I3.1 von Kiedrowski	I4.1 Nelson	I5.1 Koerner
9:40-10:15	I1.2 Cooper	I2.2 Pizzarello/Cronin	I3.2 Bartel	I4.2 Koonin	I5.2 McKay
10:20-10:40	break	break	break	break	break
10:40-11:15	I1.3 Wächterschäuser	I2.3 Eschenmoser	I3.3 Ghadiri	I4.3 Doolittle	I5.3 Nealson
	Contributed Papers	*Contributed Papers*	*Contributed Papers*	*Contributed Papers*	*Contributed Papers*
11:15-11:30	c1.4 Scorei	c2.4 Bailey	c3.4 Allen	c4.4 Blomberg	c5.4 Ehrenfreund
11:30-11:45	c1.5 Glindemann	c2.5 Goldberg	c3.5 Kozlov	c4.5 Freeland	c5.5 Clark
11:45-12:00	c1.6 Weber	c2.6 Palyi	c3.6 Salehi-Ashtianik	c4.6 Tekaia	c5.6 McDonald
12:00-12:15	c1.7 Blocher	c2.7 Kondepudi	c3.7 McGinness	c4.7 Bacher	c5.7 Rummel
12:30-2:00	lunch	lunch	lunch	lunch	lunch
Parallel A	***A1: Prebiotic Chemistry-1***	***A2: Extraterrestrial Organics***		***A3: Replication***	***Session 6: Mars***
	Ferris (Chair)	Bada (Chair)		Orgel (Chair)	McDonald (Chair)
	Chang (Co-Chair)	Becker (Co-Chair)		Deamer (Co-Chair)	Jakosky (Co-Chair)
2:00-2:15	cA1.1 Kasting	cA2.1 Foing		cA3.1 Heckl	
2:15-2:30	cA1.2 Navarro-Gonzalez	cA2.2 Cottin		cA3.2 Sowerby	
2:30-2:45	cA1.3 Draganic	cA2.3 Bar-Nun		cA3.3 Otroshchenko	I6.1 Carr - *Invited Paper*
2:45-3:00	cA1.4 Delano	cA2.4 Brinton		cA3.4 Gao	I6.2 Paige - *Invited Paper*
3:00-3:15	cA1.5 Cody	cA2.5 Dworkin		cA3.5 Sawai	*Contributed Papers*
3:15-3:30	cA1.6 Rushdi	cA2.6 Kuzicheva		cA3.6 Nelson	c6.3 McKay
3:30-3:45	cA1.7 Lancet	cA2.7 Blank		cA3.7 Zhao	
3:45-4:00	cA1.8 Boclair	cA2.8 Becker		cA3.8 Kritsky	c6.4 Glavin
4:00-4:15	cA1.9 Sipos	cA2.9 Mita		cA3.9 Davydov	
Parallel B	***B1: Prebiotic Chemistry-2***	***B2: Paleogeochemistry***		***B3: Catalysis***	
	Miller (Chair)	Arrhenius (Chair)		Joyce (Chair)	
	Robertson (Co-Chair)	Schopf (Co-Chair)		Lehman (Co-Chair)	
2:00-2:15	cB1.1 Sust	cB2.1 Joseph		cB3.1 Unrau	
2:15-2:30	cB1.2 Krishnamurthy	cB2.2 Guillemin		cB3.2 Lehman	
2:30-2:45	cB1.3 Li	cB2.3 Wdowiak		cB3.3 Robertson	
2:45-3:00	cB1.4 Yamagata	cB2.4 Schidlowski		cB3.4 Rogers	
3:00-3:15	cB1.5 Zubay	cB2.5 Westall		cB3.5 Wong	
3:15-3:30	cB1.6 Kanavarioti	cB2.6 Friedmann		cB3.6 Harada	
3:30-3:45	cB1.7 Matsuno	cB2.7 Rivkina/Dmitriev		cB3.7 Liu	
3:45-4:00	cB1.8 Cleaves	cB2.8 Shapiro		cB3.8 Nemoto	ISSOL Open Business Meeting & Poster Award (4:00-5:15)
4:00-4:15	cB1.9 Alam	cB2.9 Komissarov		cB3.9 Frjazinova	
4:30-6:00	***Poster Session 1***	***Poster Sessions 2 & 5***		***Poster Sessions 3 & 4***	

*Note that contributed talks are listed by name of first author.

[Up] [Abiotic Synthesis] [Chirality] [Replication & Catalysis] [Min. Genomes] [Exo-/Astro-Biology] [Mars Session]

Session A1
Session B1

Session 1 – Plenary Session on Abiotic Synthesis

André Brack **(Chair) &** ***Kaoru Harada*** **(Co-Chair)**

Following an ancient ISSOL tradition based on chronological order, ISSOL'99 started with the abiotic syntheses, the source of prebiotic organics. *François Raulin* opened fire by presenting an exhaustive review of gas phase chemistry in the planetary atmospheres. Following increasing chemical complexity, he presented the different pathways from volatiles to the refractory solids " tholins," the hydrolysis of which leads to many interesting prebiotic compounds. Observing and modeling the atmospheric chemistry of the planets and moons of the Solar System (giant planets, Venus, Mars, Titan) helps to better understand the physical and chemical processes which led to life on the primitive Earth.

The study of carbonaceous chondrites allows a close examination of extraterrestrial solid organic material of prebiotic importance delivered to the Earth. *George Cooper* reported the first detection of a series of polyols (sugar alcohols) in two carbonaceous meteorites, Murchison and Murray. This series extends through at least the four-carbon members. Because there was aqueous alteration on the parent bodies of carbonaceous meteorites and formaldehyde is a ubiquitous interstellar molecule; the polyols could have been abiotically synthesized via the Formose reaction, i.e. the autocondensation of formaldehyde in aqueous solution.

Günter Wächtershäuser brought experimental data demonstrating the mandatory participation of FeS in an iron sulfur world. The formation of activated acetic acid represents a key reaction in the archaic feeder pathway. The energy-conserving reduction of keto acids was presented as typical of the archaic reproduction cycle whereas the formation of amino acids by reductive amination illustrates a key reaction in the branch pathways. For many years, *Günter Wächtershäuser* was criticized for being only a theoretician. With the experimental data presented in the session, the iron sulfur world which he advocates appears rather convincing.

Gyury Steinbrecher , on behalf of the Romanian group of Craiova, promoted the role of boron compounds in prebiotic chemistry despite the low natural abundance of the element in both rocks and living systems. Boron has been shown to decrease the thermal decomposition rate of D-glucose and D-ribose at pH 8. The decomposition products form complexes with boron and the monosaccharides at high temperature and for this reason protect the latter from thermal degradation. The protective role of boron in the context of the origin of life at high temperature was discussed.

Dietmar Glindemann, Rob M. DeGraaf, and Alan W. Schwartz presented a paper on " Chemical Reduction and Activation of Phosphate on the Primitive Earth." Phosphorus is an important element in living organisms, and therefore important in chemical evolutionary processes on the primitive Earth. However, the solubilities of various orthophosphates are usually too low to participate chemical evolutionary processes. In this presentation, the authors attempted to establish an alternate route to incorporate phosphorus produced by prebiotic chemical process (lightning discharge) into bio-organic compounds. By the use of this familiar method, the authors have succeeded to reduce phosphate to phosphate in substantial yield. The phosphate might be synthesized and concentrated in volcanic area and react thermally with nucleosides to form nucleoside phosphites, which could be converted to nucleotides by oxidation. In this presentation, it has been demonstrated that lightning is an effective reducing process of phosphate to phosphate. .

Arthur L. Weber presented a paper on " Formation of Amino Acid Thioesters for Prebiotic Products Peptide Synthesis: Catalysis by Amino Acid ". The origin of life could be understood by a sequence of chemical reactions in which the catalytic activities of the products could control the whole reaction system. The paper deals with the author's [sugar model of prebiological evolution] starting with formaldehyde, glycolaldehyde, ammonia and thiol, in addition to an aqueous reaction media. The two starting aldehydes form trioses, tetrose, and a-ketoaldelyde. These carbonyl compounds could react with ammonia and thiol to form various carbonyl compound and amino acid thioesters. The latter could be converted to peptides, which was catalyzed the whole sequence of chemical reactions. The author attempts to establish the [sugar model of chemical evolution] experimentally and also speculatively using prebiological starting materials under mild reaction conditions.

Markus Blocher, Daojun Liu, Pier Luigi Luisi presented a paper entitled " Liposome-assisted Selective Polycondensation of a -amino acids and Peptides ". The presentation deals with the formation of functional polypeptide by polycondensation of amino acids in the presence of lipidic bilayers. Two kinds of reactions were carried out: 1) The polycondensation of N-carboxy anhydrides of amino acids with and without lipid, and 2) The polycondensation of dipeptides with and without lipid in the presence of condensing agent (EEDQ). In reaction 1), longer oligomers (up to 29mer) were obtained by using hydrophorbic amino acid NCAs in the presence of lipid, whereas up to 7mer was obtained without lipid. In reaction 2), dipeptide (i. e. H-TrpTrp-OH) yielded higher oligomer, up to 8mer of Trp, in the presence of lipid, whereas 4mer of Try was obtained without lipid. A mixture of four different dipeptides was subjected for copolycondensation in the presence of lipid and EEDQ. The most hydrophorbic dipeptide was selected for higher oligomer formation. The effects of hydrophorbicity and electrostatic property of the reactants in the copolycondensation were studied.

André Brack (CBM-CNRS, Orleans, France) & *Kaoru Harada* (Takarazuka, Japan)

Session 1 – Parallel Session A1 on Prebiotic Chemistry

James Ferris (Chair) & Sherwood Chang (Co-Chair)

Methane in the Archean atmosphere (*James F. Kasting*).

Methanogens can utilize hydrogen, which should have been relatively abundant in the Archean atmosphere, for the formation of methane from carbon dioxide. Model calculations predict prebiotic concentrations of 0.1%. Photochemical calculations indicate that a biological source equivalent to the present day one could have produced

ISSOL'99 Scientific Session Summaries

The chairpersons of the scientific sessions at the ISSOL'99 meeting in San Diego have provided he following summaries of the presentations from their sessions. The book of abstract from the meeting and an upcoming issue of the Journal *Origins of Life and Evolution of the Biosphere*, dedicated to full papers from the meeting, can provide additional information.

Session 1 – Plenary Session on Abiotic Synthesis, *André Brack* (Chair) & *Kaoru Harada* (Co-Chair)

Session 1 – Parallel Session A1 on Prebiotic Chemistry, *James Ferris (Chair) & Sherwood Chang* (Co-Chair)

Session 1 – Parallel Session B1 on Prebiotic Chemistry, *Stanley Miller* (Chair) & *Michael Robertson* (Co-Chair)

Session 2 – Plenary Session on Origin of Chirality, *Akira Shimoyama* (Chair) & *Dilip Kondepudi* (Co-Chair)

Session 3 – Plenary Session on Replication/Catalysis, *Graham Cairns-Smith* (Chair) & *Y. Yamagata* (Co-Chair)

Session 3 – Parallel Session A3 on Replication, Leslie Orgel (Chair) & David Deamer (Co-Chair)

Session 3 – Parallel Session B3 on Catalysis, Gerald F. Joyce (Chair) & Niles E. Lehman (Co-Chair)

Session 4 – Plenary Session on Minimum Genomes, *Antonio Lazcano* (Chair) & *Russell Doolittle* (Co-Chair)

Session 5 – Plenary Session on Exobiology/Astrobiology, *Gerda Horneck* (Chair) & *Donald L. DeVincenzi* (Co-Chair)

Session 5 (on day 2) – Parallel Session A2 on Extraterrestrial Organics, *Jeffrey L. Bada* (Chair) & *Luann Becker* (Co-Chair)

Session 5 (on day 2) – Parallel Session B2 on Paleogeochemistry, *Gustav Arrhenius* (Chair) & *Bill Schopf* (Co-Chair)

Session 6 – Plenary Session on Mars, *Glen McDonald* (Chair) & *Bruce Jakosky* (Co-Chair) methane mixing ratios on the order of 10^{-3}. Climate model calculations show that this amount of methane could have had a major warming effect on the Earth's climate and may have been important in off setting the effects of the faint young Sun.

Production of reactive nitrogen in explosive volcanic clouds (*Rafael Navarro-Gonzalez et al*).

Volcanic lightning was simulated in the laboratory using a hot and dense plasma produced by flowing a gas mixture into a microwave discharge cavity where the gases were excited at 7 torr. Nitric oxide was found to be the major product formed from a mixture of water, carbon dioxide, nitrogen, CO, and hydrogen. If was estimated that about 5×10^{12}g of NO could have been produced annually by volcanic clouds occurring about 4 Gya.

Oxygen and oxidizing free-radicals in the hydrosphere of early Earth (*Ivan G. Draganic*).

Liquid water is considered to be the medium in which the origin of life took place. Molecular oxygen, hydrogen peroxide, and various short-lived species, such as the radicals OH and HOO are formed in irradiated water. The generation of these species takes place continuously because of the decay of potassiom-40. Present radiation experiments suggest the intrinsic oxidizing capacity of the early hydrosphere.

Cr oxygen barometry: oxidation state of the mantle-derived volatiles through time (*John W. Delano*).

The oxidation state of the atmosphere of the primitive Earth is a key parameter in some scenarios for the origin of life. If the Earth's atmosphere/hydrosphere began principally by mantle degassing, the low oxidation state depends on a persistent low oxidation state of the mantle to resupply the atmosphere with volatiles at a rate to compensate for its degradation by solar UV. Since the original abundances of Cr in ancient mantle-derived magmas can be preserved, measured abundances have been used to estimate the oxidation state of the Earth's mantle and hence the composition of derived volatiles. Results indicate that the mantle reservoirs responsible for generating the greatest volumes of magmas have been at or near current oxidation states for at least 3.8 Ga.

Experimental investigations into dynamic organic reaction networks at high T and P in aqueous medium (*George T. Cody et al*).

The research focused on deep-sea hydrothermal vents as promising environments for prebiotic systems. These greatly expands the possibility of life beyond the narrow band of solar luminosity that supports liquid water and accommodates the possibility of biochemistry similar to that of terrestrial life on the early Earth and other planetary bodies. Organic reactions have been studied under conditions that mimic hydrothermal systems. Using a C-H-O system, a well-connected chemical network was found which involved a range of reversible reactions defining metastable equilibria. The reaction network is sensitive to pressure, temperature and fluid composition. Mineral catalysis, specifically with transition metal sulfides, is critical for the establishment of a number of the metastable equilibria.

Lipid formation by aqueous Fisher-Tropsch-type synthesis over a temperature range of 100-400 °C (*Ahmed I. Rushdi and Bernd R. T. Simoneit*).

The formation of lipid compounds was observed during an aqueous Fisher-Tropsch-type reaction with oxalic acid as the carbon source. The reactions were conducted in stainless steel vessels by heating the oxalic acid solutions from 100-400 °C. At temperatures above 150 °C the lipid components formed ranged from C_{12} to $>C_{33}$ and included n-alkanols, n-alkanoic acids, n-alkanes, n-alkenes and n-alkanones. Significant cracking was observed at 400 °C and polycyclic hydrocarbons and their alkylated homologues were formed. The maximum yield of oxygenated compounds was observed at 150-250 °C.

Origin of life without biopolymers: a lipid world scenario (*Doron Lancet et al*).

The possible role of lipid-like amphiphilic substances capable of forming micelles and bilayers is analyzed. A "Lipid World" scenario is proposed as an early step in molecular evolution. The model is analyzed through computer simulations with stochastic chemical kinetics rules. This results in homeostatic preservation of molecular composition and assembly growth. It is claimed that when aggregates of amphiphiles are kept from equilibrium a rudimentary form of natural selection can occur.

Layered double hydroxides and the origins of life (*Joseph D. Boclair et al*).

Layered double hydroxides (LDH) are anion exchanging minerals that occur in nature that can bind organic anionic species which may be relevant to the origins of life on Earth. The carbonate bound to the LDH hydrotalcite is not displaced by ferrocyanide but the iron complex is bound to the outside of the mineral. Hydrogen bonding is also a factor in binding to LDH minerals. Certain LDH minerals catalyze the polymerization of cyanide and the hydrolysis of urea.

Polyester facilitated condensation of α-amino acids. New model for abiotic synthesis of peptides (*Lazlo Sipos*).

alpha-Hydroxy acids are always formed with alpha-amino acids in the Miller-Urey experiment. Heating alpha-hydroxy acids with amino acids around 100 °C gives polymers with incorporated amino acids. It was found that peptide-containing compounds were formed in these polymers. The presence of the hydroxy acids inhibits the condensation of the amino acids to diketopiperazines.

James Ferris (RPI, Troy, USA)

Session 1 – Parallel Session B1 on Prebiotic Chemistry

Stanley Miller (Chair) & *Michael Robertson* (Co-Chair)

The Prebiotic Chemistry 2 parallel session was interesting and informative, with presentations of cutting edge prebiotic chemistry research from labs representing a diverse assortment of countries. A majority of the talks addressed issues [illegible] synthesis and chemistry of nucleosides, ranging from the phosphorylation of sugars and nucleosides to the oligomerization of nucleotides. Other presentations introduced a novel prebiotic acetylating agent and a hypothesis for the origin of metabolic pathways.

Carlos Estvez (with *L. Sust* and *A. Alabau*) from the Institut Universitari de Cincia i Tecnologia in Barcelona Spain described the use of chloroacetaldehyde cyanohydrin as a potentially prebiotic acetylating agent. The acetylation of aniline by chloroacetaldehyde in the presence of cyanide to form acetanilide was studied as a model system. The proposed reaction mechanism proceeds via the formation of acetyl cyanide which is the ultimate acetylating agent. Yields as high as 25% were reported for this model reaction.

Ram Krishnamurthy (with *G. Arrhenius* and *A. Eschenmoser*) from The Scripps Research Institute in La Jolla California presented recent research concerning the phosphorylation of glycoaldehyde by amidotriphosphate (AmTP). AmTP was able to efficiently phosphorylate glycoaldehyde in dilute aqueous solution under mild conditions in which other potential phosphorylating agents such as trimetaphosphate did not react. AmTP is formed from trimetaphosphate and aqueous ammonia.

Wang Wenqing (with *H. Li* and *J. Wu*) from Peking University in Beijing China spoke about the formation of novel phosphoxy derivatives of the pyrimidines cytosine, uracil, and thymine in aqueous phosphate solutions exposed to far UV irradiation. This type of UV induced damage is irreversible and would represent a potential challenge for the prebiotic accumulation of nucleobases. However, the authors also find that the presence other classes of prebiotic compounds such as amino acids and flavonoids can protect the pyrimidines from this type of UV damage.

Yukio Yamagata from the Laboratory of Chemical Evolution in Ishikawa Japan presented his investigations of the phosphorylation of nucleotides by calcium phosphate with cyanate as the condensing reagent. Using this method he was able to synthesize nucleoside-5'-diphosphates from precursor nucleoside monophosphates, and nucleoside-5'-triphosphates from nucleoside diphosphates. In one experiment, ATP was formed in 7% yield from a starting solution of AMP. The use of several other condensing agents and other metal ions were not as successful.

Geoffrey Zubay from New York's Columbia University presented a review of the current status of prebiotic nucleotide synthesis. Particular focus was placed on recent advances in the author's lab concerning the synthetic routes to purine nucleobases, selectivity for ribose synthesis imparted by the presence of lead (II) in the formose reaction, and improved methods for phosphorylating nucleosides.

Anastassia Kanavarioti (with *F. Lee*) from the University of California at Santa Cruz presented a detailed study of the dimerization of imidazolide activated nucleotides in solution. Kinetic analysis of the dimerization reaction coupled with computer simulations indicate that base stacking occurs in a cooperative fashion and is assisted by the presence of the imidazolide activating group and divalent metal ions.

Koichiro Matsuno from Nagaoka University of Technology in Nagaoka Japan described oligomerization experiments performed in a flow reactor designed to simulate submarine hydrothermal vent systems. A solution of glycine circulated through the reactor at 200-250°C eventually led to the formation of glycine oligomers up to octamers. In similar experiments, a circulated solution of AMP led to formation of dimers and trimers.

H. James Cleaves (with *S. Miller*) from the University of California at San Diego presented the theoretical framework and experimental support for a semi-enzymatic hypothesis for the origin of the biosynthetic pathways. The hypothesis requires that most reactions of primitive multi-step metabolic pathways would have initially proceeded non-enzymatically until catalysts were eventually evolved to enhance the efficiency of the reactions. Experimental support for this idea was found for the biosynthetic pathway of quinolinic and nicotinic acids from the non-enzymatic reaction of dihydroxyacetone phosphate and aspartic acid.

Stanley Miller **(UCSD, La Jolla, USA) &** ***Michael Robertson*** **(University of Texas, Austin, USA)**

[Up] [Abiotic Synthesis] [Chirality] [Replication & Catalysis] [Min. Genomes] [Exo-/Astro-Biology] [Mars Session]

[Up] [Abiotic Synthesis] [Chirality] [Replication & Catalysis] [Min. Genomes] [Exo-/Astro-Biology] [Mars Session]

Session 2 – Plenary Session on Origin of Chirality

***Akira Shimoyama* (Chair) & *Dilip Kondepudi* (Co-Chair)**

K. A. Kvenvolden presented a historical perspective of the amino acid analyses in the Murchison meteorite. He nicely described his group's application of the optical isomer separation of amino acids by a GC method and showed a successful result which had enabled to convince the presence of meteoritic amino acids in the Murchison. Further, he discussed the use of the isomer ratios to know an extent of terrestrial amino acid contamination showing a result of another Murchison sample which was analyzed after a several year of terrestrial storage. A good review was made by one of the pioneers in this field.

Cronin and Pizzarello's paper was presented comprehensively by *Pizzarello*. She showed a good GC-MS result of small but significant enantiomer excesses of alpha-methyl-alpha-amino acids in the Murchison. Since these amino acids are rare in terrestrial biosphere, terrestrial contamination for these excesses can be excluded. She proposed a possibility of partial photoresolution of racemic mixture as a result of exposure to UV circularly polarized light in the presolar cloud. It is nice to know that a new hypothesis with analytical data was brought up to the origin of homochirality from the study of amino acid enantiomers in the meteorite.

Albert Eshenmoser summarized the results of his group's study of pentopyranosyl nucleic acid (PNA) oligomerization. Oligomerization of PNA from tetramers is highly chiroselective and consequently longer polymers are predominantly homochiral. The implications of this process for the origin of biomolecular homochirality is that as "libraries" of large homochiral L- and D-polymers form, the number of possible sequences will far exceed the number of molecules. Since oligomerization is stochastic, this implies that the D- and L-libraries are no longer identical, i.e., chiral symmetry is broken due to complexity. It is then possible, that some of the sequences, either in the L- or in the D-libraries had the properties needed to establish life.

This was followed by short reports by *J. Bailey* who reported on the discovery of a large component of circular polarization in light scattered from interstellar clouds and its implications for the generation of enantiomeric excess; a report by *S. Goldberg* on the mechanisms that can produce homochirality; a report by *G. Polyi* on chiral confirmations giving rise to enantioselectivity and a report by *D. Kondepudi* on chiral autocatalysis near solid surfaces as observed in crystallization experiments and its implications for generating enantiomeric excess.

***Akira Shimoyama* (University of Tsukuba, Japan) & *Dilip Kondepudi* (Wake Forest University, Winston-Salem, NC, USA)**

[Up] [Abiotic Synthesis] [Chirality] [Replication & Catalysis] [Min. Genomes] [Exo-/Astro-Biology] [Mars Session]

Session 3 – Plenary Session on Replication/Catalysis

Graham Cairns-Smith **(Chair) & *Y. Yamagata* (Co-Chair)**

Most of us would agree that to "get clever" without a human designer a system has to be able to evolve through natural selection, and that the origin of life is, in effect, the origin of that kind of process. But to be able to evolve it is necessary to pass information on to offspring, and the easiest way to do that would seem to be through some kind of replicator structure. Those with their eyes on how "life as we know it" arose will start thinking first about nucleic acids, or perhaps other current biochemical components. Those who are thinking about life in general — alien or artificial, or perhaps our very remotest ancestors on Earth — may be more interested in the general chemical requirements for any kind of replicating structure that might form the basis of an actual chemical system able to evolve before our very eyes.

Both of these points of view were represented in the splendid Wednesday morning session. It opened with *Guenter von Kiedrowski* (Germany) asking the question: How about SPREAD? This is a procedure he has been using with DNA analogues to tackle a general problem that has been found for "minimal replicators" of different chemistries. The problem is product inhibition. After monomers (or oligomers) have locked onto a template strand and then duly joined up make a new complementary strand, the resulting duplex will then be especially disinclined to separate. Surface-Promoted Replication and Exponential Amplification of DNA analogues (SPREAD) is a way round this. You immobilize the original template strand on a solid support first, and then proceed in stages, changing the solutions to encourage successively annealing, ligation, and then finally separation, the new strands being simply eluted and re-attached elsewhere to repeat the now amplified process.

Erik Schultes, Peter Unrau, and Wendy Johnston were co-authors with *David Bartel* (USA), who delivered the second of the invited lectures. This was about Replication, with that Holy Grail of the RNA world — an RNA polymerase made of RNA — as one of the objects of desire. But it was also very much about the other half of this session's title, Catalysis, about a more general exploration of RNA space. They have found not only an RNA catalyst (ribozyme) for making short segments of RNA, but also another one that could help synthesize RNA nucleotides. That it is possible to stumble on such functionally diverse RNA catalysts starting from random sequences, and that the same RNA structural motifs can arise from very different sequences, inspires a vision of deep RNA space containing vast webs of functionally equivalent structures. These are "neutral networks" allowing an easy evolutionary drift among structurally very different, but functionally equivalent, molecules. Then, in this vision, the nets occasionally intersect so that one ribozyme can evolve into another perhaps altogether different one.

In the third of the invited lectures *Reza Ghadiri* (USA) discussed the question of what distinguishes living things, emphasizing "non-linear molecular information transfer processes." He then described to us his novel experimental replicator models based not on hydrogen bonded base pairing as in the nucleic acids, but on hydrophobic interactions between side chains of fairly short alpha-helical peptides. These systems provided the basis for a general discussion of how self organized autocatalytic networks could have appeared and evolved some of the basic characteristics of living systems.

Victoria C. Allen, Raphael M. Bennes, and Andrew Sinclair were co-authors of the next presentation given by *Douglas Philp* (UK). This piece was very much a widening of our horizons towards a more general understanding of the chemistry of replication. There are more things in chemistry than are dreamed of in biochemistry, and here was one of them. We were shown a pairing system using hydrogen bonds, but not at all the usual ones. Then a ligation via cycloaddition not condensation. And then, furthest off of all, purely diastereosomeric "information" based on chiral centers created during the cycloaddition. Like all artificial replicators that have yet been demonstrated, this one is still very minimal. But the efficiency with which one of two diastereoisomers can catalyze specifically its own further formation is impressive.

Panagiotis K. Politis, Stefan Pitsch, Bart De Bouvere, Roger Busson, Arthur Van Aerschot, Piet Herdewijn, & Leslie E. Orgel (USA, Switzerland & Belgium) were the co-authors of the next piece presented by *Igor A. Kozlov* (USA). HNA, a novel nucleic acid using a hexitol as the "sugar," was used as well as RNA and DNA as a new kind of template in a study of non-enzymatic template directed RNA and DNA synthesis. In the cases studied, HNA was shown to be more efficient than either RNA or DNA in transferring information to the daughter strand. It was also much less prone to enantiomeric cross-inhibition.

Jack Szostak was co-author of the next piece presented by *Kourosh Salehi-Ashtiani* (USA). This was the first of two items returning to that "Holy Grail" of the RNA world referred to above. The strategy adopted here was to select first for ribozymes with template directed DNA polymerase activity and then, having established that function, to start selecting for the more tricky RNA dependent RNA polymerase activity as well as other related functions.

For the final contribution, we went from one famous laboratory in the east of the USA, where molecules evolve in vitro, to another in the west. *Gerald Joyce* was the co-author of the paper presented by *Kathleen McGinness* on in vitro evolution of ligase ribozymes — again in pursuit of an RNA-dependent RNA polymerase. They have been using an indirect method of replicating RNA, via reverse transcribed DNA, which allows a continuous "hands off" operation. In this way ribozymes have been evolved (or rather evolved themselves) that are able to catalyze at least three successive phosphoester transfer reactions.

Graham Cairns-Smith **(University of Glasgow, UK) & *Yukio Yamagata* (Ishikawa, Japan)**

Session 3 – Parallel Session A3 on Replication

Leslie Orgel **(Chair) & *David Deamer* (Co-Chair)**

Sowerby et al. reported observations in which scanning tunneling electron microscopy (STM) was used to investigate molecular self-assembly of purine and pyrimidine bases on mineral surfaces. STM was able to resolve monomolecular layers of bases, thereby providing a direct demonstration that such adsorption occurs. Their results also suggest mechanisms by which organic compounds adsorbed to natural mineral surfaces such as clay would be able to act as templates for further molecular assembly processes.

Otroshchenko et al. reported the very surprising finding that non-activated nucleotides oligomerize on polynucleotide templates adsorbed on mineral surfaces. Poly A adsorbed on a clay mineral surface, for example, catalyzes the synthesis of oligouridylates up to U5 from the sodium salt of uridyfic acid.

Gao and Orgel described a method of crosslinking a preformed oligonucleotide to a mononucleotide analogue in such a way as to generate an adduct with the same geometry as a base pair.

Sawai and coworkers described a number of template-directed ligation reactions involving 2'-5'-linked templates and substrates. They found, for example, that the 2'-5'-linked U10 is a more efficient template than

3'-5'-linked U10 for the oligomerization of 2'-5'-linked pApA.

Nelson and coworkers described potentially prebiotic syntheses of some of the components of PNA, namely ethylenediamine monoacetic acid and the pyrimidine-2-acetic acids corresponding to uracil and cytosine.

Zhao and Cao asked why alpha, rather than beta amino acids predominate in biological processes. They approached this question by comparing the ability of N-phospho-alpha-amino acids and N-phospho-beta- amino acids to polymerize and phosphorylate nucleosides. Only alpha amino acids were observed to form oligomers and nucleotides, suggesting that the chemical structure of alpha amino acids would have been favored in early selection during prebiotic chemical evolution.

Kritsky et al. investigated pterins as potential pigments and redox reactants in early forms of life. Pterins are plausible candidates for such a role because they can be produced by thermolysis of amino acids. Using such compounds, these investigators observed that the photoexcited state could accept electrons from a donor such as histidine, tyrosine, and ethylene diamine derivatives. Pterins could also photocatalyze electron transfer from a donor such as EDTA to cytochrome c. These results suggest a role for pterins in early photobiological processes.

Leslie Orgel (Salk Inst., La Jolla, USA) & *David Deamer* (UCSC, Santa Cruz, USA)

Session 3 – Parallel Session B3 on Catalysis

Gerald F. Joyce (Chair) & *Niles E. Lehman* (Co-Chair)

This session explored two themes that are currently hot topics in the push to understand the catalytic capabilities and limitations of pre-cellular life. The first is the catalytic potential of nucleic acids, and the second is the possibility that, like nucleic acids, polypeptides can be made to undergo Darwinian evolution *in vitro*.

Peter Unrau (USA) opened the session by asking the question: can ribozymes make nucleosides? It is now well known that RNA can catalyze the chemical modification of macromolecules, but relatively little is known about how RNA can catalyze reactions involving small molecules, such as monosaccharides, purines, and pyrimidines. From a large pool of random-sequence RNAs, Unrau and co-workers attempted to select molecules that could catalyze the synthesis of uridine from phophoribosyl pyrophosphate (pRpp) and uracil. Using an elegant technique involving the capture of reacted catalysts on mercury-containing polyacrylamide gels, which slow the mobility of thiol-containing compounds, they selected RNAs that could form a covalent linkage between pRpp attached to their 3« end and a 4-thio-uracil substrate. They characterized a family of RNAs that catalyzed uridine synthesis at a rate more than a million-fold faster than the uncatalyzed rate of reaction.

Niles Lehman (USA) then described how alternate foldings of RNA could affect the evolutionary trajectories of polynucleotides. If a single genotype (primary nucleotide sequence) could be expressed as more than one phenotype (folded secondary and tertiary structures), then *in vitro* selection becomes a more complex phenomenon resulting from the lowered heritability of genetic information. Exploiting Wright and Joyce's continuous evolution scheme with the Bartel-Szostak ligase ribozyme, Lehman provided evidence that RNA sequences could be selected not necessarily because they are catalytically superior, but because they have a higher probability of folding into active secondary structures following transcription. This was exemplified in the selection of a 152-nucleotide ligase ribozyme that retained activity when the concentration of magnesium ion in the reaction mixture was lowered to less than 10 mM.

Another factor that could affect the complexity of an RNA world is enzyme allostery. The ability to regulate reactions would become increasingly important as genetic systems evolved greater metabolic complexity. *Michael Robertson* (USA) showed the results of several *in vitro* selection experiments that resulted in allosteric ribozymes that required the presence of a small effector molecule in order to fold into a catalytically active conformation. By utilizing affinity columns, he and his co-workers isolated families of ligase ribozymes that depended on either ATP, FMN, or theophylline co-factors to enhance their catalytic rate by up to 1,600-fold compared to the rate in the absence of the effector. Strikingly, they also were able to isolate "double aptozymes" that can be regulated by two separate effectors, such as ATP and theophylline.

Can catalytic activity be generated from ribozymes containing fewer than four nucleotides? This question was answered with an emphatic yes by *Jeff Rogers* (USA) who selected ligases that contained the nucleotides A, G, and U, but not C. Employing a mutagenesis scheme that insured that C nucleotides would no longer be available, *Rogers* and co-workers evolved variants of the Bartel-Szostak ligase that not only were active with only three nucleotides, but appeared to form radically different secondary structures compared to the parent molecule, relying on only A-U and G-U base pairs. These experiments suggest that RNA evolution could have taken place in a less information-rich sequence landscape than was previously thought possible.

Shifting the spotlight onto a more diverse primordial living system, *Tze-Fei Wong* (Hong Kong) gave a strong description of the co-evolutionary hypothesis of the origin of the genetic code that he originally proposed in the 1970s. According to this model of code evolution, codons were bequeathed from ancestral to descendant amino acids in steps that parallel the biosynthetic pathways of amino acids in the cell. For example, although Cys and Trp are chemically dissimilar, they are both generated biosynthetically from Ser and thus both share codons in the UGN box. Drawing on biochemical evidence that the single discriminator base in tRNA plays an important role in Trp tRNA recognition by aminoacyl synthetases, *Wong* described how codons could be transferred from ancestral to descendant amino acids during the diversification of the genetic code.

But can oligopeptides undergo Darwinian evolution as we know nucleic acid sequences can? This issue was raised by *Kazuo Harada* (Japan) who described an elegant *in vivo* system to do exactly that. Harada and colleagues constructed a combinatorial petide library in *E. coli* plasmids that could express short random peptides for which successful binding to a target nucleic acid (such as the rev response element from HIV) could be screened by a simple blue/white colony assay. They found it necessary to simplify their task by reducing the number of amino acids that could be encoded to 3–9, instead of the full set of 20, but nevertheless were able to select short oligopeptide sequences that could bind their targets with high affinity.

Finally, the last two speakers in the session described some exciting advances in the quest to perform polypeptide selections *in vitro* , a goal that would not only be invaluable to protein engineers, but would open up a new frontier in origins-of-life research. *Naoto Nemoto* (Japan) described how he and his colleagues made a key conceptual advance in this respect by developing an "*in vitro* virus" that successfully linked a polypeptide's phenotypic information, which the forces of selection could target, and its genotypic information, which must be present to allow evolution to occur. This coupling was made possible by the creation of fusion proteins in which a mRNA sequence is covalently linked to the polypeptide that it uncodes by means of a puromycin-driven trap that operates during cell-free translation.

Rihe Liu (USA) detailed how he and his colleagues are utilizing a similar puromycin-dependent strategy to create random polypetide libraries so that *in vitro* evolution techniques can be employed to search for novel proteins. In the construction of these mRNA-polypeptide fusions, numerous problems must be overcome, such as the random generation of stop codons that prematurely terminate the polypeptides. Liu has been tackling another problem, that of low fusion efficiency, with earlier protocols less than one-quarter of all translations produced fused proteins. However, it was discovered that a post-translational freezing of the system greatly enhances fusion efficiency. It is now routine to generate libraries with 40–70% fused sequences that retain catalytic activity and are amenable to *in vitro* selections.

Gerald F. Joyce **(Scripps R. I., La Jolla, USA) &** ***Niles E. Lehman*** **(SUNY, Albany, USA)**

[Up] [Abiotic Synthesis] [Chirality] [Replication & Catalysis] [Min. Genomes] [Exo-/Astro-Biology] [Mars Session]

Session 4 – Plenary Session on Minimum Genomes

***Antonio Lazcano* (Chair) & *Russell Doolittle* (Co-Chair)**

What is the minimal set of characteristics that a system must fulfill to be considered alive? The answer to this question has a direct bearing on the origin of life, and has led to several attempts to estimate the gene complement of a minimal free living system. Not surprisingly, some of these efforts have been superseded by the results of the ongoing genome sequencing projects, which have opened a new range of unsuspected possibilities to address this issue. However, as underlined by several of the invited and contributed papers presented in this session, this is more easily said than done.

As summarized by *Karen E. Nelson* (The Institute for Genomic Research, Rockville), analysis of the genome of Thermotoga maritima, a deeply diverging, slow evolving thermophilic bacterium, has shown that over 80 clustered genes are most similar to archaeal sequences. The high level of sequence- and gene-order conservation between Thermotoga and

deep-branching archaeal hyperthermophiles indicates that extensive lateral transfer has occurred between these two lineages, blurring the 16S-like rRNA-based phylogenies and suggesting that a single gene is not enough to describe in full the evolutionary relationships between all living beings.

Such extensive horizontal transfer, combined with other phenomena such as polyphyletic gene losses, clearly renders difficult the reconstruction of ancestral states and the description of the last common ancestor (LCA). This issue was discussed by *Eugene V. Koonin* (Natl. Center for Biotechnology Information, NIH, Bethesda USA), who reported the results of an extensive computer analysis of microbial genomes, which have allowed the characterization of approximately 100 families of orthologs, including of course those gene products involved in translation. These conserved sequences do not include the molecular machinery involved in DNA replication (e.g., DNA polymerases, primases, helicases, and others), which has been interpreted by *Koonin* and his co-workers as evidence that the LCA may have been endowed not with a DNA genome, but rather with a mixed system based on both RNA and DNA elements.

As noted by *Russell Doolittle* (UCSD, La Jolla, USA), the ribosomal data indicate that although there was an early eukaryotic lineage, it is quite likely that the LCA goes back to a split between the Archaea and the Bacteria, both of which have made major contributions to the gene complement of nucleated cells. Such a split, which a few years ago was placed approximately two billion years ago on the basis of data sets in which the archaebacteria were poorly represented, has been recalculated by *Doolittle* and his collaborators. As underlined by *Doolittle* , inclusion of the Methanococcus jannaschii and other archaeal sequences has shown that the eubacteria and the archaebacteria probably had a common ancestor more than 3 billion years ago, and perhaps even between 3 and 4 billion years ago.

Clas Blomberg (Royal Institute of Technology, Sweden) discussed a different issue. By attempting to achieve general statements on the nature of feedback processes that may have been important for the stabilization of catalyzed self-replicating systems and template-based protein synthesis, on the based of mathematical models he argued that although the genetic code may have been the outcome of a frozen accident, it was probably stabilized by enzymes controlling the mechanism by which they had been formed.

A different approach was discussed by *S. J. Freeland, R. D. Knight, L. D. Hurst and L. F. Landweber* (Princeton University, USA), who in paper presented by the former discussed extensively the error minimization hypothesis of the origin of the code, according to which codon assignments are the evolutionary outcome of processes that help to minimize the impact of genetic errors.

The paper by *F. Tekaia, B. Dujon* (both of the Institut Pasteur, Paris) and *A. Lazcano* (UNAM, Mexico), on the other hand, went back to the issue of the LCA and was based on comparative genomics to characterize the most highly conserved genes common to all the completely sequenced cellular genomes now available. As argued by *Lazcano* , this approach, which is based on the identification of orthologs in the data bases, has shown the most highly conserved protein genes are those encoding products that synthesize, degrade, or interact in one way or another with RNA, as well as some involved in nucleotide biosynthesis. These results have been interpreted by *Tekaia et al* as evidence of an early evolutionary stage during which RNA played a more conspicuous role in biological processes.

The session ended with a paper by *J. Bacher* and *A. D. Ellington* (University of Texas at Austin, USA), which reported the result of 3,500 hours of laboratory selection cycles that allowed the replacement of tryptophan by 4-flurotryptophan (4fW), an unnatural amino acid, throughout the entire proteome of E. coli. As noted by *Ellington* , the number and identity of the mutations involved in the incorporation of 4fW demonstrate that at least in some cases organisms can readily change some of their basic biochemistry. These results, which have a bearing on the design of astrobiological exploration strategies, show that in may be possible in the near future to alter not only the chemistry of proteins, but perhaps also the entire biochemistry of living beings.

***Antonio Lazcano* (UNAM, Mexico) & *Russell Doolittle* (UCSD, USA)**

[Up] [Abiotic Synthesis] [Chirality] [Replication & Catalysis] [Min. Genomes] [Exo-/Astro-Biology] [Mars Session]

Session 5 – Plenary Session on Exobiology/Astrobiology

Gerda Horneck **(Chair) &** ***Donald L. DeVincenzi*** **(Co-Chair)**

The plenary session on Exobiology/Astrobiology which took place on July 16 morning was co-chaired by *Gerda Horneck* , DLR, Germany and *Donald L. DeVincenzi* , NASA, USA. In her introduction, G. *Horneck* pointed out that the field of exobiology/astrobiology has recently received increased attention. This is mainly caused by the interdisciplinary efforts to study the phenomenon of life and the processes that lead to its origin, evolution, and distribution within a broader context, i.e. as an integral part of the evolution of the universe. This approach was reflected in the presentations which mainly dealt with the following aspects of exobiology/astrobiology: (i) formation of precursors of life in the interstellar medium and their possible preservation in the protosolar nebula; (ii) exchange of biological material between planets by natural processes, e.g. by meteorites, (iii) appropriate biosignatures in search for life on other planets; and (iv) possibility of life on Jupiter's moon Europa. Mars as a potential abode for life was dealt with in a special Mars Session, following this session.

The session started with *D.W. Koerner* (University of Pennsylvania), who presented optical and near infrared images of protoplanetary environments around young stars taken from the Hubble Space Telescope. In these disks, organic molecules are detected including CN, HCN, and PAHs. He described a scenario, where at large radial distances (e.g. >50 AU) organic compounds in the accreting material may be preserved and may be delivered to the terrestrial planets region via organic-rich icy bodies. Most of these organic molecules are generated in the interstellar medium. *P. Ehrenfreund* (Leiden Observatory) presented recent observations from ISO on interstellar and cosmic dust particles which indicate that comets contain besides pristine interstellar material also admixtures of processed material. Supported by results from laboratory simulation experiments she reconstructed a scenario of the history of organic compounds from simple carbon bearing species to complex molecules and aromatic networks and finally to prebiotic chemical evolution on Earth.

C.P. McKay (NASA ARC) discussed mechanisms by which life may expand beyond its planet of origin, one of the key questions in Astrobiology. The efficacy of interplanetary delivery processes is demonstrated by the Martian meteorites found on Earth. The suggested time scales range from a few years up to several million years. *McKay* showed several examples of terrestrial microorganisms (e.g., in permafrost, in amber and in salts) as well as results from long-term space experiments that demonstrate the ability of dormant microorganisms to survive such extended periods of time. Beyond the solar system, dust grains ejected by impacts may be the vehicles for spreading life from star to star. Finally, he pointed out that space technology provides the tool for spreading life in our own solar system. A more pessimistic view on this scenario of planetary exchange of living matter was presented by *B. C. Clark* (Lockheed Martin Aeronautics). He suggested that the ejection process and the radiation encountered in space might impose serious constraints on the chances of a successful transport of life between Venus-Earth-Mars, presently as well as in the early solar system.

K.H. Nealson (JPL, Pasadena) gave an insight into the diversity microbial life on Earth has developed since it appearance, about 4 billion years ago. He showed that almost all niches on Earth that have available energy and which are compatible with the chemistry of carbon-carbon bonds are known to be inhabited by microorganisms. Knowledge of the metabolic diversity of microbes and their strategies of adaptation to environmental extremes may provide clues to the understanding of the habitability of other planets, e.g., of Mars. Following this presentation, *G.D. McDonald* (JPL, Pasadena) showed the difficulties one faces when selecting the right biomarkers in search for extraterrestrial life. Whereas he doubted that terrestrial biochemistry may serve as an appropriate model for possible extraterrestrial life, he considered certain fundamental chemical functions as more promising biomarkers, such as oxidation and reduction processes facilitated by electron carriers, some form of compartmentalization, or some forms of cell-cell recognition. He emphasized that assessing the biodiversity in terrestrial extreme conditions might help to identify candidate extraterrestrial organic biomarkers.

Finally, *J. D. Rummel* (NASA HQ, Washington) presented recent data of Europa from Galileo and the perspectives of the presence of a liquid water ocean below the ice crust and herewith the likelihood of an indigenous biota of Europa. More insight into the question of a possible ocean on Europa is expected to be obtained from an orbiter mission to Europa the US is planning for 2003.

The session was well attended and each talk was followed by a vivid discussion.

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Gerda Horneck **(DLR, Koeln, Germany) &** ***Donald L. DeVincenzi*** **(NASA-Ames, Moffett Field, USA)**

Session 5 (on day 2) – Parallel Session A2 on Extraterrestrial Organics

Jeffrey L. Bada **(Chair) &** ***Luann Becker*** **(Co-Chair)**

This session was organized to bring together astronomers, cosmochemists, theorists, and experimentalists to evaluate the contributions of extraterrestrial organics to the origin of life on Earth and other solar system bodies. A total of nine papers were scheduled; one, "From the interstellar medium to the Earth's oceans and atmosphere via comets - An isotopic study" was not presented because the author *Akiva Bar-Nun* was unable to attend.

The session began with a paper "Evolution and survival of complex organics in space" presented by *Pascale Ehrenfreund* . Relevant laboratory and theoretical studies pertaining to the evolution, ionization, destruction and survival of complex organic molecules in the interstellar medium (ISM) was discussed. The transport and delivery of these complex organic compounds to the solar system was also discussed. This talk was followed by one titled "Experimental Simulation of the photodegradation of large organic molecules in the cometary environment" presented by *H. Cottin* . A discussion of the compound polyoxymethlene (POM), a possible parent molecule of aldehydes, and the photodegradation of hexamethyltetramine (HMT), which could be a parent molecule of the CN radical, was presented.

Karen Brinton of the Jet Propulsion Laboratory (JPL) next presented "The cosmogeochemistry of amino acid synthesis from hydrogen cyanide." Glycine was found to be the main amino acid produced from HCN polymerization, accounting for 75 % to 98% of the total amino acids produced. A discussion of the unique distribution of amino acids produced directly from HCN as a possible means of identifying the origin of these compounds in extraterrestrial samples was presented.

The next paper "Simulations of cometary ice: large molecule synthesis and self-assembly properties" by *Jason Dworkin* of NASA Ames, presented data from laboratory simulations and infrared observations of large organic molecules in cometary ices. A rich mixture of complex organic compounds, similar to those observed in some IDPs and meteorites were detected. When dispersed in water, this organic material formed 10-40 mm droplets similar to those produced from extracts of the Murchison CM chondrite in experiments conducted by *David Deamer* . The next paper "Abiogenic synthesis of guanine nucleotides under the action of vacuum ultraviolet" was presented by *Natalia Gontareva* . Dry films of guanosine, deoxyguanosine, phosphate and NaH_2PO_4 where mounted on the Mir spacecraft and exposed to UV. Low yields of both 5'-guanosinemonophosphate and 5'-deoxyguanosinemonophospate were obtained.

Jennifer Blank from the University of California, Berkeley then presented "An experimental study of the shock reactivity and stability of cometary organic matter." Using a gas-gun to produce impact velocities of 0.5 to 2.5 km/s, the survivability of the amino acids lysine and norvaline were evaluated. Both of these amino acids survived the shock heating simulated in these experiments. Next, *Luann Becker* of the University of Hawaii presented "Fullerenes and the flux of extraterrestrial helium (He@C60) to the Earth during giant impact events." Data on the detection of fullerenes in impact deposits from the Cretaceous/Tertiary (K/T) boundary was discussed and it was suggested that fullerenes can be used as a tracer of the delivery of exogenous organic compounds to the Earth over geologic time. The implications concerning the importance of fullerenes in delivering volatiles to the Earth's crustal reservoir were also considered.

The final paper of the session, "Organic compounds in the K/T boundary sediments at Kawaruppu, Japan and their comparison with those in the carbonaceous chondrites" was presented by *Mita Hykaru* of the University of Tsukuba, Japan. A suite of organic compounds (amino acids, dicarboxcylic acids and aliphatic and aromatic hydrocarbons) where shown to be present in K/T boundary sediments from Kawaruppu. There is no indication of extraterrestrial organic compounds such as the amino acids a-aminoisobutyric acid or isovaline. It was suggested, based on the distribution of the various organics detected, that there no compounds in this K/T boundary sequence derived from extraterrestrial sources.

The standard of the presentations was high and reflected the enthusiasm and interest which exists in this area of research. Due to a large and interactive audience, the discussions following the oral presentations were lively. Because of the widespread interest in the topic of extraterrestrial organics and their role in the origin of life, a similar session will hopefully be held during the 10th ISSOL in Oaxaca, Mexico in 2002.

Jeffrey L. Bada (UCSD, La Jolla, USA) & *Luann Becker* (Hawaii, USA)

Session 5 (on day 2) – Parallel Session B2 on Paleogeochemistry

Gustav Arrhenius (Chair) & *Bill Schopf* (Co-Chair)

Professor *J.P. Ferris* described experiments carried out together with *J.C. Joseph and D.W. Clarke* , using a specially designed flow reactor to model photochemical reactions of minor organic components, characteristic of Titan's nitrogen atmosphere. These atmospheric trace components, in mixing ratios comparable to those on Titan, included H2, CH4, C2H2, C2H4, and HC3N. Prof. *Ferris* outlined the several advantages of the photochemical flow reactor over static systems, and also the reaction products and the techniques used to analyze them. One of the purposes of the study was to simulate the formation of the haze on Titan by photolyzing the mixing ratios of the major and minor gases present in its atmosphere. Wall effects are minimized in the flow system so the polymer produced was formed under conditions present in the atmosphere of Titan. The polymer was characterized by its IR and UV-visible spectrum. It's UV-visible spectrum was shown to match that observed for Titan haze.

Professor *J.C. Guillemin* described photochemical reactions of alkenes and alkanes with PH3, NH3, and H2S in experiments intended to simulate processes in the Jovian and Saturnian atmospheres. It was found that reactions of these heterocompounds with ethane produced the corresponding heteroalkanes but with different reaction mechanisms inferred in each case. Methane and ethane were chosen as alkane reactants; photochemical reactions of these with the heterocompounds gave the corresponding amines, phosphines, and thiols. Since all of the reactants in question have been observed or inferred in the Jovian and Saturnian atmosphere, it was suggested that the experimentally obtained heterocompounds and further reaction products are likely to be components of the atmospheres of the giant planets.

Dr. Wdowiak presented work together with *D.G. Agresti* on the instrumentation being developed for remote Martian exploration as part of NASA's Exobiology and Planetary Instrument Definition and Development Programs. The instruments include Mössbauer and Raman spectrometers, designed for the purpose of identifying sedimentary minerals potentially associated with ancient life on Mars, including carbonaceous residues of microorganisms. The speaker showed results obtained with these techniques on terrestrial simulation materials, including evaporite minerals, hydrothermal precipitates, fossil kerogen and impact breccia. The constraints were also discussed for interrogation of the recorded data foreseen for the Athena Mars missions.

Manfred Schidlowski , the pioneer in exploration of biogenic carbon in the earliest Archean, gave a review of the enzymatic mechanisms causing the unique fractionation of the light carbon isotope 12C in autotrophic organisms, the manifestation of this effect in their carbonaceous remains in sedimentary rocks, and the trends toward re-equilibration with inorganic carbon containing fluids and carbonate during metamorphism. The speaker drew particular attention to the fact that such partial equilibration always has been found, as expected, to push up the d13C values of organic carbon towards more positive values. On the other hand, no metamorphic process has been observed in nature to affect inorganic carbon to generate graphite with an isotopic signature simulating a biogenic product. The metamorphically least altered chemofossils with d13C in the range -25 to -50 per mil in the oldest Archean metasediment are found to be encased in recrystallized minerals that presumably provide protection against exchange with carbonic fluids of inorganic origin. However, already the bulk-rock carbon isotope composition with d13C minima in the range of

-22 to -28 per mil measured in 1979 in the 3.75 Ga Isua banded iron formation left no doubt about its biogenic origin.

Frances Westall and her colleagues reported discovery of small (mm- to cm-sized), graphite-containing, stromatolite-like structures in uppermost strata of the ~3.4-Ga-old Hooggenoeg Formation (Onverwacht Group, Swaziland Supergroup) of South Africa. Although devoid of identifiable cellular remnants, the macroscopic structures ("microbialites") and the graphitic carbonaceous matter they contain are interpreted as microbial in origin.

E. Imre Friedmann and colleagues described experiments showing incorporation of 14C-labeled acetate into the lipid components of large numbers of diverse (but taxonomically unidentified) prokaryotes, isolated from Siberian permafrost incubated at temperatures as low as -20oC. By establishing the capability of microbes to grow at this low temperature, these studies suggest that Martian permafrost at similar temperatures may provide a suitable habitat for life.

In a stimulating presentation, *Robert Shapiro* discussed the difficulties involved in the prebiotic assembly of various types of replicator homopolymers (such as RNA, DNA, proteins, and peptide nucleic acids) from abiotic mixtures containing diverse suites of monomers. In his view, these difficulties may suggest that "life began as a metabolic network of reactions involving monomers, and that a [homopolymeric] replicator came later."

Gustav Arrhenius **(UCSD, La Jolla, USA) &** ***Bill Schopf*** **(UCLA, USA)**

[Up] [Abiotic Synthesis] [Chirality] [Replication & Catalysis] [Min. Genomes] [Exo-/Astro-Biology] [Mars Session]

[Up] [Abiotic Synthesis] [Chirality] [Replication & Catalysis] [Min. Genomes] [Exo-/Astro-Biology] [Mars Session]

Session 6 – Plenary Session on Mars

Gene McDonald **(Chair) &** ***Bruce Jakosky*** **(Co-Chair)**

The final scientific session of ISSOL '99 dealt with the environment of Mars, analyses of Mars meteorites, and future exploration of the red planet. *Michael Carr* of the U.S. Geological Survey presented the first paper, reviewing the evidence for surface liquid water on Mars during the early history of the planet. His conclusion was that there is evidence from Viking and Mars Global Surveyor imaging for sustained flows of liquid water on the surface. The evidence for large standing bodies of water is much less compelling, however, and the ancient streams may have been fed by underground springs or ice meltwater.

David Paige of the University of California at Los Angeles then described the Mars Polar Lander mission, which will arrive at Mars in December 1999. The Mars Volatiles and Climate Surveyor (MVACS) instrument payload, for which *Paige* is the principal investigator, will examine the atmosphere and soil in the south polar layered terrain, including a search for water and carbon dioxide in the surface material.

The session then concluded with two papers reporting recent results from analyses of Martian meteorites. *Everett Gibson* of NASA Johnson Space Center reviewed the original evidence presented by his group for biosignatures in ALH84001, and then described new possible biogenic signatures in Nakhla and Shergotty. These consist principally of structures observed by electron microscopy, which the Johnson Space Center group interprets as fossilized bacterial cells and biofilms.

Daniel Glavin of Scripps Institution of Oceanography then reported on recent amino acid analyses of Nakhla and of sediments from the Nile Delta, where the meteorite fell in 1911. The amino acid profiles of the meteorite and the Nile Delta sediments are very similar, leading Glavin and colleagues to conclude that the amino acids in Nakhla, and perhaps most of the organic material in the meteorite as well, are terrestrial contaminants rather than residue of Martian biology.

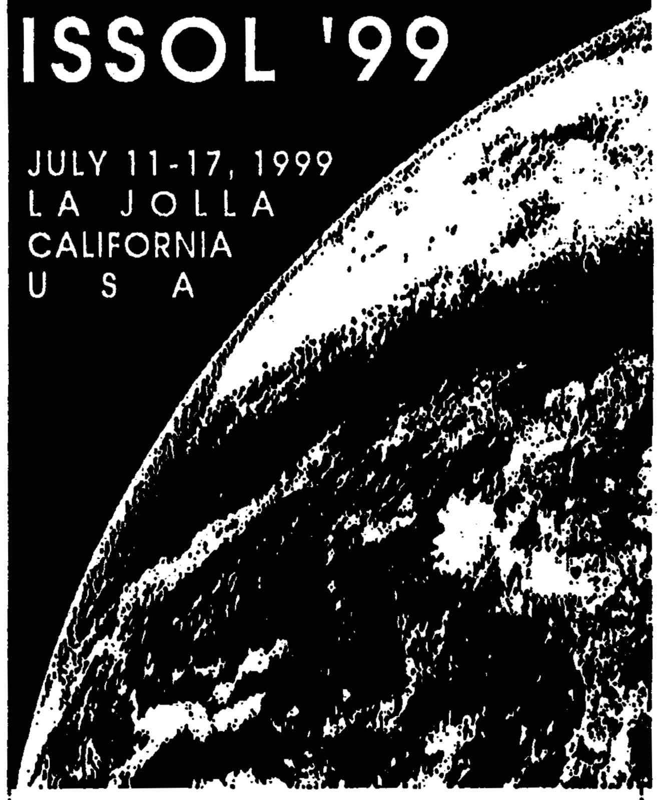
Gene McDonald (JPL, Pasadena, USA) & Bruce Jakosky (Univ. Colorado, USA)

[Up] [Abiotic Synthesis] [Chirality] [Replication & Catalysis] [Min. Genomes] [Exo-/Astro-Biology] [Mars Session]

FIRST ANNOUNCEMENT

ISSOL '99

JULY 11-17, 1999
LA JOLLA
CALIFORNIA
USA



9th ISSOL MEETING

12th INTERNATIONAL CONFERENCE ON THE ORIGIN OF LIFE

Sponsored by the NASA Specialized Center of Research and Training (NSCORT) in Exobiology

Information Availability
The primary and most up-to-date source for all information about ISSOL '99 will be the WWW site at:
http://exobio.ucsd.edu/ISSOL.htm
If you do not have access, please request email copies of the Second Announcement and Registration materials from the NSCORT office (address on reply card).

Second Announcement
The second announcement, available in November 1998, will contain instructions for preparation and submission of abstracts and posters. General information, as well as information regarding registration and hotel reservations, will also be included. Those wishing to receive this information by email or regular mail are requested to complete the pre-registration form and return it no later than October 30, 1998.

Social Activities
Cultural and social activities will be organized for participants and those accompanying them. Further details will be provided in the second announcement.

Venue
ISSOL '99 will be held at the University of California, San Diego, La Jolla, California, USA. The University campus is located approximately 15 miles from downtown San Diego and is well connected with the center of town and the San Diego Airport by public transportation. Details on reaching the campus site will be available at the WWW site.

Accommodations
Hotels and accommodations in university dorms, including low-cost housing for students will be available. Hotel and university housing accommodations will be handled by the UCSD Conference Services located at the University of California, San Diego, with information available as above.

Local Organizing Committee
The Local Organizing Committee consists of the NSCORT/Exobiology principal investigators: Gustaf Arrhenius, Jeffrey Bada, Russell Doolittle, Gerald Joyce, Leslie Orgel, Stanley Miller and Christopher Wills, as well as administrators Bill Baily and Lois Lane.

AIR MAIL

ISSOL '99
NSCORT/Exobiology Central Office
University of California, San Diego
La Jolla, CA 92093-0216

INVITATION

The 12th INTERNATIONAL CONFERENCE ON THE ORIGIN OF LIFE organized by the International Society for the Study of the Origin of Life (ISSOL) and hosted by the NASA Specialized Center of Research and Training (NSCORT) in Exobiology will be held at the University of California, San Diego, La Jolla, California from July 11 through July 17, 1999.

Studies of the origin and evolution of life are of increasing interest to the public as well as the scientific community. The aim of the conference is to integrate the most recent discoveries in astronomy, planetology, geology, paleontology, biology and chemistry into plausible scenarios for a better understanding of the origins of life on Earth and elsewhere.

The conference will permit students, teachers and researchers to obtain knowledge on the current status of research on the origins and early evolution of life. An important feature of research in this area is its strong interdisciplinary character. Each day, overview lectures and invited and contributed communications will be presented and poster presentations will be displayed.

Because of the widespread interest in the question of the origins of life, a public lecture on this topic will be presented by an internationally known scientist, Tuesday, July 13 at 7:30-9:00 p.m.

The President of ISSOL and the ISSOL '99 Organizing Committee invite you to participate in making this meeting a scientifically successful and culturally rewarding event.

Andre Brack
President,
ISSOL

Jeffrey L. Bada, NSCORT Director
Member,
ISSOL '99 Organizing Committee

The meeting is held under the auspices of
University of California, San Diego,
NSCORT/Exobiology
The Salk Institute for Biological Studies
The Scripps Research Institute
With the support of the
National Aeronautics and Space Administration

Outline of the Scientific Program
The five-day (July 11-17, 1999) scientific program will be organized in the following manner:

Overview lectures (invited) will summarize for the multidisciplinary audience the state-of the-art in the different fields of research covered by the conference:

- Abiotic Synthesis
- Origin of Chirality
- Replicating Systems
- Minimalist Genomes
- Solar System Exobiology

with a special session on Mars.

Communications (invited and contributed) will be devoted to original results in the subject matter covered.

Posters will be exhibited each day with adequate time for fruitful exchanges.

The primary source for information about the meeting is the NSCORT WWW page at:

http://exobio.ucsd.edu/ISSOL.htm

ISSOL '99
La Jolla, California
July 11-17, 1999

Fill out the WWW pre-registration form or cut and mail this form no later than October 30, 1998.

PRE-REGISTRATION FORM
Please type or use block letters.

Title: Prof. ( ) Dr. ( ) Mr. ( ) Ms. ( )

First Name: ....

Family Name: ....

....

Institution: ....

Mailing Address: ....

....

....

....

....

Phone: ....
Fax: ....
email: ....

Number of expected accompanying persons: ....

I intend to submit:

( ) a 15-minute oral presentation

( ) a poster

Area of research or approximate title:

....

....

....

....

ABSTRACT FORMS WILL BE AVAILABLE AT THE WEB SITE OR UPON REQUEST

NATURE, May 1, 1997

UNIVERSITY OF CALIFORNIA, SAN DIEGO

NASA TRAINING PROGRAM IN EXOBIOLOGY

PREDOCTORAL AND POSTDOCTORAL FELLOWSHIPS

Several predoctoral and postdoctoral fellowships are available in 1997 and 1998 at the NASA Specialized Center of Research and Training (NSCORT) in Exobiology, La Jolla, California, USA. The Center is a consortium of investigators at the University of California, San Diego (UCSD), The Scripps Research Institute at the Salk Institute for Biological Studies, and is administered through the California Space Institute at UCSD. Individuals with a PhD degree or equivalent, preferably in geochemistry, chemistry, biochemistry, or molecular biology, who have an interest in exobiology or exobiology-related research may apply. There are also fellowships available for qualified graduate students who have been accepted to an appropriate PhD program at UCSD or The Scripps Research Institute. Appointment and salary level will be commensurate with experience and determined by UC salary scales.

The program offers a unique opportunity for interdisciplinary studies related to the origins of life. The Center consists of a core facility and six laboratories under the direction of faculty members from UCSD (Gustaf Arrhenius, Jeffrey Bada, Russell Doolittle, Stanley Miller), The Scripps Research Institute (Gerald Joyce), and the Salk Institute (Leslie Orgel). Topics for research include cosmochemistry, primordial geochemistry, prebiotic chemistry, nucleic acid chemistry, RNA/protein biochemistry, peptide biochemistry, and molecular evolution.

Interested persons should send resume with a statement of research interests and the names and addresses of at least three references to Dr. Robert Tschirgi, Associate Director, NSCORT/Exobiology, University of California, San Diego, La Jolla, California 92093-0216, USA.

The University of California, The Scripps Research Institute, and Salk Institute for Biological Studies are equal opportunity/affirmative action employers.

(NW4014)E

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

Fifth Annual
Summer Student Symposium

NSCORT Exobiology Journals Club

August 19, 1997

Martin Johnson House
Scripps Institution of Oceanography
La Jolla, California

**NASA Specialized Center of Research and Training (NSCORT)
Exobiology**

Gustaf Arrhenius—Scripps Institution of Oceanograpl
Jeffrey Bada—Scripps Institution of Oceanography
Russell Doolittle—University of California, San Diegc
Gerald Joyce—The Scripps Research Institute
Stanley Miller—University of California, San Diego
Leslie Orgel—Salk Institute for Biological Studies
Christopher Wills—University of California, San Die

Program of Papers Presented at the Fifth Annual Exobiology Summer Student Symposium

NSCORT Exobiology Journals Club

August 19, 1997

Martin Johnson House
Scripps Institution of Oceanography
La Jolla, California

Chairs: Karen Brinton, Matthew Levy and Kevin Nelson

Time	Author and Title		Page
12:00	LUNCH		
1:00	**Dr. James Lyons**[1] Delivery of organics by impacts on the primitive Earth: lessons from the K/T and Comet Shoemaker-Levy 9 impacts	Keynote Speaker	3
1:20	**Alice Ormsbee** Carbon isotope fractionation and composition of spark discharge reactions	Miller (UCSD)	5
1:40	**John Makevich** A study of the total organic carbon and amino acid concentrations in Antarctic and Greenland ice	Bada (SIO)	6
2:00	**Jacob Handy** Computer analysis of the aminoacyl-tRNA synthetase sequences: a study of their origins and divergence	Doolittle (UCSD)	7
2:20	BREAK		
2:30	**Danny Glavin** Amino acid sublimation and survival during exogenous delivery	Bada (SIO)	8
2:50	**Carlos Estévez** Prebiotic chemistry of cyanoacetaldehyde	Miller (UCSD)	10

[1]NSCORT Postdoctoral Fellow

[2]Institute of Theoretical Chemistry, University of Vienna
[3]Department of Biology, Yale University (former NSCORT Postdoctoral Fellow)

Sixth Annual
Summer Student Symposium

NSCORT Exobiology Journals Club

August 19, 1998

Martin Johnson House
Scripps Institution of Oceanography
La Jolla, California

NASA Specialized Center of Research and Training (NSCORT)
Exobiology

Gustaf Arrhenius—Scripps Institution of Oceanography
Jeffrey Bada—Scripps Institution of Oceanography
Russell Doolittle—University of California, San Diego
Gerald Joyce—The Scripps Research Institute
Stanley Miller—University of California, San Diego
Leslie Orgel—Salk Institute for Biological Studies
Christopher Wills—University of California, San Diego

Program of Papers Presented at the Sixth Annual Exobiology Summer Student Symposium

NSCORT Exobiology Journals Club

August 19, 1998

Martin Johnson House
Scripps Institution of Oceanography
La Jolla, California

Chairs: Daniel Glavin and Igor Kozlov

[1]NSCORT Graduate Student Fellow

Time	Author and Title		Page
3:10	**Joakim Bebié** Reduction of molecular nitrogen from aqueous $Fe(OH)_2$ suspensions and its relevance to prebiotic chemistry	Arrhenius (SIO)	12
3:30	**Deborah Bernsen** Evolution of mitochondrial ADP/ATP carrier proteins	Doolittle (UCSD)	13
3:50	**Elizabeth Thomas** Microorganisms and the evolution of evolvability	Wills (UCSD)	14
4:10	ADJOURN		
	NSCORT Exobiology Summer Fellows 1992-1998		16

Seventh Annual

Summer Student Symposium

NSCORT / Exobiology Journals Club

August 25, 1999

San Francisco/Santa Cruz Room, Price Center
University of California, San Diego
La Jolla, California

NASA Specialized Center of Research and Training (NSCORT)
Exobiology

Gustaf Arrhenius—Scripps Institution of Oceanography
Jeffrey Bada—Scripps Institution of Oceanography
Russell Doolittle—University of California, San Diego
Gerald Joyce—The Scripps Research Institute
Stanley Miller—University of California, San Diego
Leslie Orgel—Salk Institute for Biological Studies
Christopher Wills—University of California, San Diego

Program of Papers Presented at the Seventh Annual NSCORT / Exobiology Summer Student Symposium

NSCORT / Exobiology Journals Club

August 25, 1999

San Francisco/Santa Cruz Room
Price Center
University of California, San Diego

Chairs: Daniel Glavin and Kevin Nelson

Time	Author and Title		Page
1:00	**Gene D. McDonald** Jet Propulsion Laboratory, Pasadena *Preservation of Biomolecules on Mars*	Keynote Speaker	2
1:30	**Michael McGauley** *Sampling of amino acids from saltwater using sublimation*	Bada (SIO)	3
1:55	**Jennifer Safier** *Sublimation of Organic Compounds from Humic Acid*	Bada (SIO)	5
2:20	BREAK		
2:45	**Ryan D. McAllister** *Abolishing "Percent Similarity" to Determine Homology in Aligned Protein Sequences: A computer-based study*	Doolittle (UCSD)	6
3:10	**Vincent Dion** *The Prebiotic Stability of 5-Methylcytosine*	Miller (UCSD)	7
3:35	**Ryan Kimble** *Controlling DNA Expression Through Mutational Mechanisms*	Wills (UCSD)	8
4:15	BBQ Dinner		
	NSCORT Exobiology Summer Fellows 1992-1999		9

Eighth Annual

Summer Student Symposium

NSCORT / Exobiology Journals Club

August 29, 2000

Room 100 Endurance Hall
Scripps Institution of Oceanography
University of California, San Diego
La Jolla, California

NASA Specialized Center of Research and Training (NSCORT) in Exobiology

Gustaf Arrhenius—Scripps Institution of Oceanography
Jeffrey Bada—Scripps Institution of Oceanography
Russell Doolittle—University of California, San Diego
Gerald Joyce—The Scripps Research Institute
Stanley Miller—University of California, San Diego
Leslie Orgel—Salk Institute for Biological Studies
Christopher Wills—University of California, San Diego

Program of Papers Presented at the Eighth Annual NSCORT/Exobiology Summer Student Symposium

NSCORT/Exobiology Journals Club

August 29, 2000

Room 100, Endurance Hall
Scripps Institution of Oceanography
University of California, San Diego

Chairs: Danny Glavin and Oliver Botta

3:35 **Greg Lang** Bada (SIO) 9

Design and Construction of an Interactive Web Site as Part of the Education and Public Outreach Program for the Mars Organic Detector (MOD)

4:15 BBQ Buffet at meeting site

Invited abstract submitted by NASA Planetary Biology Intership Fellow:

John Finarelli Arrhenius (SIO) 11

Carbon Phase Abundance in the Isua Supracrustal Belt, Early Archean (~3.7 – 3.8 Ga), western Greenland: Implications for Early Life on Earth

NSCORT Exobiology Summer Fellows 1992-2000 13

Ninth Annual

Summer Student Symposium

NSCORT / Exobiology Journals Club

August 23, 2001

Room 100, Endurance/Vaughan Hall
Scripps Institution of Oceanography
University of California, San Diego
La Jolla, California

NASA Specialized Center of Research and Training (NSCORT) in Exobiology

Gustaf Arrhenius—Scripps Institution of Oceanography
Jeffrey Bada—Scripps Institution of Oceanography
Russell Doolittle—University of California, San Diego
Gerald Joyce—The Scripps Research Institute
Stanley Miller—University of California, San Diego
Leslie Orgel—Salk Institute for Biological Studies
Christopher Wills—University of California, San Diego

Program of Papers Presented at the Ninth Annual Summer Student Symposium

NSCORT/Exobiology Journals Club

August 23, 2001

Room 100, Endurance/Vaughan Hall
Scripps Institution of Oceanography (SIO)
University of California, San Diego

Chairs: Oliver Botta and Gerhard Kminek

Time	Author and Title	NSCORT Laboratory	Page
2:00	**Opening Remarks** **Bill Baity**	Associate Director	
2:15	**Matthew Pagel** *The Antibiotic Selection of "Mutator" Strains of E. coli*	Wills (UCSD)	2
2:45	**Dr. John Reader** *Catalytic Activity of a Binary Informational Macromolecule*	Joyce (TSRI)	6
3:15	**Prof. Jeffrey Bada** *Bring'm Back Alive: Searching for Life on Mars in the Coming Decade*	Keynote Speaker	7
NSCORT Exobiology Summer Fellows 1992-2001			8
4:00	**Buffet at Surfside, SIO**		

NSCORT Exobiology Summer Fellows 1992-2001

Name	PI Laboratory	Summer
Pagel, Matthew	Wills	2001
Breitbart, Mya	Arrhenius	2000
Czodrowski, Paul	Doolittle	2000
Dion, Vincent	Miller	2000
Lang, Greg	Bada	2000
Pagel, Matthew	Wills	2000
Finarelli, John (NASA PBI Fellow)	Arrhenius	2000
Dion, Vincent	Miller	1999
Kimble, Ryan	Wills	1999
McAllister, Ryan	Doolittle	1999
McGauley, Michael	Bada	1999
Safier, Jennifer	Bada	1999, 1998
Alessandro, Airo	Orgel	1998
Bebié, Joakim	Arrhenius	1998
Bernsen, Deborah	Doolittle	1998
Borquez, Eduardo	Miller	1998
Casini, Carolina	Bada	1998
Handy, Jacob	Doolittle	1998, 1997
Thomas, Elizabeth	Wills	1998
Catalina, María	Arrhenius	1997
Estévez, Carlos	Miller	1997
Glavin, Daniel	Bada	1997, 1996
Makevich, John	Bada	1997
Ormsbee, Alice	Miller	1997
Maughan, Quinn	Miller	1996
Nelson, Kevin	Miller	1996, 1995

NSCORT Exobiology Summer Fellows 1992-2001

Scott, Laura	Bada	1996
Dacks, Joel	Miller	1995
Eppler, Aaron	Bada	1995
Hamilton, Healy	Bada	1995
Khalsa, Guru	Miller	1995
Levy, Matthew	Miller	1995, 1994
Zhang, Shibin	Arrhenius	1995, 1994
Catlos, Elizabeth	Bada	1994
House, Christopher	Miller	1994, 1993
Larralde, Rosa	Miller	1994
Rhew, Robert	Bada	1994
Balasingam, Kishan	Arrhenius	1993
Lloyd, Pat	Bada	1993
Woiwode, Thomas	Bada	1993, 1992
Cozzatti, Jean-Paul	Miller	1992
Foster, Krishna	Thiemens	1992
Frutos, Annabelle	Arrhenius	1992
Mojzsis, Stephen	Arrhenius	1992
Rice, Abraham	Miller	1992
Ring, Ken	Arrhenius	1992
Robertson, Michael	Miller	1992
Warden-Owen, Lisa	Arrhenius	1992

Chem 122 - Biochemical Evolution
Winter Quarter, 1997
M W F 2-3 PM
201 Center Hall

LECTURE SCHEDULE

Jan 6	Introduction. On the abundance of life in the universe.
Jan 8	The big bang and the origin of the elements.
Jan 10	Formation of the solar system
Jan 13	The primitive atmosphere.
Jan 15	Prebiotic synthesis - amino acids.
Jan 17	Prebiotic synthesis - purines, pyrimidines, sugars.
Jan 20	HOLIDAY
Jan 22	Other prebiotic syntheses. Stability of organic compounds.
Jan 24	Carbonaceous chondrites and interstellar molecules.
Jan 27	Organic synthesis on other planets. Evidence for life on Mars
Jan 29	Polymerization processes.
Jan 31	Template polymerizations.
Feb 3	Origin of optical activity.
Feb 5	Primitive enzymes and RNA enzymes.
Feb 7	MIDTERM
Feb 10	Transfer RNA. Membranes
Feb 12	Self-replicating systems.
Feb 14	Precambrian fossil record.
Feb 17	HOLIDAY
Feb 19	History of O2 in the atmosphere. Origin of biochemical synthesis.
Feb 21	Primitive fermentation schemes. Methane bacteria.
Feb 24	Origin of photosynthesis
Feb 25	Nitrogen fixation and nitrate metabolism.
Feb 28	Origin of citric acid cycle. Origin of eukaryotic organisms.
Mar 3	Introduction to protein evolution. Origin of the genetic code.
Mar 5	Gene duplication.
Mar 7	Calculation of homologies.
Mar 10	Examples of protein evolution.
Mar 12	Examples of protein evolution.
Mar 14	Review and Discussion
Mar 18	FINAL 3-6 P.M.

nature

A dip in the soup, with a pinch of salt

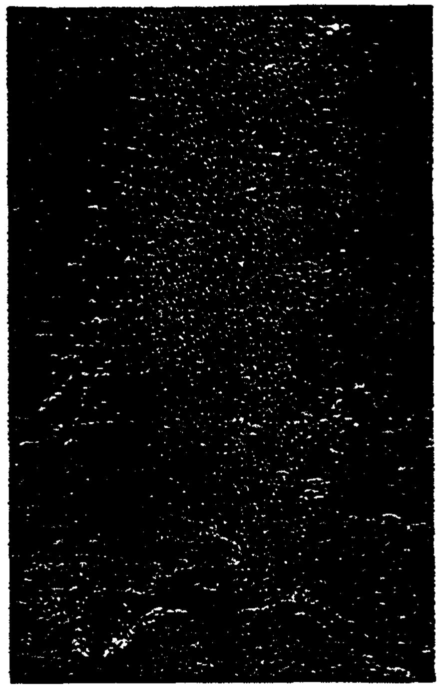
The Spark of Life: Darwin and the Primeval Soup
by Christopher Wills & Jeffrey Bada
Perseus: 2000. 288 pp. $27, £16.50

William J. Hagan

Conventional images of the early Earth portray a hostile planet with violent displays of lightning and volcanic eruptions. To these pyrotechnics, one might add the occasional asteroid impact and the smoky plumes of hydrothermal vents. Beyond providing melodrama for artistic depictions (including those reproduced in this book by Bill Hartmann of the University of Arizona), such phenomena suggest possible energy sources that may have played a role in the origin of life. In *The Spark of Life* Christopher Wills and Jeffrey Bada review our understanding of the origins of life for the informed general reader.

There has been a lot of interest in evaluating the relative importance of different routes towards the organic precursors of the first life. One strategy is to assess the fluxes of energy on the modern Earth, then to estimate the evolution of these energy sources through time, and finally, to determine the relative rates of formation and decomposition of potentially prebiotic compounds. Although the first task should be the most straightforward, the compilation of energy inputs for the modern Earth has been complicated by shortage of data and by propagation of values from the older literature. Chris Chyba and Carl Sagan pointed out in 1991, for example, that the rate of terrestrial lightning dissipation is about 20-fold lower than previous estimates.

Controversy (often acrimonious) has also centred on the role of hydrothermal vents in prebiotic synthesis, since their discovery two decades ago. Although the large temperature gradients and hydrogen-rich conditions make them attractive to those (called "ventists" in this book) who believe that vents played a major role, critics, including one of the authors, have stressed the sterilizing effect of marine cycling through these hot regions. Agreement has been hampered both by the inaccessibility of these deep environments, and by the difficulties of laboratory simulation. The latter challenge is being addressed by several research groups, whose data it is hoped will confirm the results of thermodynamic calculations. Even if vents did facilitate the formation of small biomolecules, the transient lifetime of particular smokers makes it unlikely that a sustained sequence of reactions leading to protobionts could occur there; these organic sources may have simply augmented the overall concentration of the primordial soup.



FRED MCCONNAUGHEY/SPL

Murky birth? 'Ventists' believe that the precursors to life may have originated in hydrothermal vents.

The role of sunlight in prebiotic synthesis has become less fashionable, but any ranking of energy sources always puts ultraviolet and visible radiation at the top. Calculating the distribution of sunlight on the early Earth is complicated by the fact that, during the Sun's T-Tauri stage 4.6 billion years ago, its output was about 30% dimmer and ultraviolet light was more intense. Nevertheless, the total flux at wavelengths less than 230 nanometres 4.2 billion years ago is comparable to that reaching the edge of the Earth's atmosphere today, and this energy could have played a role in the formation of small precursors such as formaldehyde. Although longer wavelengths would probably have penetrated to the surface (especially in the absence of an ozone shield), solar-driven processes in this spectral regime have been less extensively investigated in the context of the origins of life.

The Spark of Life takes a sceptical view of current models for the molecular precursors of life. As an example, the transport of organic materials to the early Earth by interplanetary dust particles, for which frictional heating would be small, yields the 'bad news' that only one microgram per litre of amino acids would be dissolved in the primordial ocean. Yet such calculations clearly depend not only on the delivery rate, but also on the (highly variable) half-lives of the organic compounds in these micrometeorites. At present, we lack enough analytical data to inform such estimates, which could yield much higher concentrations of robust molecules. Moreover, a dilute soup would be advantageous in its protection from photochemical decomposition, and most workers agree that some adsorption and/or partitioning process would have been essential for subsequent catalysis.

The authors provide an excellent and compellingly written overview of the spontaneous-generation controversy and other historical themes as they relate to the emergence of life. The coverage is not comprehensive, but is lively and includes a sampling of topical approaches, from meteorite analysis to the study of subsurface microorganisms.

Neither author is an organic chemist: Wills is a geneticist at the University of California at San Diego, and Bada is a geochemist and exobiologist at the Scripps Institution of Oceanography at La Jolla, California. This background is evident in occasional lapses, such as the claim that "RNA, which probably appeared before DNA, uses the more stable molecule uracil instead of cytosine [thymine?]". (For it is thymine in DNA, not cytosine, that forms less stable adducts than uracil — as occurs during photohydration — which could explain this base change when DNA arose in evolution.) Errors of attribution arise in the discussion of Leslie Orgel's 'life on the rocks' scenario for the synthesis of RNA oligonucleotides — although Orgel did develop the theory behind this process, he relied on the explicit collaboration of James P. Ferris, whose laboratory has pioneered the study of clay-catalysed oligomerizations of activated nucleotides. Although a popular account may be allowed some licence in the assignment of credit, the authors are notably more generous to co-workers when they are indigenous to southern California.

Nevertheless, this book provides a highly readable survey of the historical prelude to the study of the origins of life, as well as selected areas of current research, including the search for extraterrestrial life. ■

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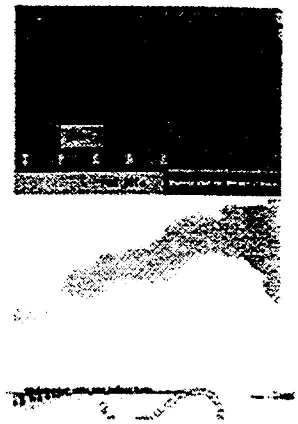
Ref. 14

Life is in the bag, or is it?



The Spark of Life
by Christopher Wills and Jeffrey Bada
Perseus · May 2000
Hardback £18.40/$27

Magdalena Zernicka-Goetz

We are all stirred in one way or another by the 'spark of life', an emotive topic that has occupied man throughout the ages. How can we contemplate a world of some 4 billion years ago at the very creation of the earth and the stage upon which life began? This is perhaps guarded by our own experiences. My concepts of life's origins were shaped in the 1980s as a student with a particular leaning towards developmental biology and a curiosity about life. I therefore approached this book wanting to know whether the ideas that were prevalent at that time still hold sway, and how they have evolved over the past twenty years. Wills and Bada provide the overview that I had hoped for in an entertaining and captivating text that held my attention.

At the core of the book lie the ideas, espoused by Oparin in the 1920s, that the organic compounds necessary for life could have been formed through natural chemical processes upon the early earth. These ideas received support from the classical experiment of Miller who, under the tutelage of Urey, synthesized organic molecules including many amino acids by sending an electric spark though a mixture of reducing gases meant to simulate the atmosphere of the early earth. Although others provided variations upon this experimental theme, Miller's findings remain perhaps the most significant step towards the creation of life in the test tube. From this core, the book follows two paths. First, from the bottom up, exploring how simple substances can end up as entities with some properties of life. Second, from the top down, demonstrating how the genetic information carried by modern life can be dissected into its essential components.

The bottom-up journey begins with the creation of the earth itself, and provides a vivid description of the Hadean environment that had to spawn the first organic molecules. Wills and Bada's writing conjures an image of an earth with a moon much closer than today, producing dramatic tides of the oceans, and a chilly sun seen through mists of corrosive gases. These environmental themes lead to a darwinian-like explanation of how early conditions could have served as a means of separating and selecting organic molecules into groups with similar properties. The sands of the early beaches are imagined as giant chromatographic systems, yielding layers of 'slimy molecules' with differing affinities for other components of the prebiotic soup. In effect, each layer could serve as a huge 'pre-cell', within which particular chemical reactions would be favoured. Add to the slime layers the provision of catalytic properties by mineral deposits to which these early molecules could tenaciously cling, and soon we have an imagined environment in which all kinds of experimental chemistry are in force in this ancient laboratory on the beach.

How many life-like chemical processes could these pre-cell layers accomplish? Did life arise first as mixtures of molecules able to carry out simple metabolism, or was the first critical step the creation of a self-replicating molecule? The authors consider RNA as a present-day molecule that can have both replicative and enzymatic properties. But could this sensitive molecule survive in the prebiotic world? Recently, peptide nucleic acids in which the phospho-sugar chain is replaced by peptide linkages have been proposed as stable prebiotic alternatives to RNA. Whether or not these molecules existed in those times is still unclear. Once, however, molecules like these were formed, then perhaps the 'slime layer' provided them with a host environment in which darwinian selection could start to take place.

Such uncertainties bring us to the top-down path. It approaches evolution through the exchange of chunks of genetic information between bacteria and archaea, and through the importance of establishing symbiotic relationships between organisms. The latter is evidenced by our own acquisition of bacterial cells in the form of mitochondria. The power of this section lies in the descriptions of the genealogies of genes themselves by searching for fundamental commonalties between today's life forms and by using the existing fossil record to establish the time scales of evolutionary processes. We are left with a retrospective of evolution that fades disquietingly into the unknown past without making a final link to life's molecular origins. The authors use this to convey a sense of excitement about the future of this field and of the challenges of making these connections. So it seems that our understandings of life's origins are rather like the molecules of the primitive cell — they are not yet 'in the bag'. However, one day they should evolve.

Throughout the book Wills and Bada capture the reader by presenting a balanced view of past and ongoing debates. They entertain by not only giving a lively description of the 'spark of life', but also by conveying the sparkle of its investigators and the nature of the scientific process. These two professors have written a book that reads like a novel, and one would be happy to have them educate one's children. The topics of the chapters were carefully chosen, with perhaps the one exception of the first chapter, a broad description of pre-twentieth century views of life's origins. Readers are recommended to persist through these first 30 pages, as having done so they will be rewarded. The authors cite Haldane — "The problem of describing the origin of life is curiously like its actual origin. In each case it seems likely that a number of attempts were made and almost all of them did not work. Natural selection eliminated them". This book should survive such selection. ☐

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Nov 30, 2000

Origin of life? Science seeks hard answers in San Diego

Neil Morgan

When Jeffrey Bada went on the Art Bell coast-to-coast talk show to talk about his book, so many phone-ins stacked up that he stayed on the line until two hours after the show ended. He gave up after twin sisters in Louisiana -- it was 4 a.m., their time -- called to say he was headed for hell but they stood ready to save his soul. A graying marine chemist at Scripps Institution of Oceanography, Bada has helped to make San Diego a frontier of exobiology, which probes the most basic of mysteries: the origin and distribution of life within the universe. Charles Darwin's theory of evolution is the bedrock of his work. Bada believes life started through Darwinian processes involving self-replicating chemicals. But creationists still abound. NASA has allotted $1 million a year to San Diego for research in exobiology since 1993, when it designated Bada, four San Diego colleagues and their 20 graduate students as a NASA Specialized Center of Research and Training. Bada's colleagues are major figures of science: Gustaf Arrhenius of Scripps Institution of Oceanography, Gerald Joyce of Scripps Research Institute, Stanley Miller of UCSD and Leslie Orgel of Salk. Their work in this far-out discipline has drawn colleagues to San Diego from around the world. Many gathered at UCSD last year for the ninth meeting of the International Society for the Study of the Origin of Life. It included a public lecture by the theoretical physicist Freeman Dyson, whose interests extend to cosmology and space travel. Bada is co-author, with UCSD biologist Christopher Wills, of "The Spark of Life: Darwin and the Primeval Soup." It has been widely reviewed, and Oxford University Press will publish a paperback edition in March. "I encounter hostility a lot," Bada says. "You can't win an argument with people who question the whole idea of trying to investigate the origin of life. The basic premise of science is that things are testable. Creationists assume everything on the subject is already understood." If we are to find life in the solar system, Bada says, "Mars is our only hope. We used to fantasize about life on our moon, but we know now it is sterile. If life ever existed on Mercury and Venus, it was obliterated by the heat. Some people still fantasize about making Mars the next colony of man." NASA's loss of its Mars polar lander a year ago (due to one missing line of code, he believes) disappointed Bada. A subsequent Mars mission was to carry an instrument he designed to detect traces of amino acids on Mars as a clue to whether life ever existed there. "I'll have to wait to have my experiment on Mars," he says. "It would be glorious to prove the origin of life took place somewhere else in space, too. What distinguishes life is its ability to transmit information from one generation to another. It requires a system incapable of perfect replication. Naked molecules replicating imperfectly would be, to us, a sign of life." Other scientists argue that metabolism came before life as a self- sustaining chain reaction of molecules. "But that's not life," Bada says. "That's chemistry." The surge in genetic research has pushed exobiology along. DNA and RNA are "far too complex to have risen spontaneously."

SAN DIEGO UNION TRIBUNE PUBLISHING COMPANY
Nov 30, 2000

Origin of life? Science seeks hard answers in San Diego (Page 2)

He expects scientists will "replicate life in a test tube, in some fashion, this decade. Whether that's relevant to life is a different question. What was the very first living entity? Can we replicate that? Maybe." Neil Morgan's column appears Sundays, Tuesdays and Thursdays. He can be reached by e-mail at neil.morgan@uniontrib.com.

Cell, Vol. 105, 307–330, May 4, 2001, Copyright ©2001 by Cell Press

Book Reviews

It Takes Two to Tango: Information, Metabolism, and the Origins of Life

The Emergence of Life on Earth: A Historical and Scientific Overview
By Iris Fry
New Brunswick, NJ: Rutgers University Press
(2000). 327 pp. $55.00

The Spark of Life: Darwin and the Primeval Soup
By Christopher Wills and Jeffrey Bada
Cambridge, MA: Perseus Publishing
(2000). 291 pp. $27.00

It might be thought that the discovery of the universal mechanisms basic to the essential properties of living beings would have helped solve the problem of life's origins. As it turns out, these discoveries, by almost entirely transforming the question, have shown it to be even more difficult than it formerly appeared.
—Jacques Monod, *Chance and Necessity*, 1974

For hundreds of years the origin of life was thought to be well understood and did not pose any problem to naturalists and lay persons alike. Interestingly, doubts began to rise with the growth of biological knowledge, and the question became a complete mystery, especially at the end of the nineteenth and the beginning of the twentieth century. (Fry, p. 1)

You would not put a fox in charge of the hen house, so why ask a molecular biologist about the origin of life? Remember, these are the people who brought you the Central Dogma that life *is* information flow: DNA makes RNA makes protein. As a group, they were not enthusiastic about the Krebs cycle; the Embden-Myerhof pathway appeared only briefly on their radar screens, probably during a midterm or final exam. Nucleotide metabolism was an unavoidable nuisance required for the above-mentioned dogmatic activities. Glycolysis, oxidative phosphorylation, and photosynthesis were just ways of generating petty cash called ATP; the real fun was spending it. Yet some of these people who barely got through introductory biochemistry have now gotten into the habit of telling you how life began. Must you believe them? Not necessarily, say the authors of these books.

As Fry points out in her scholarly, comprehensive, and down-to-earth book, *The Emergence of Life on Earth: A Historical and Scientific Overview*, the big question regarding the origin of life was framed by a mathematician: Should we conceive of "life" as the flow of information (as Schrödinger and the molecular biologists would have you believe) or the flow of metabolites (as Wächtershäuser, de Duve, Cairns-Smith, and many other "metabolists" have argued)? Fry puts it succinctly:

> Contrary to Schrödinger's focus, [John] Von Neuman's logical analysis led him to claim that life is not one thing but two, metabolism and replication. (Fry, p. 151)

Wills and Bada agree that this duality has fueled many of the most ferocious debates regarding the origins of life, and has led otherwise broad-minded people to retreat into opposing camps:

> Thinkers about the origin of life have wrestled, with varying degrees of success, with the question of how the first organisms could have acquired [the minimal essential properties that distinguish a living system from inanimate nature]. These thinkers can be roughly divided into those who believe that genes came first and those who believe that life must have started with metabolism. (Wills and Bada, p. xviii)

Evidently, the chicken and the egg need an update. In the dark ages before 1981, when proteins were the only known catalysts, we asked a simple but unanswerable question: Which came first—proteins or nucleic acids? With the discovery of catalytic RNA, and the realization that RNA could serve both as replicase and as genome, the original question was replaced by a new and equally perplexing one: How did the first functionally complex RNAs arise? The Urey/Miller experiment in 1953 provided a stunning proof-of-principle that simulated prebiotic chemistry could generate biologically interesting molecules, but progress since then has been disappointing, and plausible prebiotic pathways have not been identified for the synthesis of nucleic acids, let alone the lipids that are essential for cellularization. Thus it is beginning to look like molecular biologists put too much faith in the nutritional value of the primordial soup. Or, as de Duve puts it, "I cannot accept the view of an RNA world arising through purely random chemistry" (quoted by Fry, p. 197).

So which came first—RNA or metabolism? Maybe both. The notion of "scaffolding" was first clearly articulated by Graham Cairns-Smith in 1985: "...before the multitudinous components of present biochemistry could come to lean together they had to lean on something else" (quoted by Fry, p. 185). A Roman arch is constructed by setting stones on a wooden scaffold; the keystone is inserted last, and the arch becomes self-supporting. The scaffold is then dismantled, and all clues regarding construction are lost. If a Roman arch is an apt metaphor for the origins of life, we are in trouble. As Monod foresaw in 1974, the problem is only getting worse; although some molecular biologists are under the impression that RNA solves most of the problems, and some chemically minded biologists are under the impression that metabolism could be self-sustaining in the absence of any genetic system, there is currently no reconciling these camps. Scaffolding—however vague the term or elusive the data—may be our only hope.

Apart from fundamental agreement on the duality of life, the two books are light years apart in tone, style, and intended audience. *The Spark of Life* is a wonderful read and a perfect gift for friend, family, or colleagues who are even mildly curious about the origins of biology. The writing is graceful, the anecdotes charming, and the illustrations richly evocative; each chapter can be savored independently; little or no chemistry or biology is required to enjoy the romp; the arguments are so casual that you can dabble in the book any time of day or night (breakfast, beach, airport, bed, etc.); and you get a painless panoramic view of the major historical and scientific issues concerning the origin of life.

Wills (a biologist) and Bada (a chemist and exobiologist) had a lot of fun writing *The Spark of Life*, and you can have fun reading it. Unlike scholars who hide behind a scrim of objectivity, Wills and Bada freely confess to enjoying themselves. For example, "It is amazing in retrospect that the Earth was neither too hot nor too cold for life to appear" (p. 80). Wills and Bada also love a good fight, and do not pull punches. Sidney Fox's infamous "proteinoids" (the result of cooking amino acids under high dry heat) are discussed under the rubric "False Starts in the Move Toward Greater Complexity" (Wills and Bada, p. 52).

Nor are Wills and Bada afraid to poke fun at improbable experiments too readily accepted as gospel. They tease the chemists,

> Orgel and others have used nasty-sounding compounds such as methylimidazolide and carbonyldiimidizole as the activation reagents [for simulated prebiotic chemistry]. These reagents would cerainly not have been present in the primordial soup. How, in their absence, might the subunits have become activated? (Wills and Bada, p. 103)

as well as the molecular biologists,

> Our hunch is that the molecular biologist's dream of a simple, entirely self-replicating molecule emerging on its own from the primoridal soup is an unlikely mechanism for the origin of life. Whatever the mechanism... it must surely have been a cooperative enterprise involving more than one type of molecule... (Wills and Bada, p. 130)

and even score a direct personal hit for reasons that only later become apparent,

> Incautious investigators can also be parboiled, as happened to Cyril Ponnamperuma when the apparently solid crust near the Icelandic pool he was investigating collapsed suddenly. (Wills and Bada, p. 175)

Unlike *The Spark of Life*, *The Emergence of Life on Earth* is cold sober, methodical, comprehensive, almost devoid of illustrations, and intellectually unforgiving. The prose and arguments are dense; the more chemistry and biology you know, the better; and the text has the heft of a monograph or doctoral dissertation instead of a birthday present. Thus I was genuinely surprised, and pleased, to find the book winning me over, page by page, precisely because *Fry never stoops to conquer*. Making no effort to appeal, she allows the intrinsic fascination of the science to speak for itself. This low-key (some might say no-key) approach turns out to be a rare treat in our overhyped, oversold, overly solicitous world. Her book rewards by giving you a generous return on your investment of time and effort; the pleasure comes from learning, not from entertainment. For example, we learn that Darwin, who was right about just about everything else, did not believe that evolution as he envisioned it (descent with modification) could explain the origin of life. Indeed, he declared in a letter after publication of *The Origin of Species* that "it is mere rubbish, thinking at present of the origin of life" (Fry, p. 55). This was certainly true in the 1860s, and we can only hope that it ceased to be true with the discovery of catalytic RNA in the early 1980s.

Yet despite disparate styles and approaches, these two books have something else in common. Nobody would ever dare to say, in a book about the origin of life, that the answers may always be out of reach. A book of this kind must engender and sustain our hopes that someday, somehow, we will know more about how life emerged from nothingness. As Wills and Bada put it in their Introduction,

> Arguments about the origin of life tend to have this strange recursive quality, circling maddeningly around the problem without ever quite coming to grips with it. We are going to try to break this circle. (p. xix)

It is hardly surprising that Wills and Bada fail to "break this circle" (who has succeeded?) but they do offer a kind of solace. As Wills and Bada see the origin of life game, biologists look backward from the actual living present to the distant imaginary past (a "top-down" approach) while chemists look forward from an imagined inanimate past to the earliest imaginable living organisms (a "bottom-up" approach). The biologists are on more solid ground, but mainly because the most difficult problems are safely out of sight. Invoking the famous image of the Golden Spike, driven near Ogden, Utah in 1869 to commemorate completion of the first transcontinental railroad, Wills and Bada write,

> We predict that sometime early in this century, the top-down and bottom-up lines of investigation will indeed manage to meet. Whether there will be a golden spike ceremony to mark the occasion, with the successful teams shaking hands and grinning at the camera, remains to be seen. (p. 58)

Fry is a gradualist, not a millenialist, and offers a different kind of solace. She believes that science moves slowly, but inexorably, toward the truth. Just don't hold your breath.

Alan Weiner
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Seattle, Washington 98195

SPACE: The Final Frontier

MARS

THE NEXT STEP

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NSCORT/EXOBIOLOGY

2002 FINAL REPORT
(NASA NAG 5-4546)

PI PROGRESS REPORTS AND PUBLICATIONS

AFFILIATE PUBLICATIONS

2001-2002 Progress Report - Gustaf Arrhenius

Support from this grant has contributed to funding our research on two problems. One involves attempts to model the abiotic formation of simple source compounds for functional biomolecules, their concentration from dilute state in the hydrosphere and, in several cases, surface induced reactions to form precursor monomers for bioactive end products (1-5). With partial funding from this grant, additional support has been drawn from Grant NAG5-10667 for the research objectives reported on here. Results obtained are placed in the context of preceding and current publications also by other contributors

Because of the pervasiveness and antiquity of phosphate based biochemistry and the autocatalytic activity of p-RNA (45 a, b) we are exploring the hypothesis of a nucleic acid based world as an early stage in the emergence of life. This concept is now rather generally considered, but has been questioned due to the earlier lack of a successful scheme for the spontaneous formation of ribose phosphate, the key backbone molecule in RNA or, lately, of threose phosphate based TNA (13a,b). This latter, structurally and geosynthetically simpler nucleic acid analog, is of particular evolutionary interest since it, in contrast to pyranosyl-RNA or hexose based analogs, pairs strongly with the present-day form of RNA.

The commonly raised, but now obsolete geosynthetic argument against formation of the various forms of nucleoside phosphates has been based on the weakness of an earlier proposed pathway through the formose reaction. This relies on the autocatalytic formation of sugars and sugar derivatives by aldolization, initially of formaldehyde. The biogeochemical improbability of this process has several roots. One derives from the fact that the reaction proceeds at a constructive rate only under naturally improbable conditions (20). Second, it is non-selective and leads to a large variety of aldoses, ketoses and sugar alcohols with only miniscule fractions of potentially bioactive compounds such as ribose. Furthermore, unprotected sugars have a short lifetime against hydrolysis, making them unlikely as participants in biogenic processes (21). Finally, dilution and lack of plausible selective and effective concentration mechanisms imperil most prebiotic schemes, including the formose reaction when invoked in this context.

An objective of our research has been to establish geochemically acceptable solutions to these problems. Progress has been achieved by demonstrating probable sources in nature of activated (condensed) highly soluble and strongly sorbed and thereby concentrated phosphates (1,2), effective phosphorylation mechanisms and rapid condensation of aldehyde phosphates to form tetrose- and ribose phosphates in high yield (6,7) Of the simple aldehydes, glycolaldehyde provides a source for condensed aldehyde phosphates. It is produced in geochemically reasonable (neutral) atmospheres, as shown in the classical experiments by Loeb (22) modeling planetary electric discharge reactions.

A remaining uncertainty has been how highly dilute solutions in the hydrosphere of these uncharged aldehydes (or for that matter any uncharged molecules invoked in prebiotic chemistry) could have been selectively brought to sufficiently high concentration to permit further reaction, including charging by phosphorylation. A potential solution to this problem is offered by our recent experimental results (14). These show that sulfite ion, an abundant product in volcanic exhalates and efficiently sorbed in mineral interlayers, attracts aldehydes from dilute solution by complex formation, placing them in contact with reactive phosphate species that share the sorption sites in the expandable interlayer. The subsequent phosphorylation step has not yet been demonstrated experimentally; it is expected to occur upon removal of the sulfite in equilibrium with the sulfonate ligand.

A plausible mechanism has been found in the facile phosphorylation of aldehydes with amidotriphosphate catalyzed by magnesium ion (7). The reaction proceeds to completion even in dilute solution of the reactants. We are currently studying the extension of this process to the micromolar range of reactants by utilizing the aldehyde capture and concentration effect of surface active minerals. Other successful phosphorylation mechanisms (46, 47) become geochemically more complex by invoking adjuvants such as urea which for its formation depends on reduced nitrogen compounds as source molecules. A geochemically plausible synthesis path and concentration mechanism for such molecules must eventually be found, taking into account modern concepts of planetary atmospheric chemistry. These requirements have yet to be satisfied.

Recently our experiments relying on mineral induced catalysis for the spontaneous formation of bioorganic source molecules have been expanded to include the amorphous precursors of hydrous minerals forming by precipitation in the hydrosphere of [HMgCa] [A^-] type minerals, where A^- represents anions such as OH^-, $H(PO)_4^{2-}$,SO_3^{2-}, etc . In the ordered structures formed by Ostwald ripening of the initially amorphous precipitates , catalytically active cations such as Mg^{2+} occur at precisely, and catalytically not necessarily optimal distances in the ordered crystal structure. In contrast, in the amorphous precursor precipitates, cation-cation distances vary over a range of about 1 Å, potentially offering access to optimal cation distances for the catalysis of specific reactions. Attention has been drawn by G.Zubay to the potential importance of specific Mg-Mg distances in mineral induced catalysis, based on the observation that all known nucleic acid polymerases employ two strategically positioned divalent cations in the polymerization step with an invariant interionic distance of 3.9 Å. (48)

Experiments with amorphous precursors in the hydrotalcite-whitlockite compositional systems show that the presence of sugar phosphates or nTP in the source solution leads to initially amorphous, stoichiometric compounds with these anions, and with a range of Mg-Mg distances, comprising the Steitz value and supporting the potential of the Zubay proposition.

Collectively the mineral catalysis experiments are placing the TNA-pRNA World concept on a somewhat safer geochemical footing. The demonstration (by other authors) of photochemical energy transduction in DNA and the cellular analog function of freely expanding, surface active double layer metal hydroxide host minerals also suggest the role of these structures as compartmental systems with primitive cellular metabolic function.

Like all work in this field these experiments are oversimplifications that largely ignore competing side reactions with other compounds expected to be present. However, our choice of experimental conditions emphasizing selective concentration and reactions and simulating geophysically and geochemically plausible conditions have narrowed the credibility gap.

The second area of our research includes a search for biomarkers that can be used to trace life in the earliest rock record on Earth, and the early environments on Earth and Mars. Initial results (23), published in 1996, were obtained in preceding years with a rock sample from the Isua supracrustal formation in southern West Greenland, collected and classified by earlier workers in this field. The source rock, a graphitic metacarbonate, was at the time generally believed to be of sedimentary origin and to represent shelf- or platform facies of the banded iron formation. Some graphite particles in this rock sample showed a marked enrichment of the light carbon isotope ^{12}C, generally taken as an indication of biogenic origin of the carbon. This finding was considered unique, since it would establish traces of life as far back as 3,800 million years.

In order to follow up on these findings we took advantage of infrastructure for extended field work in the Isua region provided by the Geological Survey of Denmark and Greenland. Our group, at this stage comprising graduate student M.van Zuilen, postdoctoral researcher Aivo Lepland and myself, carried out investigations in the area , aiming at clarifying the field- and petrological relationships of graphite bearing, carbonate-rich rocks that provided basis for our earlier biologic interpretations. These field observations coupled with laboratory investigations of our extensive sample material, and together with extended field- and laboratory work by Danish, Australian, British and U.S. colleagues resulted in the finding that the graphite bearing metacarbonate is not a sedimentary formation but of metasomatic origin (formed by interaction with solutions at high temperature and pressure deep in the Earth). We further succeeded in showing that the graphite in this case is produced by disproportionation of the iron carbonate (siderite) which is the main component of the metasomatic carbonate . The graphite in this formation is therefore clearly not of biogenic origin and bulk measurements of the carbon isotope composition of the graphite does not indicate biogenic fractionation. We have publicized these findings in invited talks and contributed papers at scientific conferences (8-10, 16-18, 27, 28, 30-34), and in recent publications (24, 25, 26), demonstrating the need to reassess our earlier biologic claims.

The relegation of the Isua metacarbonates to the inorganic world, and our inability so far to reproduce the observations of graphite inclusions in the Akilia "BIF" have not disproved the existence of the earliest traces of life in the 3.8 Ga Isua supracrustal formation. The recent finding by Rosing et al. of morphologically unique and isotopically fractionated carbon in Isua rocks of undisputed sedimentary origin supports the interpretation of biochemically advanced microbial life forms at 3.8 Ga. However they were not discovered by our group; we were at the time relying on what later proved to be the wrong type of rock.

Our current work aims at establishing the significance of kinetic isotope fractionation, operating at graphite formation upon disproportionation of ferrous carbonate at high (450-500 C) temperature and pressure; the latter in itself a unique and underestimated geochemical process.

We have also initiated a collaborative effort including practically all of the research groups active in this field, setting aside their diverging interpretative opinions for the purpose of coherent documentation of disparate samples and analytical results. This effort aims at securing accurate information on sample location and composition and resolving conflicting claims, particularly with regard to the apparent lack of syngenetic graphite, isolated or as inclusions in apatite in the critical Akilia rocks.

Much of our experimental effort underlying these results has been devoted to the construction, calibration and application of a system for high sensitivity mass spectrometric measurement of nitrogen and carbon (8, 9, 17). This work, utilizing stepped combustion mass spectrometry, has demonstrated that the sedimentary banded iron formation (BIF) in the Isua Supracrustal Belt, as well as the critical Akilia rock have extremely low carbon contents which, because of its low temperature combustion characteristics, are entirely ascribable to modern bio-organic contamination. The results negate the interpretation by earlier workers who thought this minuscule amount of contaminant, modern carbon to have formed at the time of deposition of the ancient sedimentary rock. The observations have attracted much attention and have led to several calls for invited papers, e.g. at AGU, COSPAR, the 2002 Goldschmidt Conference and the Berlin Isua-Symposium.

For related purposes we have also applied high resolution electron microscopy and microbeam Raman spectrometry to clarify in detail the mineralogical and petrological features of the graphite bearing Archean metacarbonates, and sedimentary, graphitic turbidites; the latter containing uncontested evidence of 3.8 Ga biogenic graphite (10,16).

In these studies we are also searching for any physical or chemical effects on Earth of the heavy bombardment observed so far only on the Moon, culminating there around 3.8 Ga and decaying until about 3.5 Ga. These impacts are generally hypothesized to have been caused by an invasion into the inner solar system by a swarm of marauding objects, affecting all of the planets there. We have searched for the expected impact effects in the 3.8 Ga Isua sediments that would be manifest by enhanced platinum group metal concentrations in physically disturbed layers and in the finely laminated banded iron sediments using neutron activation analysis with sensitivity at the part per trillion level (35, 36). These analyses have demonstrated the absence of impacts or enhanced influx of extraterrestrial material in the sequences that we have investigated.

These and other Isua studies that have similarly failed to detect any traces of a late heavy bombardment on Earth (40, 41) cover only relatively short time segments of the planetary history after 3.8 Ga where preserved sedimentary rocks exist. However, the preceding era 4.4 to 3.8 Ga has recently been opened up to geochemical inspection by isotopic analysis of dated zircon crystals dispersed from older, disintegrated rocks in Australia (42 - 44). These isolated remnant crystals currently represent ten points in time distributed over this early 600 Myr time period, one (42 b) following only ~160 Myr upon the accretion of the planet. Without exception they testify to the existence of a hydrosphere during a time when previous speculation based on transference of the record from the Moon inferred a completely molten surface layer of the Earth, a 'magma ocean'. We are now forced to believe either that all of the zircon crystals so far analyzed, against substantial statistical odds happen to represent periods of quiescent, cool intervals, alternating with undocumented periods of intense bombardment, extensive crustal melting and evaporation of part or all of the hydrosphere.

Alternatively the documented impact sequence on the Moon may be due to co-orbital capture of a series of small original terrestrial satellites by the tidally receding Moon. This collisional evolution would thus have been characterized by low impact velocities, limited to lunar phase space and with only insignificant amounts of debris scattered out of the Moon's gravitational field (11, 12, 18, 35-37). This assumption would explain the lack of an observed record of a catastrophic 'late heavy bombardment' of Earth

A recent suggestion of an 'extraterrestrial' isotopic tungsten anomaly in Isua sediments was tentatively interpreted as evidence for infall of extraterrestrial material coeval with the 3.8 Ga banded iron formations (38). However, the same group of authors (39) has subsequently provided data pointing at an igneous source of the ^{182}W anomaly as more plausible.

References:

1. Arrhenius, G., B. Sales, S. Mojzsis, T. Lee, Entropy and charge in molecular evolution - the case of phosphate. J. theor. Biol. 187, 503-522, 1997.
2. Kolb, V., S. Zhang, Y. Xu, G. Arrhenius, Mineral-induced phosphorylation of glycolate ion - a metaphor in chemical evolution. Orig. Life Evol. Biosphere 27, 485-503, 1997.
3. Arrhenius, G., K.K. Baldridge, S. Richards- Gross, J. Siegel, Glycolonitrile oligomerization: Structure of oxazolines, potential heterocycles on early Earth. J. Org. Chem. 62, 5522-5525, 1997.
4. De Graaf, R.M., J. Visscher, Y. Xu, G. Arrhenius, A.W. Schwartz, Mineral catalysis of a potentially prebiotic aldol condensation. J. Mol. Evol. 47, 501-507 1998.
5. Mojzsis, S.J., R. Krishnamurthy, G. Arrhenius, Before RNA and after: geophysical and geochemical constraints on molecular evolution. In The RNA World II. T. Cech, R. Gesteland, J. Atkins, Eds. Cold Spring Harbor Laboratory Press, Cold Spring Harbor, 1999.
6. Krishnamurthy, R., S. Pitsch, G. Arrhenius, Mineral induced formation of pentose-2,4-bisphosphates Orig. Life. Evol. Biosphere 29, 139-152, 1999.
7. Krishnamurthy, R., G. Arrhenius, A. Eschenmoser, Formation of glycolaldehyde phosphate from glycolaldehyde in aqueous solution Origins Life Evol. Biosphere **29**, 333-354, 1999.
8. van Zuilen, M., G. Arrhenius, Trace element analysis of graphite, isolated from metasediments of the 3.7 billion year old Isua Supracrustal Belt in southern West Greenland. AGU 1998 Fall Meeting, San Francisco, CA, Dec. 1998.
9. van Zuilen, M., K. Mathew, K. Marti, G. Arrhenius, Biochemical tracers in metamorphic rocks. Abstract, AGU Fall Meeting, San Francisco, CA, Dec. 1999.
10. Lepland, A., P.U. Appel, G. Arrhenius, Phosphates in early Archean Isua BIF, West Greenland. Abstract, AGU Fall Meeting, San Francisco, CA, Dec. 1999.
11. Arrhenius, G., S.J. Mojzsis, K.J. Zahnle, The late heavy bombardment of the Moon - how did it affect Earth and Mars? Abstract, 8th International Goldschmidt Conference on Geochemistry, Toulouse, France, Aug. 1998.
12. Arrhenius, G., A. Lepland, Accretion of Moon and Earth and the emergence of life. Chemical Geology, 169, 69-82 (2000).

13 a. Schoening, K-U., P.Scholz, S.Guntha, X.Wu, R.Krishnamurthy and A.Eschenmoser, Chemical etiology of nucleic acid structure: The alpha-threofuranosyl-(3'--2') oligonucleotide system. Science, 290, 1347-1351.

13 b. Orgel, L.E., A simpler nucleic acid, Science, 290, 1306-1307.

14. Pitsch, S., R.Krishnamurthy and G. Arrhenius, Concentration of simple aldehydes by sulfite containing double layer hydroxide minerals; implications for biopoesis. Helv. Chim. Acta, 83, 2398 -2411 (2000)

15. Arrhenius, G., Earth's early atmosphere - controlling factors. Abstract AGU Fall Meeting, San Francisco, CA, Dec 2000.

16. Lepland, A., G. Arrhenius, Significance of apatite REE signatures in Early Archean; Akilia and Isua supracrustal rocks, southern-West Greenland. Abstract, AGU Fall Meeting, San Francisco, CA, Dec.2000.

17. van Zuilen, M., A.Lepland, M.Wahlen, J.Teranes and G.Arrhenius, Graphite and associated carbonates in early Archean Isua metasediments, southern West Greenland. Abstract, AGU Fall Meeting, San Francisco, CA, Dec.2000.

18. Arrhenius, G., Constraints and uncertainties in models of the early environment on Earth. Abstract, AGU Spring Meeting, Washington D.C., April 2000.

19. Arrhenius, G., Life out of chaos. Abstract, Conference on Definition and Origin of Life, Modena, Italy, Sept.2000

20. Reid, C and Orgel, L.E. Synthesis of sugars in potentially prebiotic conditions. Nature **216,** 455 (1967)

21. Miller, S., Which organic compounds could have occurred on the prebiotic Earth? Cold Spring Harbor Symp. Quant. Biol. **52,** 17-27 (1987)

22. Loeb, W., Studien ueber die chemische Wirkung der stillen elektrischen Entladung. Z. Elektrochemie **11,** 282-316, (1906)

23. Mojzsis, S.J., Arrhenius, G., McKeegan, K.D., Harrison, T.M., Nutman, A.M. and Friend, C.R.L. Evidence for life on Earth before 3,800 million years ago. Nature **384,** 55-59 (1996)

24. Lepland, A. and G. Arrhenius, Tracing life in the earliest terrestrial rock record. Precambrian Research, 2002, in press

25. van Zuilen, M. A., Lepland, A., Arrhenius, G. (2002) Reassessing the evidence for the earliest traces of life. *Nature*, 418, p. 627-630.

26. van Zuilen, M. A., Lepland, A., Teranes, J., Finarelli, J., Wahlen, M., Arrhenius, G. Graphite and associated carbonates in Early Archean Isua Supracrustal Rocks, Southern West Greenland. *Precambrian Research*, in press

27. van Zuilen, M., A. Lepland and G. Arrhenius, Earliest life on Earth; new data call for revision. American Geophysical Union Fall Meeting, San Francisco, CA, Dec.10-16, 2001. P21C-08.

28. Lepland, A., G. Arrhenius and D. Cornell, Apatite in early Archean Isua supracrustal rocks, southern West Greenland: Its origin, association with graphite and potential as a biomarker. American Geophysical Union Fall Meeting, San Francisco, CA, Dec.10-16, 2001.

29. Lepland, A., van Zuilen, M. and Arrhenius, G. Tracing life in the earliest terrestrial rock record AGU Fall Meeting, San Francisco, CA, Dec. 2001, P22B-0545.

30. van Zuilen, M. A., Lepland, A., Arrhenius, G. Tracing life in the Early Archean: The 3.8 Ga Isua Supracrustal Belt, southern West Greenland. 10th ISSOL Meeting, Oaxaca, Mexico, July 2002.

31. van Zuilen, M. A., Lepland, A., Arrhenius, G. The carbon isotope ratio of graphite; Problems associated with its use as a biomarker in Early Archean rocks. The World Space Congress Oct. 2002, Houston, Texas.

32. van Zuilen, M. A., Lepland, A., Arrhenius, G. Abiogenic and biogenic graphite in the 3.8 Ga Isua Supracrustal Belt. Astrobiology Science Conference 2002, NASA Ames Research Center, USA

33. van Zuilen, M. A., Lepland, A. and Arrhenius, G. Graphite and its isotopic composition as a biomarker in highly metamorphosed Early Archean rocks. Geochim. Cosmochim. Acta, **66**, A798 (2002)

34. Lepland, A., van Zuilen, M., Arrhenius, G. Origin and biologic significance of graphite and apatite in Early Archean supracrustal rocks from Isua Belt and Akilia association. Geochim. Cosmochim. Acta, **66**, A448 (2002)

35. Arrhenius, G., A. Lepland, F. Asaro and P.W.U. Appel, Search for an extraterrestrial impact record in Isua sediments. MRDP Symposium, Berlin, Jan. 17-19, 2002.

36. Arrhenius, G., Lepland, A. and Asaro, F. Search for an extraterrestrial impact record in Isua sediments. Geochim. Cosmochim. Acta, **66**, A32 (2002)

37. Arrhenius, G., Evolution of the Moon and its effects on Early Earth. International Conference on Tidal Dynamics, Hangzhou, China, Aug.2002

38. Schoenberg, F., Kamber, B.S., Collerson, K.D and Moorbath, S. Evidence for 3.8 Ga meteorite bombardment of the Earth. Geochim. Cosmochim. Acta, **66**, A148 (2002)

39. Collerson, K.D, Schoenberg, F. and Kamber, B.S., Unradiogenic W in kimberlites: Direct evidence for core-mantle interaction. Geochim. Cosmochim. Acta, **66**, A684 (2002)

40. Anbar, A., Zahnle, K., Arnold, G. and Mojzsis, S. Extraterrestrial iridium, sediment accumulation and the habitability of the early Earth's surface: *Journal of Geophysical Research – Planets* **106** (2): 3219-3236, (2001)

41. Mojzsis, S. and Ryder, G. Extraterrestrial accretion to the Earth and Moon ca. 3.85 Ga, In: *Accretion of Extraterrestrial Matter Throughout Earth History*, ed. B. Peuckner-Ehrenbrink and B. Schmitz: Kluwer, pp. 423-446, (2001)

42 a. Oxygen isotopic ratios and rare earth elements in 3.3 – 4.4 Ga zircons: Ion microprobe evidence for high del ^{18}O continental crust and oceans in the early Archean, Geochim. Cosmochim. Acta, **65**, 4215-4239 (2001)

42 b. Wilde, S., Valley, J., Peck, W. and Graham, C., Evidence from detrital zircons for the existence of continental crust and oceans on the Earth 4.4 Gyr ago. Nature **409**, 175–178, (2002)

43. Valley, J., Peck, W., King, E. and Wilde, S., A cool early Earth. Geology **30,** 351-354 (2002)

44. Mojzsis, S., Harrison, T.M. and Pidgeon, R., Oxygen isotope evidence from ancient zircons for liquid water at the Earth's surface 4,300 Myr ago. Nature **409**, 178-181 (2001)

45 a. Bolli, M., Micura, R. and Eschenmoser, A., Pyranosyl-RNA: chiroselective self-assembly of base sequences by ligative oligomerization of tetranucleotide-2,3'-cyclophosphates (with a commentary concerning the origin of biomolecular homochirality). Chemistry and Biology **4**, 309-320 (1997)

45 b. Bolli, M., Micura, R., Pitsch, S. and Eschenmoser, A., Pyranosyl-RNA: Further observations on replication. Helv.Chim.Acta **80**, 1901-1951 (1997)

46, Lohrmann, R. and Orgel, L.E., Science, **171,** 490-494 (1971)

47. Reimann, A. and Zubay, G., Nucleoside phosphorylation: A feasible step into prebiotic pathway to RNA. Orig. Life Evol. Biosphere, **29,** 222 – 247, 1999.

48... Steitz, T.A.and Steitz, J.A., A general two-metal-ion mechanism for catalytic RNA, Proc Natl Acad. Sci. USA, **90,** 6498-502 (1993)

49. Zubay, G. and Schechter, A. Prebiotic routes for the synthesis and separation of ribose. Chemtracts – Biochem.Mol. Biol., (2001)

1997-2002 Cumulative NSCORT/Exobiology Publications
2002 Final Report (NASA NAG5-4546)

Gustaf Arrhenius Laboratory

a. Peer-Reviewed Journals

Arrhenius, G., Carbon dioxide warming of the early Earth. *Ambio* **26**, 12-16 1997.

Arrhenius, G., K.K. Baldridge, S. Richards- Gross, J. Siegel, Glycolonitrile oligomerization: structure of oxazolines, potential heterocycles on early Earth. *J. Org. Chem.* **62**, 5522-5525, 1997.

Arrhenius, G., B. Sales, S. Mojzsis, T. Lee, Entropy and charge in molecular evolution - the case of phosphate. *J. theor. Biol.* **187**, 503-522, 1997.

De Graaf, R.M., J. Visscher, Y. Xu, G. Arrhenius, A.W. Schwartz, Mineral catalysis of a potentially prebiotic aldol condensation. *J. Mol. Evol.* **47,** 501-507, 1998.

Kolb, V., S. Zhang, Y. Xu, G. Arrhenius, Mineral-induced phosphorylation of glycolate ion - a metaphor in chemical evolution. *Orig. Life Evol. Biosphere* **27**, 485-503, 1997.

Mojzsis, S., G. Arrhenius, Phosphates on Mars: Exobiological implications and sample return consideration. *J. Geophys. Res.* **103**, 28495-28511, 1998.

Nutman, A.P., S.J. Mojzsis, C.R.L. Friend, Recognition of ≥3850 Ma water-lain sediments in West Greenland and their significance for the early Archean Earth. *Geochim. Cosmochim. Acta.* **61**, 2475-2484, 1997.

Arrhenius, G., J. Bada, G., Joyce, A. Lazcano, S., Miller, Orgel, L. Origin and ancestor; separate environments, *Science* **283**, 792, 1999.

Krishnamurthy, R., G. Arrhenius, A. Eschenmoser, Formation of glycolaldehyde phosphate from glycolaldehyde in aqueous solution *Orig. Life Evol. Biosphere* **29**, 333-354, 1999.

Krishnamurthy, R., S. Pitsch, G. Arrhenius, Mineral induced formation of pentose-2,4-bisphosphates *Orig. Life. Evol. Biosphere* **29**, 139-152, 1999.

Mojzsis, S.J., T.M. Harrison, G. Arrhenius, K.D. McKeegan, Origin of life from apatite dating? *Nature* **400**, 127-128, 1999.

Arrhenius, G., A. Lepland, Accretion of Moon and Earth and the emergence of life, *Chemical Geology* **169**, 69-82; 2000.

Pitsch, S., R.Krishnamurthy and G. Arrhenius, Concentration of simple aldehydes by sulfite containing double layer hydroxide minerals; implications for biopoesis. *Helv. Chim. Acta* **83**, 2398 –2411, 2000.

a. Peer-Reviewed Journals *(Continued)*

Wang, Y., G. Arrhenius and Y. Zhang, Drought in the Yellow River - an environmental threat to the coastal zone. *J. Coastal Research* ***17***, 1-16, 2001,

*Weigel, A., A. Lepland, S. De, K. Marti and G. Arrhenius, Leonids - did they make it to Earth? *Meteoritics and Planetary Science*, **35,** 168, 2000.

Lepland, A. and G. Arrhenius, Tracing life in the earliest terrestrial rock record. *Precambrian Research*, 2002, in press.

*van Zuilen, M. A., Lepland, A., Arrhenius, G. Reassessing the evidence for the earliest traces of life. *Nature*, 418, p. 627-630, 2002.

van Zuilen, M. A., Lepland, A., Teranes, J., Finarelli, J., Wahlen, M., Arrhenius,G., Graphite and associated carbonates in Early Archean Isua Supracrustal Rocks, Southern West Greenland. *Precambrian Research, in press.*

Journal articles in preparation:

van Zuilen, M. A., Wopenka, B., Mathew, K., Marti, K., Lepland, A., Arrhenius, G. _^{15}N and $^{40}Ar/^{36}Ar$ of trapped gases in graphite from the 3.8 Ga old Isua Supracrustal Belt, Southern West Greenland. *Geochim. Cosmochim. Acta*, (to be submitted).

van Zuilen, M. A., Valley, J. W., Spicuzza, M. J., Lepland, A., Arrhenius, G. Apatite-graphite in quartz-pyroxene rock from Akilia Island; Primary biogenic origin questioned by oxygen isotope evidence? *Am. Mineralogist* (to be submitted).

b. Book Chapters

Mojzsis, S.J., R. Krishnamurthy, G. Arrhenius, Before RNA and after: Geophysical and geochemical constraints on molecular evolution. In: *The RNA World II*, T. Cech, R. Gesteland, J. Atkins, Eds. Cold Spring Harbor Laboratory Press, Cold Spring Harbor, 1999.

*Arrhenius, G. Life out of Chaos. In: G..Palyi et al., eds, *Fundamentals of Life*, Elsevier, Paris, 2002.

c. Papers at National and International Meetings and Symposia

Arrhenius, G., S.J. Mojzsis, T.M. Harrison, Early life environments on Earth and Mars (ELEEM) *NASA-ARC Symposium, Mountainview CA*, 1997.

Arrhenius, G., W. Paplawsky, Distinguishing between production and dissolution of biogenic calcite - and old problem with new solutions. *Paleoceanography; Stockholm and Gõteborg*, 1997.

Arrhenius, G., Sailing four billion years in the wake of the Albatross. *Paleoceanography; Stockholm and Gõteborg*, 1997.

Arrhenius, G., The emergence of life. *Inaugural lecture, Royal Gothenburg Academy of Arts and Sciences, Nov.* 1998.

Arrhenius, G., NASA's Astrobiology Institute, an interdisciplinary project with international dimensions. *International Symposium on Interdisciplinary Research, Stockholm, Nov.* 1998.

Arrhenius, G., S.J. Mojzsis, K.J. Zahnle, The late heavy bombardment of the Moon - how did it affect Earth and Mars? *8th International Goldschmidt Conference on Geochemistry, Toulouse, France Aug.* 1998.

Krishnamurthy, R., S. Pitsch, A. Eschenmoser, G. Arrhenius, Toward RNA – the phosphorylation of glycolaldehyde. *NASA-ARC Symposium, Mountain View, CA, Nov.* 1997.

Mojzsis, S.J., G. Arrhenius, Early Mars and early Earth: Paleoenvironments for the emergence of life. *SPIE San Diego, CA,* 1997.

van Zuilen, M., G. Arrhenius, Trace element analysis of graphite, isolated from metasediments of the 3.7 billion year old Isua Supracrustal Belt in Southern West Greenland. *AGU 1998 Fall meeting, San Francisco, CA, Dec.* 1998.

Arrhenius, G., W.H. Ip, S.J. Mojzsis, K. Zahnle, Physical state of the early Earth - new constraints, *EGU 10, Strasbourg, France, March-April* 1999.

Arrhenius, G., R. Krishnamurthy, S. Pitsch, A. Eschenmoser, Surface active minerals as hosts for organic reactions *EGU 10, Strasbourg, France, March-April* 1999.

Arrhenius, G., The first steps toward the emergence of life - spontaneous synthesis of information carrying molecules. *AGU Fall Meeting, San Francisco, CA, Dec. 1999.*

Lepland, A., P.U. Appel, G. Arrhenius, Microstratigraphy of Isua metasediments, West Greenland, *EUG 10, Strasbourg, France, March-April,* 1999.

Lepland, A., P.U. Appel, G. Arrhenius, Phosphates in early Archean Isua BIF, West Greenland, *AGU Fall Meeting, San Francisco, CA, Dec.* 1999.

c. Papers at National and International Meetings and Symposia *(Continued)*

van Zuilen, M., K. Mathew, K. Marti, G. Arrhenius, Biochemical tracers in metamorphic rocks, *AGU Fall Meeting, San Francisco, CA, Dec.* 1999, B32A-01.

Arrhenius, G., Constraints and uncertainties in models of the early environment on Earth. *AGU Spring Meeting, Washington, D.C, April 2000.*

Arrhenius, G., Life out of chaos. *Millennial Conference on Definition and Origin of Life, Modena, Italy, Sept. 2000.*

Arrhenius, G., Earth's early atmosphere - controlling factors, *AGU Fall Meeting, San Francisco, CA, Dec. 2000.*

Lepland, A., G. Arrhenius, Significance of apatite REE signatures in Early Archean Akilia and Isua supracrustal rocks, southern-west Greenland, *AGU Fall Meeting, San Francisco, CA, Dec. 2000.*

van Zuilen, M.A., Lepland, A., Finarelli, J., Teranes, J.L., Wahlen, M., Arrhenius, G. Graphite and associated carbonates in Early Archean Isua metasediments, southern West Greenland. *AGU Fall Meeting, San Francisco,CA, Dec.2000, V5 2D-02.*

Arrhenius, G., Mineral bionization - surface chemical modeling of an RNA World. *AGU Fall Meeting, San Francisco, CA, Dec.10-16, 2001.*

van Zuilen, M., A. Lepland and G. Arrhenius, Earliest life on Earth; new data call for revision. *AGU Fall Meeting, San Francisco, CA, Dec.10-16, 2001., P21C-08.*

Lepland, A., G. Arrhenius and D. Cornell, Apatite in early Archean Isua supracrustal rocks, southern West Greenland: Its origin, association with graphite and potential as a biomarker. *AGU Fall Meeting, San Francisco, CA, Dec.10-16, 2001.*

Lepland, A., van Zuilen, M. and Arrhenius,G. Tracing life in the earliest terrestrial rock record, *AGU Fall Meeting, San Francisco,CA , Dec* 2001 *P22B-0545.*

Arrhenius, G., A. Lepland, F. Asaro and P.W.U. Appel, Search for an extraterrestrial impact record in Isua sediments. *MRDP Symposium, Berlin, Jan. 17-19, 2002.*

van Zuilen, M. A., Lepland, A., Arrhenius, G. Tracing life in the Early Archean: The 3.8 Ga Isua Supracrustal Belt, southern West Greenland. *10th ISSOL Meeting July 2002, Oaxaca, Mexico.*

van Zuilen, M. A., Lepland, A., Arrhenius, G. The carbon isotope ratio of graphite: Problems associated with its use as a biomarker in Early Archean rocks. *The World Space Congress Oct. 2002, Houston, Texas.*

c. Papers at National and International Meetings and Symposia *(Continued)*

van Zuilen, M. A., Lepland, A., Arrhenius, G. Abiogenic and biogenic graphite in the 3.8 Ga Isua Supracrustal Belt. *Astrobiology Science Conference, NASA Ames Research Center, Mountain View, CA, Nov.2002.*

Arrhenius,G., Early interaction between Moon, Earth and its postulated regular satellite system. *International Conference on Tidal Dynamics, Hangzhou, Aug. 2002.*

van Zuilen, M. A., Lepland, A.. Arrhenius, G. Graphite and its isotopic composition as a biomarker in highly metamorphosed Early Archean rocks. *Goldschmidt Conference Aug. 2002, Davos, Switzerland.*

Lepland, A., van Zuilen, M. A., Arrhenius, G. Origin and biologic significance of graphite and apatite in Early Archean supracrustal rocks from Isua Belt and Akilia association. *Goldschmidt Conference Aug. 2002, Davos, Switzerland.*

Arrhenius, G., Lepland, A. and Asaro, F. The late heavy bombardment of the Moon and the lack of evidence of its effects on Earth. *Goldschmidt Conference Aug. 2002, Davos, Switzerland.*

Arrhenius, G. (2002) The emergence of life; geochemical, molecular-biological and informational constraints on theory and experiment. *NATO Conference; Space, Time and Life, Brijuni, Croatia Aug.2002.*

d. Book Review

Arrhenius, G., Life on Others Worlds by S. Dick, *The Quarterly Review of Biology 74, 1999.*

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*Preprint or reprint submitted with this report.

2001-2002 Progress Report - Jeffrey L. Bada

The main objectives of this research have been to evaluate the possible sources, stability and composition of the organic material on the early Earth and other solar system bodies. Summaries of research in previous Progress Reports have dealt with the following topics:

- **Exogenous Delivery of Amino Acids to Planetary Bodies**
- **Sublimation and the Survival of Exogenous Organic Compounds**
- **Biomolecular Stability Under Geochemical Conditions**
- **Organics on Mars**

Extensive research has been conducted dealing with various aspects of these and related topics.

- **Sublimation and the survival of organic compounds during the delivery of IDPs to Earth and other solar system bodies**

Based on Glavin, D. P. and Bada, J. L. 2001 Survival of amino acids in micrometeorites during atmospheric entry. *Astrobiology* **1**, 259-269.

The delivery of organic matter by comets, asteroids, meteorites and interplanetary dust particles (IDPs) could have played a significant role in the seeding of the early Earth, Mars and other solar system bodies with compounds thought to be necessary for the origin of life. The detection of extraterrestrial amino acids in the carbonaceous chondrite Murchison and Antarctic micrometeorites (AMMs) have helped to bolster this theory. By far, IDPs supply the bulk of extraterrestrial material accreted to the Earth. It is still not clear, however, what fraction of the organics delivered by IDPs to Earth or Mars can survive the high temperature flash heating events associated with atmospheric entry deceleration.

Sublimation has been proposed as a mechanism by which some organic compounds such as amino acids or nucleobases could escape and survive atmospheric entry heating by subliming off the surface of IDPs and even larger meteorites before they are melted or completely vaporized. Although sublimation experiments have demonstrated that pure amino acids, purines and pyrimidines are not completely destroyed after volatilization at high temperature, there is still insufficient data on the sublimation and survival of these organic compounds from actual meteorite grains when heated to peak atmospheric entry temperatures.

We have analyzed a pulverized sample from the exterior of the Murchison meteorite for the presence of amino acids, purines and pyrimidines and have conducted several experiments designed to study the effect of high temperature and sublimation on these specific compounds after a simulated atmospheric entry heating event. A quartz glass sublimation apparatus was designed for the atmospheric entry simulations to handle temperatures up to 1100°C. The Murchison meteorite grains were used as analogue material for IDPs and micrometeorites.

The Murchison meteorite grains were heated for 5 to 60 s in the sublimation apparatus at an oven temperature of 1100°C. Using thermocouples placed at the bottom of the sublimation apparatus, we found that the temperature of the grains reached ~800°C during the 60 s experiment. This temperature is similar to the maximum temperatures reached by micrometeorites during atmospheric entry. The pressure inside the apparatus was reduced to 0.8 Torr prior to heating in order to simulate the air pressure on Earth at 80 to 100 km altitude which is in the region of maximum IDP atmospheric frictional heating. Given the slow cooling time of the glass apparatus down to room temperature (~6 min) after heating, the meteorite grains in this sublimation experiment are exposed to heat for a longer period of time than in a true IDP atmospheric entry flash heating event (a few s). Therefore, our sublimation heating experiments represent a worst-case scenario for the survival of organic compounds in meteorites during atmospheric entry.

The initial results from the Murchison meteorite sublimation experiments were unexpected. No amines were produced in the meteorite after sublimation which suggests that decarboxylation of the amino acids in Murchison did not occur. Moreover, with the exception of glycine, none of the amino acids which were shown to readily sublime from pure mixtures, could be successfully sublimed from Murchison either directly or after hot 6N HCl treatment of the meteorite grains. We found that the amino acids which did not sublime from Murchison were ultimately pyrolized and destroyed when heated to temperatures above 500°C. One possible explanation for the low amino acid sublimation yield from Murchison is that this meteorite contains kerogen, a high molecular weight non-volatile organic component that could be interacting with amino acids and thus inhibiting sublimation.

The sublimation and survival of glycine (30 %) in Murchison in our simulated atmospheric entry heating experiments was much higher than the 1 to 10% values previously estimated. These experiments have demonstrated that sublimation could be a very important mechanism in the survival of some amino acids and other volatile organic compounds in IDPs during atmospheric entry. Based on these findings, it is likely that amino acids, which are presently being delivered by micrometeorites to the surface of Mars, will survive Martian atmospheric entry heating as well.

- **Bacteria on Mars?**

Based on Glavin, D. P., Schubert, M., Botta, O., Kminek, G. and Bada, J. L. (2001) Detecting Pyrolysis Products from Bacteria on Mars. *Earth Planet. Sci. Lett.* **185**, 1-5.

The possibility that life may have arisen early in the history of Mars has been the focus of intense debate since the 1996 report of small fossilized bacteria and organic compounds in the Martian meteorite ALH84001. One of the primary objectives of the 1976 Viking missions was to determine whether organic compounds, possibly of biological origin, were present in Martian surface soils. The Viking GC/MS experiments found no evidence for any organic compounds of Martian origin above a few parts per billion in the upper 10 cm of surface soil, suggesting the absence of a widely distributed Martian biota. It should be pointed out that the Viking GC/MS instruments were not specifically designed to search for living cells on the surface of Mars, but rather to search for the pyrolysis degradation products of organic compounds of either abiotic or biotic origin. Nevertheless, it was estimated that there would have to be at least 10^5 microorganisms in 250 mg of Martian soil to correspond to 5 parts per million in weight in order for the Viking GC/MS to detect the presence of living cells. Our recent experimental evidence has confirmed that the Viking GC/MS would have been unable to detect bacterial cells present at this level.

Palagonite, an amorphous weathered basaltic glass, was used as a Martian soil analogue material. The crushed palagonite was then inoculated with ~ 10 billion *E. coli* bacteria cells. In order to simulate the pyrolytic process used to extract organic compounds for analysis by the Viking GC/MS instrument, the inoculated palagonite rock sample was sealed under Martian ambient pressure (4 to 6 mbar air) in a quartz glass sublimation apparatus, and heated in a tube furnace set at 1100°C. A cold finger, attached to the sublimation tube, was kept at -195°C with liquid nitrogen throughout the entire experiment. After 30 s, the apparatus was removed from the furnace and allowed to equilibrate to room temperature. According to thermocouple measurements of the temperature inside the apparatus, the palagonite sample was heated to at least 500°C for ~30 s during the experiment. In the Viking pyrolysis experiments, the maximum temperature reached in each oven was 500°C for 30 s.

After pyrolysis/sublimation of the inoculated palagonite was carried out, a bright yellow residue coated the end of the cold finger. The material on the cold finger was carefully rinsed off with double-distilled water and the water soluble amines then analyzed by the OPA/NAC derivatization and HPLC separation method. After heating the inoculated palagonite to 500°C for 30 s, a major fraction of the amino acids originally present in the bacterial cells had decomposed. The primary decomposition products observed were methylamine (8.6 mg/g) and ethylamine (3.2 mg/g). Although some glycine, alanine and valine sublimed from the inoculated palagonite, more than 98% of the amino acids present in the *E. coli* cells were destroyed by the pyrolysis procedure.

Our sublimation/pyrolysis technique coupled with HPLC was specifically designed to search for amine pyrolysis products derived from living bacterial cells. A previous GC/MS analysis of the pyrolysis degradation products of microorganisms indicated that amides and nitriles were the most abundant compounds generated from the cells. Our experiments indicate that volatile amines, especially methylamine and ethylamine, are also produced from cells after pyrolysis. Although the HPLC analytical method used in our experiment was different than the Viking GC/MS instrument, the pyrolysis procedures were comparable. Thus, it is likely that methylamine and ethylamine would have been generated from any cells present in the Martian soil during the Viking pyrolysis procedure. The detection limits for ethylamine and methylamine however, were not accurately determined for the Viking GC/MS instrument. A limit for amines of 0.01 mg was estimated based on the chromatographic resolution of the Viking GC column.

Assuming a best case detectability for ethylamine in the Viking GC/MS of 0.01 mg/g, it is possible to estimate an upper limit for the number of bacterial cells in the Martian soil that would yield 0.01 mg/g of ethylamine after pyrolysis. According to our data, ~10 billion cells/g of palagonite yielded 3.2 mg/g of ethylamine after heating at 500°C for 30 s under Martian pressure. Thus, at the detection limit of 0.01 mg/g, ethylamine from ~30 million bacterial cells could have been generated from a gram of Martian soil during pyrolysis, and this would have likely been missed by the Viking GC/MS instrument. Because other bacteria, as well as some blue-green algae and archaea, tend to have a lower overall dry cell weight than *E. coli*, the total number of prokaryotic cells that could have been present on the surface of Mars is even larger. Although the presence of a potent oxidant has generally been assumed to preclude the existence of any organisms in the soils analyzed by Viking, it is apparent that we cannot exclude the possibility that there could have been at least several million prokaryotic cells/g of Martian soil.

- **A cometary origin of the amino acids in the Orgueil meteorite?**

Based on Ehrenfreund, P., Glavin, D. P., Botta, O., Cooper, G. and Bada, J. L. (2001) Extraterrestrial amino acids in Orgueil and Ivuna: Tracing the parent body of CI type carbonaceous chondrites. *Proc. Natl. Acad. Sci. USA*, **98(5)**, 2138-2141.

In analyses carried out almost thirty years ago, 11 different amino acids were detected in samples of the Orgueil meteorite, a CI carbonaceous chondrite which fell in France in 1864. Surprisingly, given the extensive improvement in analytical methods used to detect amino acids and their enantiomers, no further amino acid analyses of Orgueil have been conducted. We have reexamined a well-preserved piece of the Orgueil meteorite (provided by the Institute du Mineralogie in Paris) by analyzing hot water extracts (with and without acid hydrolysis) using the same HPLC methodology we have developed to study amino acids in Martian meteorites. Carbon isotopic measurements of the Orgueil hydrolyzed hot water extracts were also carried out using Gas Chromatography-Isotope Ratio Mass Spectrometry (GC-IRMS).

The amino acid composition of Orgueil is strikingly different to other carbonaceous chondrites such as Murchison and Murray. The Orgueil hot water extract is characterized by an abundance of glycine and β-alanine, and only traces of other amino acids such as alanine and various isomers of amino-n-butyric acid. The measured D to L ratios of alanine and α-amino-n-butyric acid in Orgueil are 1.06±0.20 and 1.0±0.1, respectively, indicating an abiotic origin of these amino acids.

Preliminary carbon isotopic measurements gave values of $\delta^{13}C$ = –7 to –9 ‰ for β-alanine in Orgueil. The β-alanine isotope values fall outside the range of terrestrial values (typically –20 to –30 ‰) and suggest an extraterrestrial origin of this amino acid.

Collisions among main belt asteroids are thought to be the most likely source of meteorites. The low-albedo material on the surfaces of the C, P, and D-class asteroids is believed to consist of complex organic solids. Their presence indicates a possible source for the organics found in carbonaceous chondrites, or the precursor molecules required in order for abiotic organic syntheses to take place. As been previously suggested, the Strecker-cyanohydrin synthesis is thought to be the dominant reaction pathway for amino acid synthesis on the parent body of carbonaceous chondrites such as Murchison and Murray. This implies that a variety of carbonyl compounds, such as formaldehyde, acetone, 2-butanone, acetaldehyde, in addition to HCN and NH_3, were present on the parent bodies of these meteorites. In contrast to asteroids, comet observations have so far not detected a suite of diverse precursor molecules that would be required for the synthesis of a wide variety of amino acids.

The unique amino acid composition of Orgueil strongly suggests that this meteorite came from a different type of parent body than Murchison and Murray. A cometary origin would be one possibility since the current inventory of cometary volatiles would favor the formation of amino acids like glycine and β-alanine. Compared to the asteroidal parent bodies, comets probably contain a much more restricted set of the precursor molecules needed for amino acid syntheses. Although glycine can be efficiently formed from HCN, H_2CO and NH_3 by Strecker-cyanohydrin synthesis, it can alternatively also be formed directly from the hydrolysis of HCN polymers. The synthesis of β-alanine could proceed by Michael-addition of NH_3 to cyanoacetylene, a molecule detected in comets, followed by subsequent reduction/hydrolysis reactions.

- **Amino acid analyses of the Taglish meteorite**

Based on Kminek G., O. Botta, D. P. Glavin, J. L. Bada, 2002 Amino Acids in the Tagish Lake Meteorite, *Meteorit. Planet. Sci.* **37**, 697-702.

High performance liquid chromatography (HPLC) based amino acid analysis of a Tagish Lake meteorite sample recovered three months after the meteorite fell to Earth have revealed that the amino acid composition of Tagish Lake is strikingly different from that of the CM and CI carbonaceous chondrites. I found that the Tagish Lake meteorite contains only trace levels of amino acids (total abundance = 880 parts per billion, ppb), which is much lower than the total abundance of amino acids in the CI Orgueil (4,100 ppb) and the CM Murchison (16,900 ppb). Because most of the same amino acids found in the Tagish Lake meteorite are also present in the Tagish Lake ice melt water, I conclude that the amino acids detected in the meteorite are terrestrial contamination. I found that the exposure of a sample of Murchison to cold water lead to a substantial reduction over a period of several weeks in the amount of amino acids that are not strongly bound to the meteorite matrix. However, strongly bound amino acids that are extracted by direct HCl hydrolysis, are not affected by the leaching process. Thus even if there had been leaching of amino acids from our Tagish Lake meteorite sample during its three month residence in Tagish Lake ice and melt water, a Murchison type abundance of endogenous amino acids in the meteorite would have still been readily detectable. The low amino acid content of Tagish Lake indicates that this meteorite originated from a different type of parent body than the CM's and CI's. The parent body was apparently devoid of the reagents such as aldehyldes/ketones, HCN and ammonia needed for the effective abiotic synthesis of amino acids. Based on reflectance spectral measurements, Tagish Lake has been associated with P or D- type asteroids. If the Tagish Lake meteorite was indeed derived from these types of parent bodies, our understanding of these primitive asteroids needs to be re-evaluated with respect to their potential inventory of biologically important organic compounds.

- **The effect of ionizing radiation on amino acids and bacterial spores**

Based in part on Kminek, G., J. L. Bada, K. Pogliano, J. F. Ward, 2003 Radiation-dependent limit for the viability of bacterial spores in halite fluid inclusions and on Mars, *Rad. Res.* **159**, 722-729.

Several recent NASA sponsored workshops have addressed the question of sterilizing samples returned from Mars prior to distribution to external investigators. The scientific community has expressed a strong desire to obtain Martian samples as soon as possible after their return to Earth and the completion of the lengthy biohazard testing procedures that are required for planetary protection. The early release of returned

Martian samples would require the sterilization of a specific sub-set of samples using a method which has as little effect on the sample quality as possible. In order to accomplish this, γ-radiation has been considered as the most appropriate method for conducting a thorough, fast and cheap sterilization.

We have initiated a detailed study of the effects of the effects of γ-radiation on amino acids in various types of materials and under a variety of conditions. Amino acids were selected because they are one of the major components of terrestrial organisms and because they are substantial component of organic matter present in meteorites. Amino acids with a chiral carbon provide a way to distinguish between biotic and abiotic processes because biochemistry at least on Earth discriminates against D- and L-amino acids while the abiotic synthesis of amino acids produces a racemic mixture (D/L = 1.0). The ^{60}Co radiation source at the Jet Propulsion Laboratory, NASA, with a flux of 100 rad/s was used for all experiments. The samples were analyzed for the absolute quantity of amino acids by the OPA/NAC derivatization and HPLC separation method in order to access the extent of decomposition and racemization that resulted from the γ-radiation exposure. We conclude that sterilizing γ-radiation has only a small impact on the amino acid composition of a prospective sample from Mars. The amino acid signature of a typical carbonaceous chondrite composition or of extinct life would still be recognizable as such.

It apparent from these studies that the radiation induced decomposition of amino acids has a much wider application. The crustal environments of terrestrial planets contain radioactive isotopes. Although the quantity is usually relatively small, the accumulated effect of the natural radiation associated with radioactivity over geologic time could be substantial. We measured the radiolysis constant of amino acids, and calculated the radiation dose from long-lived radionuclides, such as 40K, 232Th, 235U and 238U, shortlived radionuclides, such as 26Al, and the Galactic Cosmic Radiation (GCR) for meteorites and for the Martian subsurface. The major result of the radiation experiments is that the radiolysis constant for the measured dry amino acid scales with their molecular weight. Carbonaceous meteorites delivered, for similar transfer times, 12 % more amino acids to the early Earth compared to today due to the radiolytic decomposition from the internal radioactivity throughout the last 3.8 billion years. Carbonaceous meteorites with diameters of less then 2 meters can accumulate enough radiation from the Galactic Cosmic Radiation (GCR) to destroy up to about 30 % of the amino acids present. This effect is also very much dependent on the transfer time form the asteroid belt to the inner solar system. The short-lived radioisotope 26Al, proposed as a heat source for planetesimals in the early solar system by Urey, might contribute substantially to the radiodecomposition early on. The total radiodecomposition of amino acids since their synthesis 4.5 billion years ago is between 24 and 62 %, depending on the presence of 26Al and the timescale of the events during the formation and early history of planetesimals. Although the radiolysis of amino acids introduces a certain fractionation, this does not change the fingerprint of a typical carbonaceous chondrite because of the heterogeneous distribution of organic molecules in the CM and CI class of chondrites. The difference or lack of certain amino acids in CM (Murchison), CI (Orgueil) chondrites and the Tagish Lake meteorite cannot be explained by selective radiolysis. The alanine/AIB ratio in CM chondrites, which is quite different of what would be expected from a typical Miller-Urey type abiotic synthesis, cannot be explained by the small difference in the radiolysis constant either.

Radiation induced decomposition of amino acids on Mars, especially from the GCR in the near surface, has some implication for exobiology lander missions. In general, the search for amino acids as biomarkers of an extinct biosphere on Mars is not limited by their radiolytic decomposition. However, it is necessary to drill to a depth of at least 1-1.5 meter for sufficient shielding from the GCR, to potentially find amino acids from an extinct biota with a original bioload of 10^4 to 10^8 cells/g of soil. The internal radioactivity from long-lived radioisotopes, in this regard, is negligible.

Finally, we have investigated the survival of bacterial spores after exposure to various radiation doses in order to access their long-term survival under various geologic/planetary conditions. When claims for the long-term survival of viable organisms are made, either within terrestrial minerals or on Mars, considerations should be made of the limitations imposed by the naturally occurring radiation dose to which they have been exposed. I investigated the effect of ionizing radiation on different bacterial spores by measuring the inactivation constants for *B. subtilis* and *S. marismortui* spores in solution as well as dry spores of *B. subtilis* and *B. thuringiensis*. *S. marismortui* is a halophilic spore, which is genetically similar to the recently discovered 2-9-3 bacterium from a halite fluid inclusion, claimed to be 250 million years old (Vreeland *et al.*, 2000). *B. thuringiensis* is a soil bacterium which is genetically similar to the human pathogens *B. anthracis* and *B. cereus* (Helgason *et al.*, 2000). To relate the inactivation constant to some realistic environments, I calculated the radiation regime in a halite fluid inclusion and in the Martian subsurface over time. Our conclusion is that the ionizing radiation dose in those environments limits the survival of viable bacterial spores over long periods of time. In the absence of an active repair mechanism in the dormant state, the long-term survival is limited to about 100 million years in halite fluid inclusions, 100 to 200 million years in the Martian subsurface below 3 meters, and to less than 600,000 years in the uppermost meter of Mars.

1997-2002 Cumulative NSCORT/Exobiology Publications
2002 Final Report (NASA NAG5-4546)

Jeffrey L. Bada Laboratory

a. Peer Reviewed Journals

Glavin, D. P., G. Matrajt, J. L. Bada, A search for extraterrestrial amino acids in Antarctic micrometeorites: implications for the exogenous delivery of organic compounds, *Adv. Space Res.*, in press.

*Lazcano, A., J. L. Bada, 2003. The 1953 Stanley L. Miller experiment: fifty years of prebiotic organic chemistry. *Origins Life Evol. Biosphere* **33**: 235-242.

Perry R.S., M. Engel, O. Botta, J. T. Staley, Amino Acid Analyses of Desert Varnish from the Sonoran and Mojave Deserts, *Geomicrobiology*, in press.

*Kminek, G., J. L. Bada, K. Pogliano, J. F. Ward, 2003 Radiation-dependent limit for the viability of bacterial spores in halite fluid inclusions and on Mars, *Rad. Res.* **159**, 722-729.

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

*Lazcano, A, J. L. Bada, 2002 Discussing the Origin of Life – Response 2002 *Science* **298**, 747.

*Bada, J.L., A. Lazcano, 2002 Origin of Life – Some like it hot, but not the first biomolecules, *Science* **296**, 1982-1983.

Grutters, M., W. van Raaphorst, E. Epping, W. Helder, J.W. de Leeuw, D.P. Glavin, J. L. Bada. 2002 Preservation of amino acids from in situ-produced bacterial cell wall peptidoglycans in northeastern Atlantic continental margin sediments. *Limnology and Oceanography* **47**, 1521-1524.

*Glavin, D. P., M. Schubert, J. L. Bada, 2002. Direct isolation of purines and pyrimidines from nucleic acids using sublimation. *Anal. Chem.* **74**, 6408-6412.

*Botta O., J. L. Bada, 2002 Extraterrestrial Organic Compounds in Meteorites, *Surveys in Geophysics* **23**, 411-467.

a. Peer Reviewed Journals *(Continued)*

*Botta O., D. P. Glavin, G. Kminek, J. L. Bada, 2002 Relative Amino Acid Concentrations as a Signature for Parent Body Processes of Carbonaceous Chondrites, *Origins Life Evol. Biosphere* **32**, 143-163.

*Kminek G., O. Botta, D. P. Glavin, J. L. Bada, 2002 Amino Acids in the Tagish Lake Meteorite, *Meteorit. Planet. Sci.* **37**, 697-702.

*Bada, J.L., A. Lazcano, 2002 Miller revealed new ways to study the origin of life – Science advances as one theory builds on another: Miller didn't just update Lob's work. *Nature* **416**, 475.

*Glavin, D. P. and Bada, J. L. 2001 Survival of amino acids in micrometeorites during atmospheric entry. *Astrobiology* **1**, 259-269.

*Glavin, D.P., Schubert, M., Botta, O., Kminek, G., and Bada, J.L. 2001. Detecting pyrolysis products from bacteria on Mars. *Earth and Planetary Science Letters* **185(1-2)**, 1-5.

*Bada, J. L. 2001 State-of-the-art instruments for detecting extraterrestrial life, *P. Natl. Acad. Sci. USA* **98(3)**, 797-800.

*Ehrenfreund, P., Glavin, D.P., Botta, O., Cooper, G., and Bada, J. L. 2001 Extraterrestrial amino acids in Orgueil and Ivuna: Tracing the parent body of Cl type carbonaceous chondrites. *Proceedings of the National Academy of Sciences of the USA* **98(5)**, 2138-2141.

Glavin, D. P., Kminek, G. and Bada, J. L., 2000. Enantiomeric determination of amino acids isolated from bone using sublimation. In: Methods in Molecular Biology (ed. D. Degusta), The Humana Press, Inc., New Jersey, in press.

Kminek, G., Bada, J. L., Botta, O., Glavin, D. P. and Grunthaner, F., 2000. MOD: An organic detector for the future robotic exploration of Mars. *Planet. Space Sci.* **48**, 1087-1091.

a. Peer Reviewed Journals *(Continued)*

Kvenvolden, K. A., Glavin, D. P. and Bada, J. L., 2000. Extraterrestrial amino acids in the Murchison meteorite: Re-evaluation after thirty years. In: Perspectives in Amino Acid and Protein Geochemistry (eds. G. A. Goodfriend, M. J. Collins, M. L. Fogel, S. A. Macko and J. F. Wehmiller), Oxford University Press, New York, p 7-14.

Bada, J. L. and A. Lazcano, 2000. Stanley Miller's 70th birthday. *Origins Life Evol. Biosphere* **30**, 107-112.

Levy, M., S. L. Miller, K. Brinton and J. L. Bada, 2000. Prebiotic synthesis of adenine and amino acids under Europa-like conditions. *Icarus* **145**, 609-613.

Orgel, L., M. A'Hearn, J. L. Bada, J. Baross, C. Chapman, M. Drake, J. Kerridge, M. Race, M. Sogin and S. Squyres, 2000. Sample return from small solar system bodies. *Adv. Space Res.* **25**, 239-248.

Bunch, T. E., L. Becker, D. Des Marais, A. Tharpe, P. H. Schultz, W. Wolbach, D. P. Glavin, K. L. Brinton and J. L. Bada, 1999. Carbonaceous matter in the rocks of the Sudbury Basin, Ontario, Canada. In: Large Meteorite Impacts and Planetary Evolution II (ed. B. O. Dressler and V. L. Sharpton), *Geol. Soc. Am. Special Paper* **339**, 331-343.

Hutt, L. D., D. P. Glavin, J. L. Bada and R. A. Mathies, 1999. Microfabricated capillary electrophoresis amino acid chirality analyzer for extraterrestrial exploration. *Anal. Chem.* **71**, 4000-4006.

Glavin, D. P., J. L. Bada, K. L. F. Brinton and G. D. McDonald, 1999. Amino acids in the Martian meteorite Nakhla. *Proc. Natl. Acad. Sci. USA* **96**, 8835-8838.

George, J. C., J. L. Bada, J. Zeh, L. Scott, S. E. Brown, T. O'Hara and R. Suydam, 1999. Age and growth estimates of bowhead whales (*Balaena mysticetus*) via aspartic acid racemization. *Can. J. Zool.* **77**, 571-580.

Arrhenius, G., J. L. Bada, G. F. Joyce, A. Lazcano, S. L. Miller and L. Orgel, 1999. Origin and ancestor: Separate environments. *Science* **283**, 792-793.

Becker, L., B. Popp, T. Rust and J. L. Bada, 1999. The origin of organic matter in the Martian meteorite ALH84001. *Earth Planet. Sci. Letters* **167**, 71-79.

a. Peer Reviewed Journals *(Continued)*

Bada, J. L., X. S. Wang and H. Hamilton, 1999. Preservation of key biomolecules in the fossil record: current perspectives and future challenges. *Phil. Trans. Roy. Soc. Lond. B* **354**, 77-86.

Bada, J. L., 1999. Biogeochemistry of organic nitrogen compounds. In: Nitrogen-containing macromolecules in the bio-- and geospheres. (Eds. B. A. Stankiewics and P. F. van Bergen) *ACS Symposium Series* **707**, 64-73.

Brinton, K. L. F., C. Engrand, D. P. Glavin, J. L. Bada and M. Maurette, 1998. A search for extraterrestrial amino acids in carbonaceous Antarctic micrometeorites. *Origins Life Evol. Biosphere* **25**, 413-424.

National Research Council, Authors: Orgel, L. (chair), M. A'Hearn, J. L. Bada, J. Baross, C. Chapman, M. Drake, J. F. Kerridge, M. Race, M. Sogin and S. Squyres, 1998. Evaluating the biological potential in returned samples from planetary satellites and small solar system bodies: framework for decision making. National Academy Press.

Glavin, D. P. and J. L. Bada, 1998. Isolation of amino acids from natural samples using sublimation. *Anal. Chem.* **70**, 3119-3122.

Bada, J. L., D. P. Glavin, G. D. McDonald and L. Becker, 1998. A search for endogenous amino acids in Martian meteorite ALH84001. *Science* **279**, 362-365.

Bada, J. L. 1997. Extraterrestrial Handedness? *Science* **275**, 942-943.

Becker, L., D. P. Glavin and J. L. Bada, 1997. Polycyclic aromatic hydrocarbons (PAHs) in Antarctic Martian meteorites, carbonaceous chondrites and polar ice. *Geochim. Cosmochim. Acta* **61**, 475-481.

b. Abstracts of Papers at National/International Meetings

Glavin, D.P., G. Matrajt, J. L. Bada 2002 A Search for extraterrestrial amino acids in Antarctic micrometeorites, *Geochimica et Cosmochimica Acta* **66**, A277.

b. Abstracts of Papers at National/International Meetings *(Continued)*

Britt, D.T., C. Agee, C. Allen, J.L. Bada, J.F. Bell, D. Blaney, J. Bradley, B. Clark, D. Durda, K. Housen, D. Kring, H. McSween, M. Robinson, P. Thomas, E. Young 2002, The Gulliver mission: A short-cut to martian sample return. *Meteoritics & Planetary Science* **37**, A25.

Botta O., P. Ehrenfreund, J. L. Bada, "The Amino Acid Composition of Carbonaceous Chondrites: Clues to their Parent Bodies", *Asteroids, Comets, Meteors* Conference Proceedings..

Botta O., D. P. Glavin, E. Pierazzo, P. Ehrenfreund, J. L. Bada, "Exogenous Material Delivery to Earth-like Planets and Moons", *ESLAB* Conference Proceedings, ESA SP 514, 173-180 (2002).

Glavin D. P., Schubert M., Botta, O., Kminek, G., Bada J. L. (2002), "Detecting Pyrolysis Products from Bacteria on Mars", *Lunar and Planetary Science XXXIII*, Abstract #1094, Lunar and Planetary Institute, Houston (CD-ROM).

Botta O., Bada J. L. (2002), "Amino Acids in the Antarctic CM Meteorite LEW 90500", *Lunar and Planetary Science XXXIII*, Abstract #1391, Lunar and Planetary Institute, Houston (CD-ROM).

Botta O., D. P. Glavin, G. Kminek, J. L. Bada, "Identification of Amino Acid Signatures in Carbonaceous Chondrites", *Meteorit. Planet. Sci.* **36** (9), A26 (2001).

Bada, J. L. "The transition from abiotic to biotic chemistry: When and where?", *American Geophysical Union*, 2001 Fall Meeting, San Francisco, CA December 9-14, 2001.

Kminek, G. and Bada, J. L. " Limit for the survivability from potassium decay of bacterial spores in halite fluid inclusions.", *American Geophysical Union*, 2001 Fall Meeting, San Francisco, CA December 9-14, 2001

Kminek, G. and Bada, J. L., "The Effect of Sterilizing Gamma Radiation on Amino Acids." In *Lunar and Planetary Science XXXII*, Abstract #1918, Lunar and Planetary Institute, Houston TX, March 12-16, 2001.

b. Abstracts of Papers at National/International Meetings *(Continued)*

Glavin, D. P., Bada, J. L., Botta, O., Kminek, G., Grunthaner, F. and Mathies, R., "Integrated Micro-Chip Amino Acid Chirality Detector for MOD." In *Lunar and Planetary Science XXXII*, Abstract #1442, Lunar and Planetary Institute, Houston. TX, March 12-16, 2001.

Botta, O., Glavin, D. P., Kminek, G. and Bada, J. L., "Classification of Carbonaceous Meteorites Through Amino Acid Signatures?" In *Lunar and Planetary Science XXXII*, Abstract #1245, Lunar and Planetary Institute, Houston TX, March 12-16, 2001.

Grutters, M., van Raaphorst, W., Epping, E., Helder, W., Glavin, D., Bada, J. L. and de Leeuw, J. W., "Amino acid D/L-enantiomers as indicators of in situ production of bacterial cell walls in marine sediments." Amer. Chem. Soc. National Meeting, April, 2001. *Amer. Chem. Soc. Abst. of Papers*, **221** GEOC, 038 (2001).

Bada, J. L. and Miller, S. L., "Simulated hydrothermal vent studies should not forget the Arrhenius equation!" Amer. Chem. Soc. National Meeting, April, 2001. *Amer. Chem. Soc. Abst. of Papers*, **221** GEOC, 152 (2001).

Schoenginer, M. J., J. L. Bada, 2001 Carbon and nitrogen stable isotope variation in primate hair reflects ecologicla and dietary variation. *Am. Chem. Soc. Abstracts of Papers* **221**, 115-GEOC.

Bada, J. L., Glavin, D. P. and Botta, O., "Clues to the nature of carbonaceous meteorite parent bodies from amino acid signatures." Amer. Chem. Soc. National Meeting, April, 2001. *Amer. Chem. Soc. Abst. of Papers*, **221** SOCED, 002 (2001).

Glavin, D. P., Ehrenfreund, P., Botta, O., Cooper, G. and Bada, J. L., "Amino Acid Chemistry as a Link Between Small Solar System Bodies and Carbonaceous Chondrites." In Near-Earth Asteroid Sample Return Workshop, p. 17. LPI Contribution No. 1073, Lunar and Planetary Institute, Houston TX, December 11-12, 2000.

b. Abstracts of Papers at National/International Meetings *(Continued)*

Bada, J. L. "Miniaturized instruments for searching for signs of life on solar system bodies." Workshop on Life, Millennial World Meeting of University Professors, Modena/Rome, Italy, September 3-10, 2000.

Botta, O., Kminek, G., Kurat, G. and Bada, J. L. , "The Miller-Urey Experiment in Space." Gordon Conference on the Origin of Life. Plymouth, NH, July 9-14, 2000.

Kminek, G., and Bada, J. L. "Effect of gamma-radiation on amino acids in mars simulants." European Geophysical Society : XXV General Assembly, Nice, France, April 25-29, 2000.

Botta, O., Glavin, D. P., Cooper, G. W., Ehrenfreund, P., J. L. Bada, J. L. "Extraterrestrial Organics in Meteorites." European Geophysical Society : XXV General Assembly, Nice, France, April 25-29, 2000.

Bada, J. L. "Amino acid racemization: use in age dating and assessment of genetic informational molecule preservation." Pittcon 2000, New Orleans, LA, March 12-17, 2000.

Glavin, D. P., Ehrenfreund, P., Botta, O., Cooper, G. and Bada, J. L. "Amino acid chemistry as a link between small solar system bodies and carbonaceous chondrites." Near-Earth Asteroid Sample Return Workshop, Lunar and Planetary Institute, Houston, TX, December 11-12, 2000.

Botta, O., Ehrenfreund, P., Glavin, D. P., Cooper, G. W., Kminek, G. and Bada, J. L. "A cometary origin of the amino acids in the Orgueil meteorite?" 31st Lunar and Planetary Science Conference, Houston, TX, March 15-19, 2000.

Ehrenfreund, P., D. P. Glavin, O. Botta, G. Cooper, S. Charnley, G. Kminek and J. L. Bada "Extraterrestial amino acids in the Orgueil meteorite: The link of organics in the universe." AGU 1999 Fall Meeting, San Francisco, CA, December 13-17, 1999.

Muckerheide, M., J. Horn, D. P. Glavin, J. L. Bada, M. Levy, K. Nelson, J. Cleaves and S. L. Miller "Payload G-768: a space probe into the chemistry of life." NASA Small Payloads Meeting, Anapolis, Maryland, September, 1999.

O. Botta, D. P. Glavin, X. S. Wang and J. L. Bada "Determination of nucleobase content in geochemical samples and meteorites." IAU Symposium 197, Astrochemistry: from molecular clouds to planetary systems, Sogwipo, South Korea, August 23-27, 1999.

b. Abstracts of Papers at National/International Meetings *(Continued)*

Glavin, D. P. and J. L. Bada "The sublimation and survival of amino acids and nuclebases in the Murchison meteorite during a simulated atmospheric entry heating event." 30th Lunar and Planetary Science Conference, Houston, TX March 15-19, 1999 and at the 12th International Conference on the Origin of Life and 9th International Society for the Origin of Life Meeting, La Jolla, CA July 11-16, 1999.

Bada, J. L., G. Kminek and A. Lazcano "Electric discharges and the origin of life: a historical reassessment of early experimental work." 12th International Conference on the Origin of Life and 9th International Society for the Origin of Life Meeting, La Jolla, CA July 11-16, 1999.

Brinton, K. L. F., G. D. McDonald, J. P. Dworkin, M. Levy, S. L. Miller and J. L. Bada "The cosmochemistry of amino acid synthesis from hydrogen cyanide." 12th International Conference on the Origin of Life and 9th International Society for the Origin of Life Meeting, La Jolla, CA July 11-16, 1999.

Glavin, D. P., J. L. Bada, K. L. F. Brinton and G. D. McDonald "Amino acids in Martian meteorite Nakhla." 12th International Conference on the Origin of Life and 9th International Society for the Origin of Life Meeting, La Jolla, CA July 11-16, 1999.

Kminek, G., O. Botta, D. P. Glavin, J. L. Bada and F. Grunthaner "Recovery of amino acids, purines and pyrimidines from natural samples using sublimation." NASA/National Cancer Institute Workshop on Sensors for Bio-Molecular Signatures, JPL, Pasadena, CA, June, 2-4, 1999.

Kminek, G. and J. L. Bada "Effects of sterilzing gamma-radiation on organics." XXIV General Assembly of the European Geophysical Society, The Hague, The Netherlands, April, 19-23, 1999.

Glavin, D. P. and J. L. Bada "Isolation of amino acids, purines and pyrimidines from natural samples using sublimation." Amer. Chem. Soc. National Meeting , March, 1999. *Amer. Chem. Soc. Abst. of Papers*, **217 ANYL**, 053 (1999).

Hutt, L. D., R. A. Mathies, F. Grunthaner and J. L. Bada "Mircofabricated capillary electrophoresis chips for in situ analyses on Mars." Amer. Chem. Soc. National Meeting , March, 1999. *Amer. Chem. Soc. Abst. of Papers*, **217 GEOC**, 072 (1999).

Bada, J. L., "Geochemical Preservation of Key Biomolecules: Current Knowledge and Future Challenges." Royal Society of London Discussion Meeting on "Molecular information and prehistory", London, June 24-25, 1998.

b. Abstracts of Papers at National/International Meetings *(Continued)*

Bada, J. L., "Life and Mars: perspectives from Martian meteorites and other evidence." American Society for Microbiology, Atlanta, Georgia, May 18-21, 1998.

Bada, J. L., G. Arrhenius, R. Doolittle, G. Joyce, S. L. Miller and L. Orgel "The NSCORT/Exobiology Program," Sixth Symposium on Chemical Evolution, NASA Ames Research Center, November 17-19, 1997.

Becker, L., G. D. McDonald, D. P. Glavin, J. L. Bada and T. E. Bunch, "Sublimation: a mechanism for the enrichment of organics in Antarctic ice" Meteoritical Society Meeting, Maui, Hawaii, 1997. *Meteoritics Planet. Sci.* **32**, Supplement, A10-A11 (1997).

Brinton, K. L. F., C. Engrand, J. L. Bada and M. Maurette, "A search for extraterrestrial amino acids in Antarctic micrometeorites" Amer. Chem. Soc. National Meeting, April, 1997. *Amer. Chem. Soc. Abst. of Papers,* **213 GEOC,** 216 (1997).

Becker, L., D. P. Glavin and J. L. Bada, "Polycyclic aromatic hydrocarbons (PAHs) in Antarctic Martian meteorites, carbonaceous chondrites and polar ice" Amer. Chem. Soc. National Meeting, April, 1997. *Amer. Chem. Soc. Abst. of Papers,* **213 GEOC,** 240 (1997).

Bada, J. L., "What compounds do we look for in Martian (SNC) meteorites for evidence of abiotic and/or biotic chemistry on Mars?" Amer. Chem. Soc. National Meeting, April, 1997. *Amer. Chem. Soc. Abst. of Papers,* **213 GEOC,** 242 (1997).

Wang, X. S., L. E. Scott and J. L. Bada, "HPLC separation of pyrimidine bases using 4-bromomethyl-6,7-dimethoxycoumarin as a fluorescence labeling agent" Amer. Chem. Soc. National Meeting, April, 1997. *Amer. Chem. Soc. Abst. of Papers,* **213 ANYL,** 089 (1997).

Bada, J. L., L. Becker and G. McDonald, "What compounds do we search for in extraterrestrial samples for evidence of abiotic and/or biotic chemistry", SPIE Meeting, July, 1997.

c. Book Reviews

Bada, J. L., 1999. "The Search for Life on Other Planets" by Bruce Jakosky, Cambridge University Press, *Meteorites and Planetary Science* **34**, 680-681.

d. Popular Books

Botta, O., J. L. Bada, 2003 The Early Earth, In: *The Genetic Code and the Origin of Life*, ed. L. Ribas de Pouplana (Landes Bioscience, 2003)

Wills, C. and J. L. Bada, 2000. *The Spark of Life: Darwin and the Primeval Soup* (Perseus Publishing, ISBN: 0738201960), pp. 288. Re-issued in paper back 2001.

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2001-2002 Progress Report – Russell F. Doolittle

The bulk of our activities in this final year of NSCORT funding continued to center around the comparison of amino acid sequences.

In this regard, we have extended the computer-assisted comparison of sequences to a new genomics project in which we are attempting to assemble the 167,000 reported contigs of the zebrafish genome on the basis of 12,480 reported scaffolds from the pufferfish (fugu). Our approach involves a fast-scanning algorithm coupled with an evolutionary bias. So far the project has been mainly educational, many unexpected aspects confounding a simple solution, but we are optimistic it will pan out in the end.

Meanwhile, we have continued in our attempts to probe the enigmatic problem of why such a largefraction of gene products in fully sequenced genomes cannot be assigned specific functions. Is it because these are mostly ordinary genes that have simply changed at a such a fast rate that they cannot be recognized by standard sequence comparison methods? Or are they newly spawned genes with ill-defined functions?

Our approach to the problem has been to search exhaustively completely sequenced genomes from bacteria to isolate all URFS (unidentified reading frames) from simple ORFS (open reading frames). Simple but fast programs for accomplishing these ends have
been written by Dr. Da Fei Feng. We have also engaged Dr. Yong Jiang in these projects. Although originally trained as a molecular biologist, he is fast becoming a real bioinoformaticist.

1997-2002 Cumulative NSCORT/Exobiology Publications
2002 Final Report (NASA NAG5-4546)

Russell F. Doolittle Laboratory

a. Peer-Reviewed Journals

Tsyguelnaia I; Doolittle RF. (1998) Presence of a fibronectin type III domain in a plant protein. *Journal of Molecular Evolution*, **46**:612-4.

Feng DF; Cho G; Doolittle RF. (1997) Determining divergence times with a protein clock: update and reevaluation. *Proceedings of the National Academy of Sciences of the United States of America* , **94**:13028-33.

Handy, J.; Doolittle, R.F. (1999) An attempt to pinpoint the phylogenetic introduction of glutaminyl-tRNA synthetase among bacteria. Journal of Molecular Evolution, **49**:709-715.

Doolittle, RF; Feng, DF; Cho, G. (1999) Determining divergence times with protein clocks. *Biological Bulletin*, **196**:356-357.

Kollman, JM; Doolittle, RF (2000) Determining the relative rates of change for prokaryotic and eukaryotic protetins with anciently duplicated paralogs. *Journal of Molecular Evolution*, **51**:173-181.

*Doolittle, Russell F. and York, Amanda L. 2002, "Bacterial actins? An evolutionary perspective" BioEssays 24:293-296.

*Rojas, Ana and Doolittle, R. F. 2002, "The Occurrence of Type S1A Serine Proteases in Sponge and Jellyfish" JME, **55**:790-794.

*Doolittle, R. F. 2002, "The Grand Assault" Nature, **419**:493-494.

b. Book Chapters & Invited Reviews

Doolittle RF; Spraggon G; Everse SJ. (1997) Evolution of vertebrate fibrin formation and the process of its dissolution. *Ciba Foundation Symposium* **212**:4-17; discussion 17-23.

Doolittle, RF; Handy, J. (1998) Evolutionary anomalies among the amino acyl-tRNA synthetases. *Curr. Opin. Genetics & Develop.* **8**: 630-636.

Doolittle, RF (2000) Searching for the common ancestor. *Research in Microbiology*, **151**:85-99.

Doolittle, RF (2000) On the trail of protein sequences. *Bioinformatics*, **16**:24-33.

b. Book Chapters & Invited Reviews *(Continued)*

*Doolittle, R. F. (2001) "Gene Transfers Between Distantly Related Organisms". Horizontal Gene Transfer (2nd Edition, Professor M. Syvanen and Professor C. I. Kado, Editors) 269-275.

c. General Interest

Doolittle RF. (1998) Microbial genomes opened up. *Nature*, **392**:339-42.

Doolittle, RF. (1997) Some reflections on the early days of sequence searching. *Journal of Molecular Medicine* **75:** 239-241.

Doolittle, RF (1999) Finding partners in a crowded genome (title inexplicably changed to "Do You Dig My Grove" by an idiot editor). *Nature Genetics*, **23**:6-8.

*Doolittle, R.F. 2002, "Microbial genomes multiply" Nature 416:697-700.

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*Preprint or reprint submitted with this report.

2001-2002 Progress Report – Gerald F. Joyce

Nucleic Acid Enzymes from a Restricted Set of Chemical Building Blocks

The modern genetic alphabet relies on two types of complementary base pairs to store genetic information: A•U (or T) and G•C. However, due to the chemical instability of cytosine, which readily deaminates to uracil, a primitive genetic system composed of the bases A, U, G and C may have been difficult to establish. It has been suggested that the first genetic material may have contained only a single base-pairing unit. We have demonstrated that binary informational macromolecules, containing only two different nucleotide subunits, can act as catalysts. *In vitro* evolution was used to obtain ligase ribozymes composed of only 2,6-diaminopurine (D) and U nucleotides, which catalyze the template-directed joining of two RNA molecules, one bearing a 5′-triphosphate and the other a 3′-hydroxyl. The active conformation of the fastest isolated ribozyme had a catalytic rate that was about 36,000-fold faster than the uncatalyzed rate of reaction. This ribozyme is specific for the formation of biologically relevant 3′,5′-phosphodiester linkages.

The starting point for the evolution of a catalyst that contains only two different subunits was the R3 ligase ribozyme, developed previously in the laboratory, which contains only A, G, and U. This ribozyme catalyzes the template-directed attack of the 3′-hydroxyl of an RNA substrate on the 5′-triphosphate of the ribozyme, forming a 3′,5′-phosphodiester and releasing inorganic pyrophosphate. The chemistry of this reaction is identical to that catalyzed by modern RNA polymerase proteins. The R3 ligase operates with a k_{cat} of 0.013 min^{-1} and K_m of 6.2 μM. It was found to be highly tolerant of base substitutions involving replacement of every A residue by a D residue. The fully D-substituted R3 ligase exhibited a k_{cat} of 0.0010 min^{-1} and K_m of 12 μM.

The next step in developing a DU-containing catalyst involved substituting as many of the G residues as possible by either D or U, while still retaining at least some detectable activity. Substitutions were tolerated throughout the stem-loop regions of the ribozyme, replacing G•U wobble pairs by D•U pairs, and replacing G by D at most of the unpaired nucleotide positions. The final substituted ribozyme contained only three of the 16 G residues that were present in the starting molecule. The last step involved *in vitro* evolution to compensate for removal of the final G residues and improve catalytic activity. The sequence of the ribozyme that contained only three G residues was modified by replacing the remaining G residues by either D or U, then introducing random mutations (either D→U or U→D) at a frequency of 12% per nucleotide position. A total of 10 rounds of *in vitro* evolution were carried out. The final DU-containing ribozyme exhibited Michaelis-Menten saturation kinetics, operating with a k_{cat} of 0.0011 min^{-1} and K_m of 1.6 nM. The uncatalyzed rate of ligation, measured under the same reaction conditions, was 3×10^{-8} min^{-1}. Thus the catalytic rate enhancement of the final DU-containing ribozyme was ~36,000-fold.

Nucleic acid enzymes composed of only D and U residues pay a heavy price for their simplified composition in terms of both catalytic rate and the fraction of molecules that are in an active conformation. Nonetheless, Darwinian evolution can discover catalytically active structures even from such a severely restricted chemical repertoire. Perhaps ribozymes composed of other pairs of nucleotides, such as A and U, G and C, or even A and I (inosine) are possible. It seems less likely that polymers composed of only two amino acids could exhibit appreciable catalytic activity. The absolute minimum number of distinct subunits that could be used to construct a functional informational macromolecule is two, as was the case in the present study. Without at least two different subunits there is no information and thus no basis for Darwinian evolution.

1997-2002 Cumulative NSCORT/Exobiology Publications
2002 Final Report (NASA NAG5-4546)

Gerald F. Joyce Laboratory

a. Peer-Reviewed Journals

Hendrix, M., Priestley, E.S., Joyce, G.F. and Wong, C.-H. (1997): Direct observation of aminoglycoside-RNA interactions by surface plasmon resonance. *J. Am. Chem. Soc.* **119,** 3641-3648.

Wright, M.C. & Joyce, G.F. (1997): Continuous *in vitro* evolution of catalytic function. *Science* **276,** 614-617.

Santoro, S.W. & Joyce, G.F. (1997): A general-purpose RNA-cleaving DNA enzyme. *Proc. Natl. Acad. Sci. USA* **94,** 4262-4266.

Bruick, R.K., Koppitz, M., Joyce, G.F. & Orgel, L.E. (1997): A simple procedure for constructing 5′-amino-terminated oligodeoxynucleotides in aqueous solution. *Nucleic Acids Res.* **25,** 1309-1310.

Joyce, G.F. (1997): Evolutionary chemistry: getting there from here. *Science* **276,** 1658-1659.

Santoro, S.W. & Joyce, G. F. (1998) Mechanism and utility of an RNA-cleaving DNA enzyme. *Biochemistry* **37**, 13330-13342.

Joyce, G.F. & Orgel, L.E. (1998): The origins of life – a status report. *Am. Biol. Teacher*, **60(1),** 10-12.

Joyce, G.F. (1998): Nucleic acid enzymes: playing with a fuller deck enzyme. *Proc. Natl. Acad. Sci. USA* **95**, 5845-5847.

Joyce, G.F. (1999): The counterforce. *Curr. Biol.* **9,** R500-501.

Nowakowski, J., Shim, P.J., Prasad, G.S., Stout, C.D. & Joyce, G.F.(1999): Crystal structure of an 82-nucleotide RNA-DNA complex formed by the 10-23 DNA enzyme. *Nature Struct. Biol.* **6**, 151-156.

Nowakowski, J., Shim, P.J., Joyce, G.F. & Stout, C.D. (1999): Crystallization of the 10-23 DNA enzyme using a combinatorial screen of paired oligonucleotides. *Acta Cryst.* D**55**, 1885-1892.

Rogers, J. & Joyce, G.F. (1999): A ribozyme that lacks cytidine. *Nature* **402**, 323-325.

Ordoukhanian, P. & Joyce, G.F. (1999): A molecular description of the evolution of resistance. *Chem Biol.* **6**, 881-889.

Jaeger, L., Wright, M. C. & Joyce, G. F. (1999): A complex ligase ribozyme evolved *in vitro* from a group I ribozyme domain. *Proc. Natl. Acad. Sci. USA* **96,** 14712-14717.

Santoro, S.W., Joyce, G.F., Sakthivel, K., Gramatikova, S. & Barbas, C.F. (2000): RNA cleavage by a DNA enzyme with extended chemical functionality. *J. Am. Chem. Soc.* **122,** 2433-2439.

Nowakowski, J., Shim, G.S., Stout, C.D. & Joyce, G.F. (2000): Alternative conformations of a nucleic acid four-way junction. *J. Mol. Biol.* **300,** 93-102.

Sheppard, T.L., Ordoukhanian, P. & Joyce, G.F. (2000): A DNA enzyme with *N*-glycosylase activity. *Proc. Natl. Acad. Sci. USA* **97,** 7802-7807.

Joyce, G.F. (2000): Ribozyme evolution at the crossroads. *Science* **289,** 401-402.

Dai, X. & Joyce, G.F. (2000): *In vitro* evolution of a ribozyme that contains 5-bromouridine. *Helv. Chim. Acta* **83,** 1701-1710.

Sheppard, T.L., Wong, C.-H. & Joyce, G.F. (2000): Nucleoglycoconjugates: design and synthesis of a new class of DNA-carbohydrate conjugates. *Angew. Chemie* **39,** 3660-3663.

*Rogers, J. & Joyce, G.F. (2001): The effect of cytidine on the structure and function of an RNA ligase ribozyme. *RNA* **7**, 395-404.

*McGinness, K. & Joyce, G.F. (2002): Substitution of ribonucleotides in the T7 RNA polymerase promoter element. *J. Biol. Chem.* **277,** 2987-2991.

*McGinness, K.E. & Joyce, G.F. (2002): RNA-Catalyzed RNA ligation on an external RNA template. *Chem. Biol.* **9,** 297-307.

*McGinness, K.E. & Joyce, G.F. (2002): Continuous *in vitro* evolution of a ribozyme that catalyzes three successive nucleotidyl addition reactions. *Chem. Biol.* **9,** 585-596.

*Joyce, G.F. (2002): The antiquity of RNA-based evolution. *Nature*, **418,** 214221.

*Paul, N. & Joyce, G.F. (2002) A self-replicating ligase ribozyme. *Proc. Natl. Acad. Sci. USA* **99,** 12733-12740.

*Ordoukhanian, P. & Joyce, G.F. (2002) RNA-cleaving DNA enzymes with altered regio- or enantioselectivity. *J. Am. Chem. Soc.* **124,** in press.

*Reader, J. & Joyce, G.F. (2002) Catalytic activity of a binary informational macromolecule. *Nature* **419,** in press.

Book Chapters

Joyce, G.F. & Orgel, L.E. (1999): Prospects for understanding the origin of the RNA world. In *The RNA World*, second edition (R. F. Gesteland, T. R. Cech, & J.F. Atkins, eds.) Cold Spring Harbor Laboratory Press, Cold Spring Harbor, NY, pp. 49-77.

Joyce, G.F. (1999): Reactions catalyzed by RNA and DNA enzymes. In *The RNA World*, second edition (R. G. Gesteland, T. R. Cech, & J. F. Atkins, eds.) Cold Spring Harbor Laboratory Press, Cold Spring Harbor, NY, pp. 687-690.

Kumar, R. M. & Joyce, G. F.(1999) : Developing ribozymes for therapeutic applications through *in vitro* evolution. In *Intracellular Ribozyme Technology: Protocols and Applications* (J. J. Rossi & L. Couture, eds.) Horizon Scientific Press, Norfolk, England, pp. 21-35.

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2001-2002 Progress Report - Stanley L. Miller

Our main research objective is to demonstrate the prebiotic synthesis and investigate the aqueous chemistry of various small organic molecules that could have been important for the origin of life. Of special interest are those compounds that would be able to be assembled into a primordial genetic material in the pre-RNA world.

PNA as a Potential First Genetic Material

We have been investigating whether the components of peptide nucleic acid (PNA) could have been prebiotic compounds and possibly in the first genetic material. The first task was to show that the backbone monomer, N-(2-aminoethyl)glycine (AEG), is prebiotic. We therefore looked for AEG in a spark discharge synthesis. The yields of AEG are about 10^{-5} % compared to about 1 % yield of glycine. Similar yields are obtained in a polymerization of ammonium cyanide. However, the yield of ethylenediamine is greatly increased if HCHO is added to the cyanide polymerization. Ethylenediamine leads directly to AEG via the Strecker synthesis, a reaction that is robust at high dilution with yields as high as 78%. AEG is a very soluble compound and preliminary experiments indicate that when heated at 80-100°C AEG forms oligomers more rapidly than do α-amino acids heated under similar conditions. The purine substituted acetyl units of PNA are produced from the cyanide polymerization in the presence of glycine and the pyrimidine substituted acetyl units are produced in high yield from the reaction of hydantoic acid with cyanoacetaldehyde. These results were published in Nelson, Levy & Miller. Peptide nucleic acids rather than RNA may have been the first genetic molecule. *Proc. Nat. Acad. Sci. USA* (2000) **97**:3868-3871.

A Reinvestigation of Nucleobase Production from HCN Polymerizations

We have been investigating the effect of temperature, concentration, and hydrolysis time on adenine synthesis from NH_4CN polymerizations. Preliminary results indicate that the yield of adenine is approximately independent of temperature between -80 and 100°C. We have also found that shorter hydrolysis times in 6 M HCl and hydrolysis at pH 8, which is a better prebiotic model, substantially increase the yield of adenine. In addition, there is no decrease in the yield during neutral hydrolysis because of the stability of adenine at pH 8. We are also investigating the concentration dependence of nucleobase synthesis from NH_4CN polymerizations between 10^{-3} M to 8.3 M. At high concentrations of NH_4CN, adenine was the most abundant nucleobase detected and the yield appears to be approximately dependent on the square of the NH_4CN concentration. Preliminary results suggest that uracil and guanine may be produced more efficiently at lower concentrations. We are also looking for other heterocycles such as 4,5-dihydroxypyrimidine, 5-hydroxyuracil, nicotinic acid, 2,6-diaminopurine. Our results show that the NH_4CN polymerization is a more efficient prebiotic source of A, U and G than previously thought. The presence of these compounds indicates that there may have been a large variety of nucleobases and alternative bases available on the early earth for the origin of life. These results have been submitted to *Origins of Life and the Evolution of the Biosphere*.

The Origin of the Metabolic Pathways
A program to understand the origin of the metabolic pathways has been initiated. The working model is that the early pathways started as non-enzymatic reaction sequences giving a metabolite in low yield. The enzymatic steps were then added one at a time in any order. The initial non-enzymatic reaction sequence would likely be in low yield. We have shown that this scheme works for the biosynthetic pathway for nicotinic and quinolinic acids from dihydroxyacetone phosphate and aspartic acid. This suggests that NAD enzymes were among the earliest, and possibly present in the RNA world. We have also shown that this scheme may account for the origin of the folic acid biosynthetic pathway and various steps in the shikimic acid pathway. Some of these results have been published (Cleaves & Miller. The Nicotinamide Biosynthetic Pathway Is a By-Product of the RNA World. *J. Mol. Evol.* (2001) **52**:73-77).

The Synthesis of Pyrimidines in Drying Lagoons
The efficient prebiotic synthesis of cytosine from urea and cyanoacetaldehyde has recently been claimed to be invalid on the basis of possible side reactions of the starting materials and the inapplicability of prebiotic syntheses using drying beach conditions. We have therefore investigated the synthesis of cytosine and uracil from urea and cyanoacetaldehyde at 100° C under dry down conditions, and in solution at 4° C and -2° C. We find that cytosine is produced from both experiments more efficiently than calculated from the Arrhenius extrapolation from higher temperatures. In addition, we find that cyanoacetaldehyde dimer is as efficient as the monomer in cytosine synthesis. We also studied whether evaporating very dilute solutions of organic compounds will concentrate according to theory. Solutions as dilute as 10^{-6} M concentrate from H_2O approximately according to theory. A similar solution from 0.5 M NaCl gave less than theoretical concentrations due to absorption, but concentrations near dryness were very high. These results were reported in: Robertson & Miller. An efficient prebiotic synthesis of cytosine and uracil. *Nature* (1995) **375**:772-4; Robertson, Levy, & Miller Prebiotic synthesis of diaminopyrimidine and thiocytosine. *J. Mol. Evol.* (1996) **43**:543-550. Nelson, Robertson, Levy, & Miller, Concentration by evaporation and the prebiotic synthesis of cytosine. *Origins of Life Evol. Biosphere* (2001) **31**:221-229.

The Prebiotic Synthesis and Stability of 5-Substituted Pyrimidines
The hydrolysis of cytosine to uracil is the second most common type of damage in DNA. The discrimination between uracil and thymine in DNA allows repair enzymes to replace uracil with cytosine. It is possible that an early genetic system could make use of 5-methylcytosine and uracil for the purposes of proofreading. We have therefore investigated the prebiotic syntheses and relative stabilities of various 5-substituted pyrimidines. Our preliminary results show that 5-methylcytosine is somewhat less stable than cytosine. The hydrolysis of thymine to uracil has also been studied by a summer student in this laboratory, Vincent Dion.

5-Bromocytosine decomposes by two pathways to produce a mixture of uracil, 5-bromouracil, 5-hydroxyuracil and cytosine. 5-Bromouracil generates uracil and 5-hydroxyuracil while 5-methylcytosine primarily deaminates to thymine. In general, the alkyl derivatives of uracil and cytosine appear to be more stable than their parent compounds under the conditions investigated and the bromo and hydroxy derivatives less so. Although brominated pyrimidines are unlikely prebiotic DNA precursors and are mutagenic, 5-ethyluracil might be able to replace thymine in a biological error-repair system that detects and replaces potentially mutagenic uracil residues resulting from the deamination of cytosine in DNA.

Previous work in this laboratory has developed robust syntheses for cytosine. The concentration of formaldehyde in the primordial ocean is calculated to be sufficient to convert much of the cytosine to the 5-hydroxymethyl derivative. We have investigated the reduction of 5-hydroxymethylcytosine 5HMC to 5-MC from concentrated solutions of formate, hydrazine or isopropanol under various conditions of temperature and pH. The deamination of HMC to 5-hydroxymethyluracil (HMU) competes with the reduction to 5-MC, and product 5-MC in turn deaminates to thymine. Additional thymine is produced by the reduction of HMU. We have identified 5-MC as a product of this reaction.

Studies with formate as a reductant were performed. Yields of 5MC in excess of 50% were obtained by heating millimolar HMC with 15 M potassium formate at pH 9-10 at 135°-150° C for several hours in sealed tubes. A small amount of thymine was also seen in these reactions and may result from the deamination of 5MC. The Arrhenius activation energy is ~ 28 kcal/mole for the reduction of HMC to 5MC by formate.

Using hydrazine as reductant uniformly low yields of 5MC were obtained with a maximum conversion of about 8% at pH 9.5, at 100° after 120 hours. A 10-fold lower concentration of hydrazine gave a maximum yield was 0.018 % at 72 hrs.

Isopropanol under acid conditions reduces HMU to thymine by hydride tranfer, but did not reduce HMC to 5MC under analogous conditions.

Although hydrazine reduces hydroxymethyluracil to thymine in basic solution, it also degrades pyrimidines to urea and substituted pyrazoles by reacting across the 4 and 6 positions of the ring and is used for this purpose in the Maxam and Gilbert DNA sequencing procedure. Furthermore, hydrazine may replace the amino groups of cytosine, its derivatives and its degradation products. These side reactions complicate the analysis of experiments. Additionally, the hydroxymethyl groups of HMU and HMC are expected to react with hydrazine to form hydrazinomethyl derivatives.

Dr. John Chalmers has been working on a prebiotically plausible synthesis of 5-methylcytosine (5MC) and his results were presented at the ISSOL 2002 meeting in Oaxaca, Mexico. The degradation of 5-substituted pyrimidines was investigated by Vincent Dion and his results were presented at the 2001 NSCORT Summer Sstudent Symposium.

The Prebiotic Synthesis of Acrolein

Acrolein had been suggested as an intermediate in the prebiotic synthesis of several γ-subsituted α-amine acids, such as methionine, glutamic acid, and homoserine. It has also been suggested as an intermediate in the prebiotic synthesis of several alternative primordial genetic materials. Acrolein is generated from acetaldehyde and formaldehyde over basic catalysts in aqueous solution. It was thererfore of interest to determine the scope of this reaction for producing acrolein from "mixed" formose reactions of acetaldehyde and formaldehyde. We have found that acrolein is generated in low but significant steady state concentrations from HCHO and CH_3CHO at very low dilution and temperature under mildly basic and neutral conditions. Acrolein is synthesized more robustly than are the respective dimers of CH_3CHO and HCHO. The high reactivity of acrolein with nucleophiles such as amino acids and nucleobases, and the facility with which these adducts and acrolein itself undergo base-catalyzed polymerization, make this a significant sink for prebiotic organic compounds. This data has been published Cleaves. The Prebiotic Synthesis of Acrolein. *Monatsh. Chem.* (2003) **134**:585-593.

The Reaction of Acrolein with Nitrogen Heterocycles

Since acrolein is so easily produced and its reactivity with likely important prebiotic nucleophiles is so great, it was of interest to investigate the nature of the reactions of acrolein with various prebiotic heterocyclces which could have been incorporated into a primordial genetic material. It was found that there is a high degree of regioselectivity in the reaction of compounds such as the nucleobases with acrolein. This could also have been a significant impedance to the prebiotic synthesis of RNA and DNA. For example, the equilibrium for the addition of uracil to acrolein was found to be some 10^6 higher than the addition of uracil to ribose under equivalent conditions (pH 9, 20°C). The reaction was also shown to be under thermodynamic rather than kinetic control. This reactivity could have been an easy method of generating nucleoside analogues that might have been important for the synthesis of other genetic materials. These in turn may have properties that make them more amenable to the origin of self-replicating systems. These results were published in Cleaves. The reactions of nitrogen heterocycles with acrolein: scope and prebiotic significance. *Astrobiology* (2002) **2**:403-15.

The Prebiotic Synthesis of α-PNA.

α-PNA is a peptide nucleic acid analogue consisting of repeating units of homoserine and another α-amino acid in which the nucleobases are substituted at the γ-position of the homoserine residue. Polymers of these analogues have been shown to form complementary structures with themselves and with RNA and DNA. We have shown that α-PNA monomers are more easily generated prebiotically than ribosides or deoxyribosides. α-PNA monomers can be synthesized prebiotically from the nucleobase-acrolein adducts followed by a Strecker synthesis. The stability of these analogues was investigated. They were found to be more stable than the natural nucleosides and deoxynucleosides, although their polymerization is not extremely robust. Problems similar to those of most α-amino acids are encountered, including diketopiperazine formation for the dimers. The use of the DKP analogues for the starting point of a ring-opening lactam polymerization is under investigation.

The Prebiotic Synthesis of Acyclic Nucleoside Analogues

Alternatively, the acrolein adducts of the nucleobases might be a branch point to form acyclic hydroxy alkyl analogues of the nucleosides. The one-pot reaction of several nucleobases with formaldehyde and acetaldehyde has been investigated and several interesting results have been obtained. The reaction has been found to proceed at very low temperatures (< 20°C) and concentrations (< mM). The reaction produces a variety of analogues of the natural nucleosides in a regioselective manner which is dependant on the pH and relative ratio of HCHO and CH_3CHO. Several novel analogues of the natural nucleosides have been synthesized and their stability is under investigation. It is possible that the selective degradation of some of them might result in an excess of a predominant type of analogue. This chemistry is so robust that it may have been a significant hurdle to the prebiotic synthesis of RNA and DNA, and may preclude consideration of these two polymers having played role in the origin of life on earth or elsewhere. The investigation of the polymerization of these analogues under plausible prebiotic conditions is under way.

The Synthesis of Nitrogen Heterocycles from Frozen HCN Polymerizations

It has been demonstrated previously that the eutectic freezing of HCN results in high yields of DAMN (diaminomaleonitrile) which is an intermediate in the prebiotic synthesis of several nitrogenous heterocycles of prebiotic interest. We have shown that the freezing of extremely dilute solutions of HCN results in the synthesis of the same heterocycles as those produced from more concentrated solutions of HCN, but which would not be generated from the same dilute solutions of HCN at higher temperatures. These results suggest that cold conditions, as opposed to the high temperatures suggested by advocates of hydrothermal vent synthesis, are more conducive to the synthesis of more complex organic compounds. These results suggest that a cool early earth, with regions that were capable of freezing would have been more conducive to the synthesis of organic material. These results may have significant implications for constraining the conditions on the early earth and for identifying the types of locales that may have allowed for prebiotic synthesis from HCN polymerizations. These results were published in Miyakawa, Cleaves & Miller. The cold origin of life: B. Implications based on pyrimidines and purines produced from frozen ammonium cyanide solutions. *Origins of Life Evol. Biosphere* (2002) **32**:209-18.

The Rates of Hydrolysis of HCN and Formamide

HCN and formamide have been implicated as important sources of prebiotic compounds such as amino acids and nucleobases. Most of the reactions of these compounds are second-order with respect to HCN or formamide. It is then of importance to be able to determine the relative rates of synthesis and destruction of these compounds to be able to determine the steady-state or maximal concentrations of these compounds in any given prebiotic locale. Many of the parameters for the hydrolysis of these compounds have not been precisely determined. Their central location in prebiotic synthesis warrants definitive determination of these quantities. We have measured the rates of hydrolysis of HCN and formamide effectively across a wide pH and temperature range, and find that lower temperatures are essential to the build-up of significant quantities of these compounds. Most significantly, we have found that only at extremely low temperatures could HCN have become sufficiently concentrated to polymerize, and that it is extremely unlikely that formamide could ever have served as a useful prebiotic solvent. The major uncertainty in these calculations is the production rate of HCN. Whether HCN was produced from atmospheric syntheses on the primitive earth or delivered from extraterrestrial sources, it is clear that the temperature of the early earth must have been rather low for the polymerization of HCN to have been an important process. This has important implications for constraining the composition of the early atmosphere if HCN polymerization was important for the origin of life. These results were published in Miyakawa, Cleaves & Miller. The cold origin of life: A. Implications based on the hydrolytic stabilities of hydrogen cyanide and formamide. *Origins of Life Evol. Biosphere* (2002) **32**:195-208.

Prebiotic Synthesis from CO Dominated Atmospheres

Most models of the primitive atmosphere around the time life originated suggest that the atmosphere was dominated by carbon dioxide, largely based on the notion that the atmosphere was derived via volcanic outgassing, and that those gases were similar to those found in modern volcanic effluent. These models tend to downplay the possibility of a strongly reducing atmosphere, which had been thought to be important for prebiotic synthesis and thus the origin of life. However, there is no definitive geologic evidence for the oxidation state of the early atmosphere and bioorganic compounds are not efficiently synthesized from CO_2 atmospheres. In the present study, it was shown that a CO-CO_2-N_2-H_2O atmosphere can give a variety of bioorganic compounds with yields comparable to those obtained from a strongly reducing atmosphere. Atmospheres containing carbon monoxide might therefore have been conducive to prebiotic synthesis and perhaps the origin of life. CO-dominant atmospheres could have existed if the production rate of CO from impacts of extraterrestrial materials were high or if the upper mantle had been more reduced than today. This investigation was published in Miyakawa, Yamanashi, Kobayashi, Cleaves & Miller. Prebiotic synthesis from CO atmospheres: Implications for the origins of life. Proc. Nat. Acad. Sci. USA (2002) **99**: 14628-14631

1997-2002 Cumulative NSCORT/Exobiology Publications
2002 Final Report (NASA NAG5-4546)

Stanley L. Miller Laboratory

a. Peer-Reviewed Journals

S. L. Miller. "Peptide Nucleic Acids and Prebiotic Chemistry." *Nature Structural Biology* **3**, 167-169 (1997).

S. L. Miller, J. W. Schopf, and A. Lazcano. "Oparin's "Origin of Life": Sixty Years After." *J. Mol. Evol.* **44**, 351-353 (1997).

J. P. Dworkin. "Attempted Prebiotic Synthesis of Pseudouridine." *Orig. Life Evol. Biosphere* **26**, 345-355 (1997).

R. Amirnovin. "An Analysis of the Metabolic Theory of the Origin of the Genetic Code." *J. Mol. Evol.* **44**, 473-476 (1997).

T. A. Kral, K. M. Brink, S. L. Miller, and C. P. McKay. "Hydrogen Consumption by Methanogens on the Early Earth." *Origins of Life and Evolution of the Biosphere* **28**, 311-319 (1998).

H. J. Cleaves and S. L. Miller. "Oceanic Protection of Prebiotic Organic Compounds from UV Radiation." *Proc. Nat. Acad. Sci. U.S.A.* **95**, 7260-7263 (1998).

M. Levy and S.L.Miller. "The Stability of the RNA Bases: Implications for the Origin of Life." *Proc. Nat. Acad. Sci. U.S.A.* **95**, 7933-7938 (1998).

R. Amirnovin and S. L.Miller. "The Coevolution Theory of the Origin of the Genetic Code." *J. Molec. Evol.* **48**, 253-255 (1999).

M. Levy and S. L. Miller. "The Prebiotic Synthesis of Modified Purines and Their Potential Role in the RNA World." *J. Molec. Evol.* **48**, 631-637 (1999).

M. Levy, S. L. Miller, and J. Oró. "Production of Guanine from NH_4CN Polymerizations." *J. Molec. Evol.* **49**, 165-168 (1999).

A.Lazcano and S. L. Miller. "On the Origin of Metabolic Pathways." *J. Molec. Evol.* **49**, 424-431 (1999).

K. E. Nelson, M. Levy and S. L. Miller. "Peptide Nucleic Acids Rather than RNA May Have Been the First Genetic Molecule. *Proc.Nat. Acad. Sci. U.S.A.* **97**, 3868-3871 (2000).

J. P. Dworkin and S. L. Miller. "A Kinetic Estimate of the Free Aldehyde Content of Aldoses." *Carbohydrate Research* **329**, 359-365 (2000).

* M. Levy and S. L. Miller. Prebiotic Synthesis of Adenine and Amino Acids Under Europa-like Conditions. *Icarus* **145**, 609-613 (2000).

* H. J. Cleaves and S. L. Miller. "The Nicotinamide Biosynthetic Pathway is a By-Product of the RNA World. *J. Molec. Evol.* **52**, 73-77 (2001).

* K. E. Nelson, M. P. Robertson, M. Levy and S. L. Miller. "Concentration by Evaporation and the Prebiotic Synthesis of Cytosine." *Origins Life Evol.Biosphere* **31**, 221-229, 2001.

a. Peer-Reviewed Journals *(Continued)*

*J. P. Dworkin, A. Lazcano and S. L. Miller. "The Roads To and From the RNA World." (Submitted) *J. Theor Biol.* 2001.

*S. Miyakawa, H. J. Cleaves and S. L. Miler. "The Cold Origin of Life: A. Implications Based on the Hydrolytic Stabilities of Hydrogen Cyanide and Formamide." *Origins Life Evol.Biosphere* **32**, 195-208, 2002.

*S. Miyakawa, H. J. Cleaves and S. L. Miller. "The Cold Origin of Life: A. Implications Based on Pyrimidines and Purines Produced from Frozen Ammonium Cyanide Solutions." *Origins Life Evol.Biosphere* **32**, 209-218, 2002.

*S. Miyakawa, H. Yamanashi, K. Kobayashi, H. J. Cleaves and S.L. Miller. "Prebiotic Synthesis from CO Atmospheres: Implications for the Origins of Life." *Proc.Nat. Acad. Sci. U.S.A* , In press (2002).

b. Conference Volumes/Book Chapters

S. L. Miller. "The Endogenous Synthesis of Organic Compounds." **In** *The Molecular Origins of Life - Assembling Pieces of the Puzzle.* Edited by A. Brack (Cambridge University Press, Cambridge U.K. 1998) pp.59-85.

S. L. Miller and A. Lazcano. "Facing up to Chemical Realities: Life did not Begin at the Growth Temperatures of Hyperthermophiles." **In** *Thermophiles: The Keys to Molecular Evolution and the Origin of Life?* Edited by J. Wiegel and M.W.W. Adams (Taylor & Francis, London) pp 127-133 (1998).

M. Levy and S. L. Miller. "Prebiotic Synthesis of Adenine and Amino Acids Under Europa-like Conditions." *Icarus* **145**, 609-613 (2000).

c. General Interest Articles

S. L. Miller, J.W. Schopf and A. Lazcano. "Point Counterpoint: Oparin and Lysenko." *J. Mol. Evol.* **45**, 339-341 (1997).

S. L. Miller and J.R. Lyons. Technical comment on "The Early Faint Sun Paradox: Organic Shielding of Ultraviolet-Labile Greenhouse Gases." by C. Sagan and C. Chyba. *Science* **279**, 775 (1998).

S. L. Miller and J. R. Lyons. "Organic Shielding of Greenhouse Gases on the Early Earth." *Science* **278**, 779 (1998). http://www.sciencemag.org/cgi/content/full/279/5352/779a

d. Abstracts of Papers at National/International Meetings

S. L. Miller. "Prebiotic Synthesis of Organic Compounds and the Origin of Life." COSMOS, Life and Human Being. Fourth International Symposium of the Graduate University for Advanced Studies, Hayama, Kanagawa, Japan, March 6-8, 1997.

S. L. Miller. "The Pre-RNA World: Alternatives to AUGC and the Ribose Phosphate Backbone in the First Genetic Material." Symposium on Origin of Life, Swedish Natural Science Research Council, Arken, Sweden, April 7, 1997

d. Abstracts of Papers at National/International Meetings *(Continued)*

M. Levy and S. L. Miller. "A Temperature Estimate for the Aqueous Alteration of the Murchison Meteorite Based on the Presence of Purines and Pyrimidines." ACS 213th Ntl Meeting, Geological Chemistry Division, San Francisco, California, April 17, 1997. *ACS Abstracts of Papers* **213**:GEOC214 (1997).

S. L. Miller. "Prebiotic Chemistry and the Origin of Life on the Earth." Montana State University, Bozeman, Montana. April 29, 1997

S. L. Miller. "Prebiotic Chemistry and the Origin of Life on the Earth." National Institute of Standards and Technology, Gaithersburg, Maryland. June 3, 1997

S. L. Miller. "Origin and Early Evolution of Life." Universidad deGuadalajara, Mexico. July 22, 1997

J. L. Bada, S. L. Miller, G. Arrhenius, R. F. Doolittle, and C. Wills. "The NASA Specialized Center of Research and Training (NSCORT) in Exobiology." Sixth Symposium On Chemical Evolution and the Origin and Evolution of Life. Ames Research Center, Moffett Field, California. November 17-20, 1997

S. L. Miller, and M. Levy. "Innovations in College Chemistry Teaching." Modular Chemistry Consortium Research Conference. January 4-8, 1998

H. J. Cleaves and S. L. Miller. "Oceanic Protection of Prebiotic Organic Compounds from Ultra-violet Radiation." EOS Transactions American Geophysica Union **79(1)**, Ocean Sciences Supplement OS 56 (1998)

M. Levy and S. L. Miller. "A high temperature origin of life may be possible, but it is inconsistent with an RNA world." EOS Transactions American Geophysica Union **79(1)**, Ocean Sciences Supplement OS 56 (1998)

A. Lazcano and S. L. Miller. "The Stability of Early Macromolecules: Where are they now?" EOS Transactions American Geophysica Union **79(1)**, Ocean Sciences Supplement OS 55 (1998)

J. R. Lyons and S. L. Miller. "The Production of Organics in a N_2, CO_2 H_2 Early Atmosphere." EOS Transactions American Geophysica Union. **79(1)**, Ocean Sciences Supplement OS 55 (1998)

S. L. Miller. "The Origins of Life on the Earth." Lawrence Livermore Laboratory, Livermore, California. May 14, 1998

S. L. Miller. "The Origins of Life on the Earth." International Symposium on Origins of Species and Evolutionary Change. Ramon Areces Foundation, Madrid, Spain. June 8, 1998

S. L. Miller. "Prebiotic Chemistry of the Origin of Life." Universidad Internacional Menéndez Pelayo Origen de la Vida ¿En la Tierra Y Otros Planetas? Valencia, Spain October 13, 1998

S. L. Miller. "The Building Blocks of Life." Symposium on Fundació "la Caixa"(The Limits of Life) Museu de la Ciéncia Barcelona, Spain November 12, 1998

S. L. Miller. "The Origins of Life on Earth." Societat Catalana de Biologia Filial de L'Institut D'Estudis Catalans Barcelona, Spain November 16, 1998

C. Sagan and C. Chyba. Technical Comment on "The Early Faint Sun Paradox: Organic Shielding of Ultraviolet-Labile Greenhouse Gases". S. L. Miller and J. R. Lyons, Science **279**, 775 (1998), www.sciencemag.org/content/full/279/5352/779a

d. Abstracts of Papers at National/International Meetings *(Continued)*

E. Borquez and S. L. Miller. "The Insoluble HCN Polymer is a Prebiotic Source of Adenine" **P1**, 8 International Symposium on the Study of the Origin of Life, San Diego, California, August, 1999.

J. P. Dworkin, M. Levy, S. L. Miller, and J. L. Bada. "The Cosmo-geochemistry of Amino Acid Synthesis from Hydrogen Cyanide," **C A2** 4, International Symposium on the Study of the Origin of Life, San Diego, California, August, 1999.

H. J. Cleaves and S. L. Miller. "The Semi-Enzymatic Origin of the Biosynthetic Pathways" **C B1** 8, International Symposium on the Study of the Origin of Life, San Diego, California, August, 1999.

J. J. Eisch, S. L. Miller, "Photochemical Transition Metal-Mediated Reactions in Prebiotic Synthesis", **P1** 9, International Symposium on the Study of the Origin of Life, San Diego, California, August, 1999.

C. Estevez, S. L. Miller, "Equilibrium and Kinetics of the Aldol Condensation of Cyanoacetal-dehyde" **P1** 10, International Symposium on the Study of the Origin of Life, San Diego, California, August, 1999.

M. Levy and S. L. Miller, "Modified Purines from the Reaction of Hydrogen Cyanide Novel Phosphoxy-Derivatives of Cytosine", **P1**, 22, International Symposium on the Study of the Origin of Life, San Diego, California, August, 1999.

Q. Maughan, S. L. Miller, "A Novel Prebiotic Synthesis of Amino Acids", **P1** 23, International Symposium on the Study of the Origin of Life, San Diego, California, August, 1999.

K. E. Nelson, M. Levy and S. L. Miller, "The Prebiotic Synthesis of the Componentsof Peptide Nucleic Acid, A Possible First Genetic Material", **C A3** 6, International Symposium on the Study of the Origin of Life, San Diego, California, August, 1999.

K. E. Nelson, M. Levy and S. L. Miller, "Peptide Nucleic Acids Rather than RNA may have been the First Genetic Molecule," Sixth Trieste Conference on Chemical Evolution, Trieste, Italy, September 18-22, 2000.

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*Preprint or reprint submitted with this report.

2001-2002 Progress Report – Leslie Orgel

(a.) Non-Enzymatic Synthesis of Peptides in Aqueous Solution

A major problem for prebiotic chemistry is the synthesis of peptides in aqueous solutions using plausibly "prebiotic" condensing agents. One of our publications describes earlier work using thio acids. Here I describe our most recent experiments.

Salts of trimetaphosphoric acid have been studied extensively as condensing agents for the formation of glycine peptides. The reactions are interesting because trimetaphosphates are formed readily from inorganic phosphates by heating, an optimally "prebiotic" synthesis. Unfortunately, these reactions are relatively inefficient.

We have discovered that aspartic acid is activated efficiently by the trimetaphosphate ion via a novel mechanism. If decaglutamic acid is incubated with aspartic acid (1M) and sodium trimetaphospate (0.5M) at 37°C, adducts with up to 10 aspartic acid residues are found (Fig. 1). The mechanism of the reaction is surprising, involving a cyclic anhydride. The product consists of a core of decaglutamic acid decorated with aspartic acid residues (Fig. 2). The proposed mechanism explains why only aspartic acid reacts efficiently. This research will be published in Helvetica Chem Acta.

(b.) Amyloids and Peptide Replication

The possibility that certain peptide sequences might be self-replicating has been explored for reactions in homogenous aqueous solution, but with very little experimental success. We have began to explore the possibility of peptide replication on the surface of an insoluble ß sheet aggregate. This work is at a very preliminary stage, and I propose to continue working in the general area in a specialized peptide biology laboratory at SRI.

Our initial work was with oligo(glutamine)s. We succeeded in showing that certain alternating peptides, particularly (gln arg) repeats, adhere to the surface of oligoglutamine amyloids and prevent the growth of the aggregates. This kind of inhibition clearly has implications for the prevention of amyloid deposition. We have not yet succeeded in using amyloids as templates for self-replication.

(c.) Prebiotic Synthesis of Biomonomers

This is a minor part of our program. We did discover a very simple, single step synthesis of adenine from hydrogen cyanide tetramep and ammonium formate. The maximum yield was about 15% This is another variation on a well-explored theme.

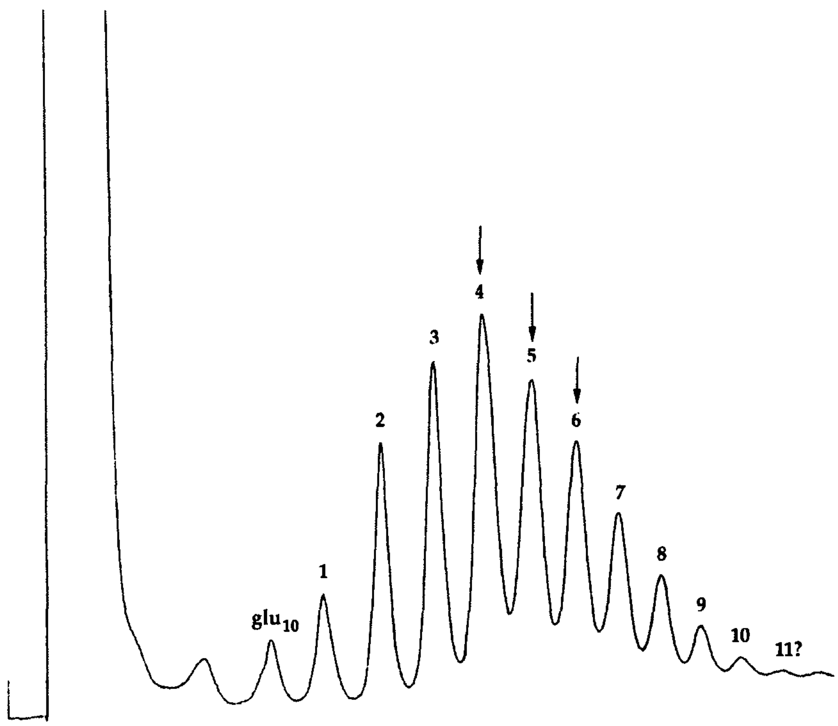

Figure 1. HPLC elution profile, using a slow gradient, of products From a reaction with 1M aspartic acid, 2mM glu_{10}, 0.5 trimetaphosphate, 1M $MgCl_2$ at 37° for 1 day. The numbers above the peaks indicate the oligomer lengths. The arrows mark the material that was collected for analysis by mass spectroscopy.

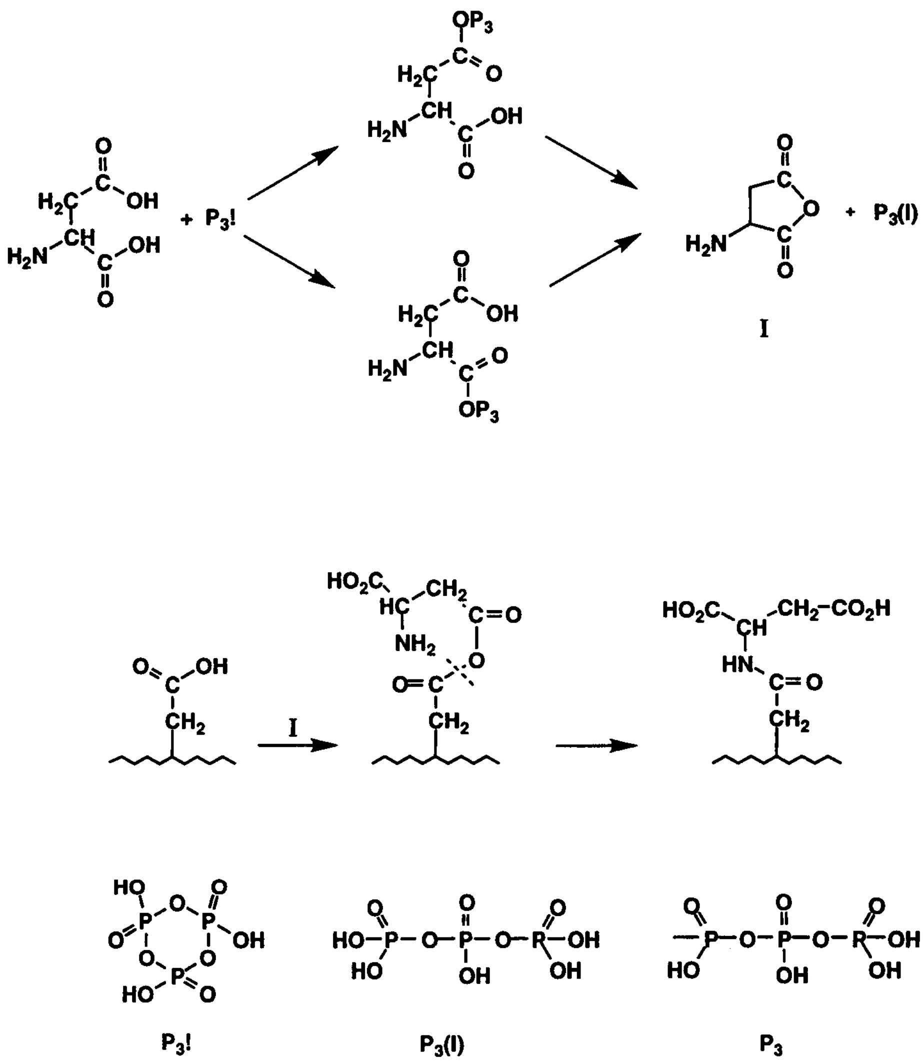

Figure 2. Proposed steps in the addition of aspartic acid to the side-chains of glu_{10}.

1997-2002 Cumulative NSCORT/Exobiology Publications
2002 Final Report (NASA NAG5-4546)

Leslie E. Orgel Laboratory

a. Peer-Reviewed Journals:

Schmidt, Jurgen G., Nielsen, Peter E. and Orgel, Leslie E. (1997) "Enantiomeric cross-inhibition in the synthesis of oligonucleotides on a nonchiral template," *J. Amer. Chem. Soc.* **119(6):** 1494-1495.

Bruick, Richard K., Koppitz, Marcus, Joyce, Gerald F. and Orgel, Leslie E. (1997) "A simple procedure for constructing 5'-amino-terminated oligodeoxynucleotides in aqueous solution," *Nucleic Acids Res.* **25(6):**1308-1316.

Liu, Rihe and Orgel, Leslie E. (1997) "Efficient oligomerization of negatively-charged β-amino acids at -20°C," *J. Amer. Chem. Soc.* **119(20):**4791-4792.

Liu, Rihe and Orgel, Leslie E. (1997) "Oxidative acylation using thioacids," *Nature* **389**:52-54.

Schmidt, Jurgen G., Nielsen, Peter E. and Orgel, Leslie E. (1997) "Information transfer from peptide nucleic acids to RNA by template-directed syntheses," *Nucleic Acids Res.* **25**:4797-4802.

Schmidt, Jurgen G., Christensen, Leif, Nielsen, Peter E. and Orgel, Leslie E. (1997) "Information transfer from DNA to peptide nucleic acids by template-directed syntheses," *Nucleic Acids Res.* **25**:4792-4796.

Liu, Rihe and Orgel, Leslie E. (1998) "Polymerization of β-amino acids in aqueous solution," *Orig. Life Evol. Biosphere*. **28**:47-60.

Orgel, Leslie E. (1998) "The origin of life - how long did it take?" *Orig. Life Evol. Biosphere*. **28**:91-96.

Orgel, Leslie E. (1998) "Polymerization on the rocks: theoretical introduction," *Orig. Life Evol. Biosphere* **28**:227-234.

Hill, Jr., Aubrey R., Bohler, Christof, and Orgel, Leslie E. (1998) "Polymerization on the rocks: negatively charged a-amino acids," *Orig. Life Evol. Biosphere*. **28**:235-243.

Liu, Rihe and Orgel, Leslie E. (1998) "Polymerization of β-amino acids and arginine," *Orig. Life Evol. Biosphere*. **28**:245-257.

Koppitz, Marcus, Nielsen, Peter E. and Orgel, Leslie E. (1998) "Formation of oligonucleotide-PNA chimeras by template-directed ligation," *J. Am. Chem. Soc.* **120**:4563-4569.

a. Peer-Reviewed Journals *(continued):*

Kozlov, Igor A., Nielsen, Peter E. and Orgel, Leslie E. (1998) "A method for the ^{32}P labeling of peptides or peptide nucleic acid oligomers," *Bioconjugate Chemistry* **9**:415-417.

Kozlov, Igor and Orgel, Leslie E (1998) "The synthesis of 2'-deoxy-L-cytidine-3'-phosphate," *Nucleosides and Nucleotides* **17**:2249-2254.

Kozlov, Igor A., Pitsch, Stefan and Orgel, Leslie E. (1998) "Oligomerization of activated D- and L-guanosine mononucleotides on templates containing D- and L-deoxycytidylate residues," *Proc. Natl. Acad. Sci. U. S. A.* **95**: 13448-13452.

Orgel, Leslie E. (1998) "The origin of life – a review of facts and speculations," *Trends in Biochemical Sciences* **23**:491-500.

Joyce, G. F. and Orgel, L. E. In *The RNA World, Second Edition* (R. F. Gesteland, T. R. Ceck and J. F. Atkins, editors), pp. 49-77. Cold Spring Harbor Laboratory Press, Cold Spring Harbor, New York. (1998).

Hill, Aubrey R. Jr. and Orgel, Leslie E. (1999) "Oligomerization of L-γ-carboxyglutamic acid," *Orig. Life Evol. Biosphere* **29:** 115-122.

Eriksson, Magdalena; Christensen, Leif; Schmidt, Jurgen; Haaima, Gerald; Orgel, Leslie E. and Nielsen, Peter E. (1998) "Sequence dependent N-terminal rearrangement and degradation of peptide nucleic acid (PNA) in aqueous solution," *New J. Chem.* **22**:1055-1059

Kozlov, Igor A.; Politis, Panagiotis K.; Pitsch, Stefan; Herdewijn, Piet; Orgel, Leslie E. (1999) "A highly enantio-selective hexitol nucleic acid template for nonenzymatic oligoguanylate synthesis," *J. Amer. Chem. Soc.*, **121:** 1108-1109

Kozlov, Igor A.; Politis, Panagiotis K.; Van Aerschot, Arthur; Busson, Roger; Herdewijn, Piet; Orgel, Leslie E. (1999) "Nonenzymatic synthesis of RNA and DNA oligomers on hexitol nucleic acids templates: The importance of the A-structure," *J. Amer. Chem. Soc.*, **121:** 2653-2656

Kozlov, Igor A.; De Bouvere, Bart; Van Aerschot, Arthur; Herdewijn, Piet; Orgel, Leslie E. (1999) "Efficient transfer of information from hexitol nucleic acids to RNA during non-enzymatic oligomerization," *J. Amer. Chem. Soc.,* **121:** 5856-5859

Chu, Barbara C. F.; Orgel, Leslie E. (1999) "Peptide-formation on cysteine-containing peptide scaffolds," *Origins Life Evol. Biosphere*, **29:** 441-449

Kozlov, Igor A.; Orgel, Leslie E (1999) "Oligomerization of deoxyguanosine 5'phosphoro-2-methylimidazolide on a polycytidylate template," *Origins Life Evol. Biosphere*, **29:** 593-595

a. Peer-Reviewed Journals ***(continued)***

Kozlov I.; Zielinski, M,; Allart, B.; Kerremans, L.; Van Aerschot, A.; Busson, R.; Herdewijn, P.; Orgel, L.E. (2000) "Nonenzymatic template-directed reactions on altritol oligomers, pre-organized analogues of oligonucleotides," *Chemistry-A European Journal,* **6:** 151-155

Gao, Kui; Orgel, Leslie E. (1999) "Nucleic acid duplexes incorporating a covalently-bonded base pair," *Proc. Nat'l. Acad. Sci., USA,* **96:** 14837-14842

Gao, Kui and Orgel, Leslie E. (2000) "Polyphosphorylation and non-enzymatic template-directed ligation of oligonucleotides," *Origins Life Evol. Biosphere,* **30:** 45-51.

Kozlov, Igor A. and Orgel, Leslie.E. (1999) "Nonenzymatic oligomerization reactions on templates containing inosinic acid or diaminopurine nucleotide residues," *Helvetica Chem Acta,* **82:** 1799-1805

Maurel, Christine-Marie and Orgel, Leslie E. (2000) "Oligomerization of α-thioglutamic acid," *Origins of Life Evol. Biosphere,* **30:** 423-430.

Gao, K.; Orgel, L.E. (2000) "A convenient synthesis of a novel nucleoside analogue: 4-(α-diformyl-methyl)-1-(β-D-ribofuranosyl)-2-pyrimidinone," *Nucleosides and Nucleotides,* **19**: 935-940.

Zielinski, M.; Kozlov, I.; Orgel, L.E. (2000) "A comparison of RNA with DNA in Template-Directed Synthesis," *Helvetica Chem Acta* **83**: 1678-1684.

Orgel, L.E. (2001) "The origin of biological information," Proceedings of the 11th Annual CSEOL Symposium, April 7, 2000 (Berkeley, CA: Univ. of California Press), J.W. Schopf (Ed.)

*Kozlov I.; Orgel, L.E.; Nielsen, P.E. (2000) "Remote enantio selection transmitted by an achiral PNA backbone," Angewandte Chemie **39**: 4292-4295.

Kozlov I.; Orgel, L.E. (2000) "Nefermentativnyi matricno-napravlennyi sintez RNK," *Molekularnaya Biologlya* (in Russian), **34** (6), 1-10.

Orgel, L.E. (2000) "Self-organizing biochemical cycles," *Proc. Nat'l. Acad. Sci. U.S.A.*,**97**: 12503-12507.

*Wen, K; Han, H.; Hoffman, T. Z.; Janda, K. D.; Orgel, L. E. (2001) "The synthesis of β-peptides containing guanidino groups," *Bioorganic & Medicinal Chemistry Letters,* **11**: 689-691.

*Wen, K; Orgel, L. E. (2001) 'The specificity of peptide chain extension by N-carboxyanhydrides," *Origins Life Evol. Biosphere,* **31**: 241-248.

*Orgel, L.E. (2000) "A simpler nucleic acid," *Science,* **290**: 1306-1307.

a. Peer-Reviewed Journals *(continued)*

*Chu, B.C.F. and Orgel, L.E. (2001) "Inhibition of oligo(glutamine) precipitation by glutamine-containing peptides," *Biochemical and Biophysical Communications*, **283**: 351-355.

*Gao, Kui and Orgel, Leslie E. (2001) "Hydrolysis of $tRNA^{Phe}$ on suspension of amino acids," *Helvetica Chimica Acta*, **84**: 1347-1354.

b. Book Chapters

Orgel, Leslie E. (2002) The Origin of Biological Information, in *Life's Origin, The Beginnings of Biological Evolution* (ed. J. William Schopf), University of California Press, Berkeley, CA. 140-157.

---

*Reprint submitted with this report.

1997-2002 Cumulative NSCORT/Exobiology Publications
2002 Final Report (NASA NAG5-4546)

Albert Eschenmoser Laboratory

a. Peer-Reviewed Journals

Bolli, M., Micura, R., Eschenmoser, A. Pranosyl-RNA: chiroselective self-assembly of base sequences by ligative oligomerization of tetranucleotide-2',3'-cyclophosphates (with a commentary concerning the origin of biomolecular homochirality) *Chemistry & Biology* **4**, 309-320, 1997.

Lehmann, C., Schweizer, B., Leumann, C., Eschenmoser, A. Chemie von α-Aminonitrilen. 22. Mitt. Regioselektive Synthese und Kristallstruktur von Uroporphyrinogen-(Typ I)-octanitril (Oskar Jeger zum 80. Geburtstag gewidmet) *Helv.Chim.Acta* **80**, 1421-1442, 1997.

Bolli, M., Micura, R., Pitsch,S., Eschenmoser, A. Pyranosyl-RNA: Further Observations on Replication (Dedicated to Dieter Seebach on the occasion of his 60th birthday) *Helv.Chim.Acta* **80**, 1901-1951, 1997.

Eschenmoser, A. Towards a Chemical Etiology of Nucleic Acid Structure, *Origins Life Evol. Biosphere* **27**, 535-553, 1997.

R. Micura, R., Bolli, M., Windhab, N., Eschenmoser, A. Auch Pyranosyl-RNA bildet Haarnadel-Strukturen. *Angew.Chem.* **109**, 899-902, 1997. Pyranosyl-RNA Also Forms Hairpin Structures. *Angew.Chem.Int.Ed.Engl.* **36**, 870-873, 1997.

Groebke, K., Hunziker, J., Fraser, W., Peng, L., Diederichsen, U., Zimmermann, K., Holzner, A., Leumann, C., Eschenmoser, A. Why Pentose- and Not Hexose-Nucleic Acids? Part V. Purine-Purine Pairing in homo-DNA: Guanine, Isoguanine, 2,6-Diaminopurine, and Xanthine. *Helv. Chim. Acta.* **81**, 375-474, 1998.

Micura, R., Kudick, R., Pitsch, S., Eschenmoser, A. "Gegensätzliche Orientierung der Rückgratneigung bei Pyranosyl-RNA und homo-DNA korreliert mit entsprechend gegensätzlicher Orientierung von Duplexeigenschaften". Opposite Orientation of Backbone Inclination in Pyranosyl-RNA and Homo-DNA Correlates with Opposite Directionality of Duplex Properties. *Angew. Chem Int. Ed.* **38**, 680-683, 1999.

Krishnamurthy, R., Arrhenius, G., Eschenmoser, A. Formation of glycolaldehyde phosphate from glycolaldehyde in aqueous solution *Origins Life Evol. Biosphere* **29**, 333-354, 1999.

a. Peer-Reviewed Journals *(Continued)*

Beier, M., Reck, F., Wagner, T., Krishnamurthy, R., Eschenmoser, A. Chemical Etiology of Nucleic Acid Structure: Comparing Pentopyranosyl-(2'$\rightarrow$4') Oligonucleotides with RNA. *Science* **283**, 699-703, 1999.

Jungmann, O., Wippo, H., Stanek, M., Huynh, H. K., Krishnamurthy, R., Eschenmoser, A. Promiscuous Watson-Crick Cross-Pairing within the Family of Pentopyranosyl (4'$\rightarrow$2') Oligonucleotides. *Organic Letters* **1**, 1527-1530, 1999.

Reck, F., Wippo, H., Kudick, R., Krishnamurthy, R., Eschenmoser, A. L-α-Lyxopyranosyl (4'$\rightarrow$3') Oligonucleotides: A Base-Pairing System Containing a Shortened Backbone. *Organic Letters* **1**, 1531-1534, 1999.

Eschenmoser, A., "Chemical Etiology of Nucleic Acid Structure" (Review), Science **284**, 2118-2124, 1999.

Eschenmoser, A., Krishnamurthy, R. Chemical Etiology of Nucleic Acid Structure. *Pure Appl. Chem.*, **72**, 343-345, 2000.

Krishnamurthy, R., Guntha, S., Eschenmoser. A. Regioselective α-Phosphorylation of Aldoses in Aqueous Solution. *Angewandte Chemie Int. Ed.* **39**, 2281-2285, 2000.

Schöning, K.-U., Scholz, P., Guntha, S., Wu, X., Krishnamurthy, R., Eschenmoser, A. Chemical Etiology of Nucleic Acid Structure: The α-Threofuranosyl-(3'$\rightarrow$2') Oligonucleotide System. *Science* **290**, 1347-1351, 2000.

*Reck, F., Wippo, H., Kudick, R., Krishnamurthy, R. Eschenmoser, A. Pentopyranosyl Oligonucleotide Systems. The a-L-Lyxopyranosyl-(4'Æ2')-oligonucleotide System. *Helv. Chim .Acta.* **84**, 1778-1804, 2001.

*Wippo, H., Reck, F., Kudick, R, Ramasehsan, M., Ceulemans, G., Bolli, M., Krishnamurthy, R., Eschenmoser, A. Pentopyranosyl Oligonucleotide Systems. Systems with Shortened Backbones: (D)-b-Ribopyranosyl(4'Æ3')- and (L)-a-Lyxopyranosyl-(4'Æ3')-oligonucleotide System. *Bioorg. Med. Chem.* **9**, 2411-2428, 2001.

*Wagner, T., Hoan, H. K., Krishnamurthy, R., Eschenmoser, A. Pentopyranosyl Oligonucleotide Systems. Systems with Shortened Backbones: *b*-(D)-Xylopyranosyl-(4'Æ2')-oligonucleotide System. *Helv. Chim .Acta.* **2002**, *85*, 399-416.

* Wu, X., Guntha, S., Ferencic, M., Krishnamurthy, R., Eschenmoser, A. Base-Pairing Systems Related to TNA: a-Threofuranosyl Oligonucleotides Containing Phosphoramidate Linkages. *Org. Lett.* **2002**, *4*, 1279-1282.

a. Peer-Reviewed Journals *(Continued)*

*Wu, X., Delgado, G., Krishnamurthy, R., Eschenmoser, A. 2,6-Diaminopurines in TNA: Effect on Duplex Stabilities and on the Efficiency of Template-Controlled Ligations. *Org. Lett.* **2002**, *4*, 1283-1286.

b. Book Chapters

Eschenmoser, A. Thoughts and Experiments on a Chemical Etiology of Nucleic Acid Structure. *In:* Pioneering Ideas for the Physical and Chemical Sciences. Fleischhacker, W., Schönfeld, T. (Eds.). Plenum Press, New York, NY, 1997, p. 41.

Eschenmoser, A. Foreword, in: B. Kräutler, D. Arigoni, B.T. Golding (Eds.), 'Vitamin B_{12} and B_{12}-Proteins' (4th European Symposium on 'Vitamin B_{12} and B_{12}-Proteins', Innsbruck/A, Sept. 1996), Wiley-VCH Verlag GmbH, Weinheim, 1998, p. V-VI.

c. General Interest articles

Eschenmoser, A. Vladimir Prelog zum Gedenken, Chimia **52**, 74-75, 1998.

Eschenmoser, A. In memoriam Vlado Prelog, Chimia **53**, 126-132, 1999.

Eschenmoser, A. Gedenkworte für Alexander Lord Todd (2.10.1907-10.1.1997) in: 'Reden und Gedenkworte', Orden pour le mérite für Wissenschaften und Künste, Lambert Schneider, Gerlingen, 1997, Bd. 27, S. 31-37

Eschenmoser, A.Ein 'Dorfältester' in der Welt der Chemie. Vladimir Prelog zum Gedenken, 'Neue Zürcher Zeitung', Nr. 19, 24./25.1.1998

d. Papers at National and International Meetings and Symposia

Krishnamurthy, R., Pitsch, S., Eschenmoser, A., Arrhenius, G. Toward RNA – the phosphorylation of glycolaldehyde, *NASA-ARC Symposium, Mountainview, CA, Nov.*1997.

Arrhenius, G., Krishnamurthy, R., Pitsch, S., Eschenmoser, A. Surface active minerals as hosts for organic reactions, *EGU 10, Strasbourg, France, March-April* 1999.

Krishnamurthy, R, Arrhenius, G., Eschenmoser, A. Formation of Glycolaldehyde Phosphate from Glycolaldeyde in Aqueous Solution, *12th International Conference on the Origin of Life and 9th ISSOL, San Diego, California, USA, July* 1999.

d. Papers at National and International Meetings and Symposia *(Continued)*

Eschenmoser, A., Krishnamurthy, R. Chemical Etiology of Nucleic Acid Structure, *International IUPAC Symposium on Bioorganic Chemistry (ISBOC-5), Pune, India, Jan.-Feb.* 2000.

Krishnamurthy, R. The Synthesis of Sugar Phosphates, *Gordon Research Conference on Origin of Life, July* 2000.

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1997-2002 Cumulative NSCORT/Exobiology Publications
2002 Final Report (NASA NAG5-4546)

Antonio Lazcano Laboratory

a. Peer-Reviewed Journals

S. L. Miller, J. W. Schopf, and A. Lazcano. 1997 "Oparin's "Origin of Life": Sixty Years After." *J. Mol. Evol.* **44**, 351-353.

A.Lazcano and S. L. Miller. 1999 "On the Origin of Metabolic Pathways." *J. Molec. Evol.* **49**, 424-431.

Bada, J. L. and A. Lazcano, 2000. Stanley Miller's 70th birthday. *Origins Life Evol. Biosphere* **30**, 107-112.

Becerra, A., Silva, E., Velasco , A., Lloret, L., Islas, S., and Lazcano, A. 2000 Molecular phylogenies and the origin or life: des liasons dangereuses?

Bada, J.L., A. Lazcano, 2002 Origin of Life – Some like it hot, but not the first biomolecules, *Science* **296**, 1982-1983.

Lazcano, A, J. L. Bada, 2002 Discussing the Origin of Life – Response 2002 *Science* **298**, 749.

Bada, J.L., A. Lazcano, 2002 Miller revealed new ways to study the origin of life – Science advances as one theory builds on another: Miller didn't just update Lob's work. *Nature* **416**, 475.

Dworkin, J., Lazcano, A., and Miller, S. L. (2001) The roads to and from the RNA world. Journal of Theoretical Biology (submitted).

Chela Flores, J., Raulin, F., and Oro, J. (eds). 2002 Proceedings of the Sixth Trieste Meeting on Chemical Evolution (Kluwer, Dordrecht) (in progress).

b. Books Chapters

S. L. Miller and A. Lazcano. "Facing up to Chemical Realities: Life did not Begin at the Growth Temperatures of Hyperthermophiles." **In** *Thermophiles: The Keys to Molecular Evolution and the Origin of Life?* Edited by J. Wiegel and M.W.W. Adams (Taylor & Francis, London) pp 127-133 (1998).

c. Abstracts of Papers at National/International Meetings

A. Lazcano and S. L. Miller. "The Stability of Early Macromolecules: Where are they now?" EOS Transactions American Geophysica Union **79(1)**, Ocean Sciences Supplement OS 55 (1998).

Bada, J. L., G. Kminek and A. Lazcano "Electric discharges and the origin of life: a historical reassessment of early experimental work." 12th International Conference on the Origin of Life and 9th International Society for the Origin of Life Meeting, La Jolla, CA July 11-16, 1999.

1997-2002 Cumulative NSCORT/Exobiology Publications
2002 Final Report (NASA NAG5-4546)

Julius Rebek Laboratory

a. Peer-Reviewed Journals

R. Meissner, X. Garcias, S. Mecozzi and J. Rebek, Jr., "Synthesis and Assembly of New Molecular Hosts: Solvation and the Energetics of Encapsulation." J. Am. Chem. Soc. 119, 77-85 (1997).

S. Mecozzi and J. Rebek, Jr., "The 55% Solution: A Formula for Molecular Recognition in the Liquid State." Chemistry-A European Journal 4, 1016-1022 (1998).

*J. Chen, S. Körner, S.L. Craig, D.M. Rudkevich, J. Rebek, Jr. Amplification by compartmentalization. *Nature*, **2002**, *415*, 385-386.

*J. Chen, S. Körner, S.L. Craig, S. Lin, D.M. Rudkevich, J. Rebek, Jr. Chemical Amplification with Encapsulated Reagents. *Proc. Natl. Acad. Sci. USA*, **2002**, *99*, 2593-2596.

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1997-2002 Cumulative NSCORT/Exobiology Publications
2002 Final Report (NASA NAG5-4546)

Christopher Wills Laboratory

a. Peer-Reviewed Papers:

Field, D. and C. Wills 1998. Abundant microsatellite polymorphism in S. cerevisiae, and the different distributions of microsatellites in prokaryotes and eukaryotes, result from strong mutational pressures and a variety of selective forces. Proc. Natl. Acad. Sci. U.S. 95: 1647-1652.

Metzgar, D., D. Field, R. Haubrich and C. Wills 1998a. Sequence analysis of a complex coding-region microsatellite in Candida albicans resolves homoplasies and provides a high-resolution tool for genotyping. FEMS Immunol. and Med. Microbiol. 20: 103-109.

Metzgar, D., A. van Belkum, D. Field, R. Haubrich and C. Wills 1998b. Random amplification of polymorphic DNA and microsatellite genotyping of pre- and post-treatment isolates of Candida albicans from HIV-infected patients on different fluconazole regimens. J. Clin. Microbiol. 36: 2308-2313.

Moxon, R. and C. Wills 1999. DNA microsatellites: agents of evolution? Scientific American 280: 72-77.

Field, D., M. O. Magnasco, E. R. Moxon, D. Metzgar, M. M. Tanaka, C. Wills and D. S. Thaler 1999. Contingency loci, mutator alleles, and their interactions. Ann. N.Y. Acad. Sci. 870: 378-382.

Davis, C., D. Field, D. Metzgar, T. Westmoreland, R. Saiz, P. Morin, I. L. Smith, S. A. Spector and C. Wills 1999. Numerous length polymorphisms at short tandem repeats in a viral genome. J. Virol. 73: 6265-6270.

Metzgar, D. and C. Wills 2000. Evolutionary changes in mutation rates and spectra and their influence on the adaptation of pathogens (review). Microbes and Infection 2: 1513-1522.

Metzgar, D., J. Bytof and C. Wills 2000. Selection against frameshift mutations limits microsatellite expansion in coding DNA. Genome Research 10: 72-80.

*Metzgar, D., E. Thomas, C. Davis, D. Field and C. Wills 2000. The microsatellites of Escherichia coli: an analysis of the variability and distribution of short repetitive DNAs in a nonpathogenic prokaryote. Mol. Biol. Evol. 39:183-190.

a. Peer-Reviewed Papers *(Continued)*

Birdsell, J. and C. Wills 2001. The Evolutionary Origin and Maintenance of Sexual Recombination: a Review of Contemporary Models. Evolutionary Biology (in press).

Metzgar, D. and C. Wills 2000. Evidence for the adaptive evolution of mutation rates (review). Cell 101: 581-584.

*Wills, C. 2000. How we defend ourselves against infectious disease. ASM News 66: 523-530.

*Chang, D. K., D. Metzgar, C. Wills and C.R. Boland (2001). Microsatellites in the eukaryotic DNA mismatch repair genes as modulators of evolutionary mutation rate. Genome Research **11**: 1145-1146.

*Metzgar, D., L. Liu, C. Hansen, K. Dybvig and C. Wills (2002). Domain-level differences in microsatellite distribution and content result from different relative rates of insertion and deletion mutations. Genome Research 12: 408-413.

*Smith, D., D. Metzgar, J. Fierer and C. Wills (2002). Fatal Saccharmyces cerevisiae aortic graft infection. Journal of Clinical Microbiology: 40: 2691-2692.

.

b. Reviews

Metzgar, D. and C. Wills 2000. Evidence for the adaptive evolution of mutation rates (review). Cell 101: 581-584.

Birdsell, J. and C. Wills 2001. The Evolutionary Origin and Maintenance of Sexual Recombination: a Review of Contemporary Models. Evolutionary Biology (in press).

c. Books

Wills, C. and J. Bada. 2000. The Spark of Life: Darwin and the Primeval Soup. Cambridge, MA, Perseus Books.

Wills, C., R. Condit, S. Hubbell, R. Foster and N. Manokaran (2002). Comparable non-random forces act to maintain diversity in both a new- and an old-world forest plot. Forest Diversity and Dynamics: Results from a Network of Large-Scale Tropical Forest Tree Plots. E. Leigh and E. Losos eds. Chicago, U. of Chicago Press: in press.

Wills, C., 2003. Understanding Evolution (textbook). To be published by W.H. Freeman in early 2003.

Freed, N., T. Zarubin and C. Wills, 2002. Phenotypic effects of microsatellite-containing pathogenesis-related genes in Candida albicans. In preparation.

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