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From Stars to Genes: An Integrated Study of the Prospects for Life in the Cosmos

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From Stars to Genes: an Integrated Study of the Prospects for Life in the Cosmos

Proposal to Participate in the NASA Astrobiology Institute – Cycle 3

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Executive Summary

Building on seven years of experience and accomplishments in the planning, implementation, and operation of the NASA Astrobiology Institute, UCLA lead team members propose to embark on another five-year plan of research, education, and public outreach in astrobiology that makes full use of the remarkable sets of talents and tools that have been assembled for these purposes over the past five years. The UCLA Center for Astrobiology (CAB) is one of five centers of the UCLA branch of the University of California-wide Institute of Geophysics and Planetary Physics (IGPP) and one of the eleven founding lead teams of the NASA Astrobiology Institute (NAI). Research, education, and public outreach activities of the Center are aimed at the long-term questions and goals of astrobiology, namely: How do planetary processes give rise to life? How are planets formed? Are there habitable planetary bodies outside our Solar System? When and how did life appear on Earth and, possibly, Mars? What are the biological innovations that allow life to climb to complexity on planetary timescales?

The team consists of more than 50 investigators. If this proposal is successful, UCLA will contribute ~ $1.3 million to match the $7.2 million requested of NASA. In addition to the University contribution, and in the spirit of the Cooperative Agreement, CAB participants bring to the project a wide range of skills and resources. Our plan calls for distributing these resources in ways that maximize the scientific and educational output beyond that which would be achieved by the investigators on an individual basis. We will use a method of strategic allocation of funds to promote interdisciplinary research that would be difficult to carry out without the existence of the Center. Examples of interdisciplinary research planned for the next five years include: collaborations between astronomers, atmospheric chemists, and cosmochemists that are leading to entirely new theories for the way that our Solar System evolved; the bringing together of paleontologists, atmospheric chemists, and isotope geochemists to study atmospheric evolution on ancient Earth; integration of advanced orbital and rotational dynamical calculations into studies of mass extinctions and the climate history of Mars; and collaborations between paleontologists and microbiologists with the goal of understanding the origins of eukaryotic life. In some cases the impetus for interdisciplinary work proposed here has come from merely bringing workers with disparate backgrounds together at CAB meetings. In other cases CAB funds will allow individuals to have access to facilities they might not have been aware of, much less had access to, previously. In still other cases the support of a student or a researcher will allow an investigator to participate in transdisciplinary studies that they would not otherwise engage in. In all cases, the new avenues of research will further the goals of astrobiology as a discipline and will be possible through the activities of the UCLA Center for Astrobiology in the coming years.

The title of this proposal reflects the breadth of research to be carried out if it is funded. Our investigators and collaborators have expertise in astronomy, cosmochemistry, geology, geobiology, geophysics, geochemistry, paleontology, planetary science, microbiology, organismic and molecular biology, and, of course, astrobiology. They represent UCLA's Departments of Atmospheric Sciences, Chemistry & Biochemistry, Earth & Space Sciences, Mathematics, Microbiology, Immunology & Molecular Genetics, Molecular, Cell & Developmental Biology, Organismic Biology, Ecology & Evolution, Physics & Astronomy, and the Molecular Biology Institute, as well as many other off-campus institutions.

The team assembled for this proposal includes a comparatively large (relative to our previous group) number of astronomers and cosmochemists. This reflects our goal of assuming a leadership role in helping to strengthen the astro component of astrobiology, as suggested by the National Research

Council’s Committee on the Origins and Evolution of Life in their 2002 assessment of NASA’s astrobiology program. While astronomers may not work directly with microbiologists, CAB astronomers will work with the cosmochemists in ways that they have not before, and the cosmochemists in turn will work with geochemists who at the same time will collaborate with microbiologists in novel ways. In this fashion, progress in a given area will be informed by work in even the most dissimilar discipline when the need arises. Such a *chain of informed inquiry* is crucial to a field that seeks to define the range of possible habitable environments in all planetary systems and to match this range of habitats with the full spectrum of possible forms of life.

The UCLA astrobiology research plan for the next five years focuses on four themes: (1) Extrasolar Planetary Systems; (2) Habitability of Planets and their Satellites; (3) Earth's Early Environment and Life; and (4) Evolution of Biological Complexity. UCLA lead team members have considerable experience in each of these areas. Their accomplishments range from the recent detection of asteroids and comets around another star to identifying the earliest evidence for life on Earth. Some members of our team have been at the forefront of technological advances in measuring isotope ratios at microscopic scales in natural materials, capabilities that are central to many of the studies planned as part of this program. Others are Principal Investigators or Co-Investigators on exciting new astronomy missions that are equally important to our proposed research program. Still others are leaders in the fields of microbiology and paleontology.

How typical is our Solar System? This is a key question that arises when one attempts to gauge the likelihood for life elsewhere in the Galaxy. UCLA lead team members are beginning to answer this question by studying both extrasolar planetary systems and the Solar System itself. The most successful method for detecting planets beyond the Solar System has been to measure the wobbles exerted by planets on their stars. The method, by its very nature, is biased towards detecting giant planets in close proximity to the star. It is generally recognized that such planetary systems – with giant planets much closer to their stars than Jupiter is to the Sun – are unlikely to harbor life. Members of the UCLA team are developing and applying methods more suitable for detecting planetary systems that more closely resemble the Solar System. The underlying assumption is that these systems are more likely to have Earth-like planets. Even where planets can not be detected, our group proposes to search for indirect evidence for planet formation. Rock and ice debris around some stars may signify the existence of comets and asteroids, the precursors to, or vestiges of, rocky planets that could resemble Earth. We will do all of this with access to the finest tools, including the Keck observatories and new platforms for observations from space (SIRTF) and in the stratosphere (SOFIA) that permit imaging with infrared wavelengths with minimal interferences from air, as well as various radio telescope facilities.

Looking over the shoulders of the astronomers are those members of our team studying meteorites and the story these rocks have to tell about the origin of the Solar System. By virtue of their involvement in the Center for Astrobiology, the cosmochemists and astronomers are working together to discover the ways in which water might be incorporated into Earth-like planets, and whether photochemistry in the disks of dust and gas surrounding young stars is instrumental in determining the nature of the organic and inorganic building blocks of planets. This synergistic activity has already resulted in proposals for new astronomical measurements that would not otherwise have been made.

While hunting for extrasolar planetary systems and comparing them to the Solar System is requisite for gauging the prospects for life elsewhere, it is not sufficient. It is also necessary to define those objects that are habitable. Our team is addressing this issue by studying the factors that might control the habitability of the icy moons of Jupiter, the time-dependent climate of Mars, potential links between the dynamics of rocky planets and their long-term habitability, the influence of orbital dynamics on the prospects for Earth-like planets in extrasolar planetary systems, and the role that impacts play is survival and evolution of life.

Manifestations of Earth's earliest life are controversial and our understanding of the environment that nurtured early life on Earth is poor. Sophisticated isotopic analyses of Earth's oldest materials, including >4.0 billion year old zircon crystals and 3.9 to 2.5 billion year old sulfur minerals will be used by our team to determine the ages of Earth's atmosphere, hydrosphere, and geodynamo, relate these ages to the earliest signs of life, and assess how the emergence of life changed our planet. Experiments will be performed to investigate interactions between ancient microorganisms and their environs. Chemical interactions between organisms and their inorganic and organic environs will be monitored using the newly developed transition metal isotope systems. The pooled results from these disparate studies will provide new information about the antiquity of life on Earth and provide a firm basis for life-detection on other bodies in the Solar System.

The appearance of Eukaryotes in Earth history coincided with dramatic changes in the planet's climate, ocean chemistry, atmospheric chemistry, and tectonic configurations, suggesting that emergence of biological complexity may be linked to evolving climate. Understanding the early part of this progressive history may therefore reveal general principles that are applicable to the growth of complexity in any living system. UCLA lead team investigators are studying the evolution of eukaryotes using information from molecular biology and the fossil record. The goals are to better understand the order in which important universal properties of eukaryotes (nucleus, sterols, cytoskeleton, endoplasmic reticulum, organelles, multicellularity, etc.) were acquired, and to try to date these events using both the fossil record and molecular clocks. The nature of the common ancestor and the source of the prokaryotic donations to the genome(s) of the last common ancestor of all living eukaryotes are outstanding problems in evolutionary biology that will be addressed by our work. As part of this effort, CAB members will also examine the steps by which eukaryotes obtained and lost their energy-producing organelles.

The Cambrian period of Earth history was a time of rapid evolutionary innovation. The exponential advance in animal diversity and complexity near the start of the Cambrian demands understanding as it is one of the signature features in the evolution of life on our planet. Our group will examine this rapid advance by studying the morphological development of trilobites, the emergence of skeletons by searching for the responsible developmental genes, and fossils that represent stem groups of modern phyla that reveal the ways in which animal body plans developed.

The UCLA Center for Astrobiology will continue to be engaged in numerous activities that serve to strengthen the field of astrobiology in general. These activities include continued support of the UCLA Astrobiology Society, introduction of an Astrobiology General Education course, participation in the NAI Minority Institution Involvement Faculty Sabbatical Program, participation in the Minority Institution Astrobiology Collaboratory (MIAC), organizing public lectures, and convening of Rubey Colloquia, which serve as forums for rapidly developing topics of interest. The Astrobiology Society is the first student-run organization devoted to fostering the discipline of astrobiology at the university level. In the coming years the Society will be engaged in replicating their success at other institutions, especially those serving minorities in particular. UCLA was one of the first hosts in the new Faculty Sabbatical Program and this connection has resulted in a closer tie between our lead team and the MIAC.

Research and Management Plan

1 INTRODUCTION

BUILDING on seven years of experience and accomplishments in the planning, implementation, and operation of the NASA Astrobiology Institute, UCLA lead team members propose to embark on another five-year plan of research, education, and public outreach in astrobiology that makes full use of the remarkable sets of talents and tools that have been assembled for these purposes over the past five years. Research will focus on four themes: (1) Extrasolar Planetary Systems; (2) Habitability within the Solar System and Beyond; (3) Earth's Early Environment and Life; and (4) Evolution of Biological Complexity. Sections of the proposal that describe the research plans of each of these themes are cross-referenced in Table 1 with the seven goals of the NASA Astrobiology Roadmap (astrobiology.arc.nasa.gov/roadmap). The UCLA team is well placed to advance Astrobiology - the discipline - as this exciting new field increasingly contributes to the recruitment of young people into careers in science and technology and to long-term planning for NASA missions.

The UCLA Center for Astrobiology (CAB) is one of five centers of the UCLA branch of the UC-wide Institute of Geophysics and Planetary Physics (IGPP) and one of the eleven founding lead teams of the NASA Astrobiology Institute (NAI). The Center is composed of faculty, researchers, students, and staff, plus collaborators at other institutions, who have expertise in astronomy, cosmochemistry, geology, geobiology, geophysics, geochemistry, paleontology, planetary science, microbiology, organismic and molecular biology, and, of course, astrobiology. Research, education, and public outreach activities of the Center are aimed at the long-term questions and goals of astrobiology, namely: How do planetary processes give rise to life? How were planets formed? Are there habitable planetary bodies outside our Solar System? When and how did life appear on Earth and, possibly, Mars? What are the biological innovations that allow life to climb to complexity on planetary timescales?

Clearly, answers to these questions will require advances in a broad spectrum of disciplines. It will be necessary to establish a firm astrophysical context for the birth and evolution of our Solar System if we are to assess the likelihood for similar systems elsewhere. We will require a better knowledge of the diverse forms that life might take in different environments if we are to gauge the habitability of bodies in the Solar System and beyond. Conversely, searches for the bounds of habitability will be guided by the range of environments found to exist on other planets and their satellites.

In order to begin to answer these transdisciplinary questions, and explain them to others, special people and special tools are required. These are listed below. This proposed investment of time and real resources ($1.3 million) represents a substantial commitment by UCLA and the associated institutions to the success of the cooperative endeavor known worldwide as the NASA Astrobiology Institute.

Table 1. The UCLA CAN-3 proposal in the context of the 2002 Astrobiology Roadmap

Astrobiology ROADMAP Goals	**UCLA theme** **EXTRASOLAR PLANETARY SYSTEMS**	**UCLA theme** **HABITABILITY IN PLANETARY SYSTEMS**	**UCLA theme** **EARTH'S EARLY ENVIRONMENT AND LIFE**	**UCLA theme** **EVOLUTION OF BIOLOGICAL COMPLEXITY**
Goal 1 Habitable Planets	Proposal §5	Proposal §6.2, 6.3, 6.4		
Goal 2 Life in our Solar System		Proposal §6.2, 6.5, 6.6, 7.2		
Goal 3 Origins of Life			Proposal §7.4, 7.5	
Goal 4 Earth's Early Biosphere and its Environs			Proposal §7.2, 7.3, 7.4, 7.6	
Goal 5 Evolution, Environment, and Limits of Life				Proposal §8
Goal 6 Life's Future on Earth and Beyond		Proposal §6.5		
Goal 7 Signatures of Life	Proposal §5.2		Proposal §7.5	

2 UCLA LEAD TEAM INVESTIGATORS

David G. Agresti (Collaborator) is Professor of Physics, Department of Physics, The University of Alabama, Birmingham (UAB). Agresti is the PI for the UAB Raman imaging facility and will work with Schopf on samples containing ancient fossil microbes (§7.5) (agresti@uab.edu).

Jonathan Aurnou (Collaborator) is Assistant Professor in the Department of Earth and Space Sciences. He is an experimental fluid dynamicist interested in understanding how conductive fluid flow generates magnetic fields. He will work with numerical modelers (§6.3) to explore planetary conditions needed for magnetic fields and plate tectonics, both possibly important for habitability (aurnou@ucla.edu).

Stanley M. Awramik (Collaborator) is Professor in the Department of Geological Sciences at the University of California, Santa Barbara. He studies Precambrian microfossils and stromatolites and will contribute his many years of field experience (awramik@geol.ucsb.edu).

Eric E. Becklin (Collaborator) is Professor in the Department of Physics and Astronomy, and Director Designate of the NASA Stratospheric Observatory for Infrared Astronomy (SOFIA). Becklin's research deals with infrared observations in and beyond the Solar System. Here, he proposes (§5.2) the modification of an existing SOFIA instrument to allow for the detection of organic molecules in these environments (becklin@astro.ucla.edu).

Gary R. Byerly (Collaborator) is the Robey H. Clark Professor in the Department of Geology and Geophysics, Louisana State University. He and Lowe have decades of experience mapping the early Archean Barberton Greenstone Belt in Africa. They and their collaborators propose (§6.5) to further explore the Archean history of large impacts and their possible effects on early life (gbyerly@geol.lsu.edu).

James Farquhar (Collaborator) is Assistant Professor in the Department of Geology at the University of Maryland. His research applies stable isotope geochemistry to atmosphere-surface interactions, atmospheric evolution, sulfur and oxygen biogeochemistry, meteorite studies, isotopic exchange, and geothermometry. Proposed collaborative research on mass-independent sulfur isotope effects (§7.3) is aimed at understanding the unusual chemistry as well as using these effects to probe the Archean environment (jfarquha@essic.umd.edu).

Sorel T. Fitz-Gibbon (Collaborator) will be an Assistant Research Molecular Biologist (from July 1, 2003) in the Institute of Geophysics and Planetary Physics. Having assembled and annotated the genome the hyperthermophile *Pyrobaculum aerophilum*, she became concerned with both whole-genome comparisons and the evolution of methane and sulfur metabolisms. She will contribute to the proposed (§7.3) collaborative research on the early history of sulfur cycling (sorel@ucla.edu).

James G. Gehling (Collaborator) is Research Scientist in Palaeontology at the South Australian Museum. His work over several decades on the end-Precambrian Ediacaran biotas will be used (§8.3) to examine how global ("snowball Earth") glaciations influenced the evolution of complex multicellular life (Gehling.Jim@saugov.sa.gov.au).

Andrea M. Ghez (Co-Investigator) is Professor in the Department of Physics and Astronomy and the Institute of Geophysics and Planetary Physics. Ghez's work is focused on using and developing high spatial resolution imaging techniques to study the formation of stars and planets. She is Associate Director of Astronomical Science for the National Science Foundation's Technology Center for Adaptive Optics. Here, she proposes (§5.2) to investigate grain growth in early evolving planetary systems (ghez@astro.ucla.edu).

Michael Ghil (Collaborator) is Professor in the Department of Atmospheric Sciences and the Institute of Geophysics and Planetary Physics and also holds a chair at the École normale supérieure, Paris. His main research interests are in climate dynamics; here, he will contribute (§8) mathematical tools to an understanding of the evolution of complexity (ghil@lmd.ens.fr).

Kathleen Grey (Collaborator) is in the Mineral and Petroleum Resources Branch of the Geological Survey of Western Australia and is a member of the Australian Centre for Astrobiology. She studies Precambrian fossils and microfossils with a view to understanding their biology and time significance. She will collaborate (§8.2) on assembling paleontological evidence for the Proterozoic history of eukaryotes (kath.grey@doir.wa.gov.au).

Brad Hansen (Co-Investigator) is Assistant Professor in the Department of Physics and Astronomy and the Institute of Geophysics and Planetary Physics. Hansen is investigating the evolution of planetary systems, including the inward migration of giant planets and the dynamical interactions between asteroids and comets and planets. He proposes (§5.4) to investigate theoretically the interaction of planetismals with the giant planets being discovered in extra-Solar planetary systems as well as the accumulation processes of terrestrial planets in our own and other systems (hansen@astro.ucla.edu).

T. Mark Harrison (Co-Investigator) is Professor in the Department of Earth and Space Sciences and the Institute of Geophysics and Planetary Physics, and is currently the Director of the Research School of Earth Sciences at the Australian National University. Harrison applies his expertise in isotope geochemisty to broad problems to fields that include Himalayan tectonics, Earth's oldest materials, and the early evolution of life. He and colleagues aim (§7.2) to obtain sufficient material from 4.0+ billion-year-old minerals to allow them to investigate Earth's earliest atmosphere and hydrosphere (mark.harrison@anu.edu.au).

Christopher H. House (Collaborator) is Assistant Professor in the Department of Geosciences at Pennsylvania State University and a member of the Penn State Astrobiology Research Center. He studies geomicrobiology using living and fossil organisms, genomics, and novel analytical techniques. He will collaborate on two aspects of the proposed research - the characterization of Earth's earliest life (§7.4) and the evolution of microbial metabolisms (§7.5) (chouse@geosc.psu.edu).

David K. Jacobs (Co-Investigator) is Professor in the Department of Organismic Biology, Ecology, and Evolution and a Member of the Molecular Biology Institute. Jacobs studies the role of developmental genes in the animal evolution. His lab will investigate (§8.3) the role of genes involved in the production of mineral skeletons as possible triggers for the Cambrian explosion of bilaterian animals (djacobs@ucla.edu).

Patricia J. Johnson (Co-Investigator) is Professor in the Department of Microbiology, Immunology, and Molecular Genetics and a Member of the Molecular Biology Institute. Johnson's work with human parasites led to her interest in the origins of energy producing organelles in the evolution of eukaryotes. Her proposed (§8.2) work on the origin of energy-producing organelles will contribute significantly to a collaborative study of the origins of eukaryotes (johnsonp@ucla.edu).

Per M. Jögi (Collaborator) is Programmer/Analyst in the Institute of Geophysics and Planetary Physics. He is using the mathematical methods of condensed matter physics to model the growth of the earliest stromatolites (§7.5) (jogi@physics.ucla.edu).

Michael A. Jura (Collaborator) is Professor in the Department of Physics and Astronomy. Jura studies the astrophysics of materials in the interstellar medium as well as debris, comets, and asteroids around other stars. He proposes (§5.2) to use ground-based and SIRTF observations to study protoplanetary dust in extra-Solar systems (jura@astro.ucla.edu).

Isaac R. Kaplan (Collaborator) is Professor Emeritus in the Department of Earth and Space Sciences and the Institute of Geophysics and Planetary Physics. His enormous experience in stable isotope biogeochemistry and environmental geochemistry will be available to members of the team working on isotope fractionations, organic molecules, and biochemical pathways (§6.6, 7.3, 7.4, 7.5) (irk@zymaxusa.com).

Abby Kavner (Collaborator) is Assistant Professor in the Department of Earth and Space Sciences and the Institute of Geophysics and Planetary Physics. She will work on investigations of iron isotope fractionations using electrochemical techniques (§7.4) (akavner@igpp.ucla.edu).

Artem Kouchinsky (Collaborator) is a Postdoctoral Researcher in the Institute of Geophysics and Planetary Physics working primarily in the Jacobs lab on the origins of mineral skeletons and their effects on the evolution of carbon cycling during and after the Cambrian explosion (§8.3) (akouchin@ucla.edu).

Anatoliy Kudryavstev (Collaborator) is Research Assistant Professor of Physics, Department of Physics, The University of Alabama, Birmingham (UAB). Kudryavstev works in the UAB Raman imaging facility and will collaborate with Schopf on samples containing ancient fossil microbes (§7.5) (wdowiak@uab.edu).

Frank T. Kyte (Co-Investigator) is an Adjunct Associate Professor in the Department of Earth and Space Sciences and an Associate Research Geochemist in the Institute of Geophysics and Planetary Physics. Kyte documents (§6.5) the geological and geochemical evidence for impacts on Earth ranging in age from the Archean to the present (kyte@igpp.ucla.edu).

James A. Lake (Co-Investigator) is Professor in the Department of Molecular, Cell, and Developmental Biology and a Member of the Molecular Biology Institute. Lake's research is concerned with organismic and genomic evolution, the history of hyperthermophilic prokaryotes (§7.6), and the origin of eukaryotes (§8.2) (lake@mbi.ucla.edu).

Donald R. Lowe (Co-Investigator) is Professor in the School of Earth Sciences at Stanford University. Lowe is a sedimentologist who focuses his research on the history of Earth's early environment, particularly the role of large early impacts (§6.5) and the context of the early evolution of life (lowe@pangea.stanford.edu).

James R. Lyons (Co-Investigator) is Assistant Research Geochemist in the Institute of Geophysics and Planetary Physics. Lyons works on the generation and transfer of isotopic signatures in planetary atmospheres. He proposes to study the photochemistry of oxygen and sulfur in the atmospheres of Earth (§7.3), Mars (§6.6) and the early Solar nebula (§5.4) (jrl@ess.ucla.edu).

Kevin D. McKeegan (Co-Investigator) is Professor in the Department of Earth and Space Sciences and Director of the ion microprobe laboratory of the W. M. Keck Foundation Center for Isotope Geochemistry. His research relevant to this proposal includes origins of isotope anomalies in the early solar nebula (§5.4), the age of Earth's hydrosphere (§7.2), sulfur cycles (§7.3), and paleobiology (§7.5). McKeegan is a Co-Investigator of NASA's GENESIS Discovery mission and a member of the science team for STARDUST (kdm@ess.ucla.edu).

Ian S. McLean (Collaborator) is a Professor in the Department of Physics and Astronomy and Director of the UCLA Infrared Imaging Detector Laboratory. He is known for early work on astronomical polarimetry, both visible and infrared, and recent work on infrared studies of star-forming regions, low-mass stars, the Galactic Center, and primeval galaxy formation. He will work on instrumentation for SOFIA (§5.2) (mclean@astro.ucla.edu).

Craig E. Manning (Co-Investigator) is Professor in the Department of Earth and Space Sciences. Manning is an experimental geochemist and petrologist working on a wide range of problems that includes the structure of supercritical fluids, the permeability structure of Earth's crust, and the role that hydrothermal systems may have on the origin and early evolution of life (§7.4) (manning@ess.ucla.edu).

Rudolf A. Marcus (Collaborator) is Arthur Amos Noyes Professor of Chemistry at the California Institute of Technology. He received the Nobel Prize in chemistry in 1992 for his contributions to the theory of electron transfer reactions in chemical systems. He will collaborate (§7.3) on understanding the chemistry of mass-independent isotopic effects in sulfur compounds (ram@caltech.edu).

Stephen J. Mojzsis (Collaborator) is Assistant Professor in the Department of Geological Sciences and a member of the Center for Astrobiology at the University of Colorado, Boulder. He is a geologist who studies all aspects of the Hadean and Archean Earth from an astrobiological perspective. He will work with Harrison on the earliest evidence for life on Earth (§7.2) (mojzsis@colorado.edu).

William B. Moore (Collaborator) is a Postdoctoral Researcher in the Department of Earth and Space Sciences working on the geophysics of the Galilean moons of Jupiter, especially Europa. His work (§6.2) will contribute to the understanding of Europa needed for planning a future astrobiological mission (bmoore@avalon.ess.ucla.edu).

Mark R. Morris (Co-Investigator) is Professor in the Department of Physics and Astronomy. He studies galactic nuclei, mass loss from giant stars, and the photochemistry of protoplanetary disks.

Morris will use infrared observational techniques to study photochemistry (§5.4) and grain growth (§5.2) in protoplanetary disks (morris@astro.ucla.edu).

William I. Newman (Co-Investigator) is Professor in the departments of Earth and Space Sciences, Mathematics, and Physics and Astronomy. Newman's research focus is on the dynamical evolution of the early Solar System, the response of planetary atmospheres to catastrophic impacts (§6.5), and problems in astrophysics (win@ucla.edu).

Francis Nimmo (Collaborator) is an Adjunct Assistant Professor in the Department of Earth and Planetary Sciences. Nimmo is a planetary scientist studying the structure and evolution of planets and satellites, especially Mars, Venus, and Europa. His work (§6.2) will contribute to the understanding of Europa needed for planning a future astrobiological mission (nimmo@ess.ucla.edu).

David A. Paige (Collaborator) is an Associate Professor in the Department of Earth and Space Sciences. His research is aimed at understanding the role that volatiles have played in the evolution of Mars and the evolution of planetary atmospheres in general. He proposes to analyze existing Mars datasets in order to assist in the planning of future astrobiological missions to Mars (§6.6) (dap@mars.ucla.edu).

Susannah M. McG. Porter (Collaborator) is NAI National Research Council Postdoctoral Research Associate in the Department of Earth and Space Sciences and the Institute of Geophysics and Planetary Physics. She is incoming Assistant Professor in the Department of Geological Sciences at the University of California, Santa Barbara and proposes collaborative research on the evolution of eukaryotes (§8.2) and the Cambrian explosion (§8.2-8.3) (suporter@ucla.edu).

Maria C. Rivera (Collaborator) is an Assistant Research Molecular Biologist in the Institute of Geophysics and Planetary Physics and the Molecular Biology Institute. She will investigate the evolution of microbial metabolisms (§7.6) and the prokaryotic sources of eukaryote genes (§8.2) (rivera@mbi.ucla.edu).

Alan E. Rubin (Collaborator) is Associate Researcher in the Institute of Geophysics and Planetary Physics who works mainly on the originally molten components of meteorites (chondrules). He will help understand sulfur isotope effects in the solar nebula and on early Earth using sulfides in primitive meteorites (§7.3) (aerubin@ucla.edu).

Bruce N. Runnegar (Collaborator) is Professor in the Department of Earth and Space Sciences and the Institute of Geophysics and Planetary Physics and a Member of the Molecular Biology Institute. He is currently on extended leave, as Director of the NASA Astrobiology Institute, at the NASA Ames Research Center. His research is concerned with the history of early life on Earth using evidence from geology (§7.5), paleontology plus molecular biology (§7.6, 8.3), and stable isotope geochemistry (§7.3) (bruce.n.runnegar@mail.arc.nasa.gov).

Stanley P. Sander (Collaborator) is group leader of the Chemical Kinetics group at the Jet Propulsion Laboratory. Sander works on laboratory studies of the kinetics of gas-phase reactions of relevance to the Earth's stratosphere. He has extensive experience with discharge flow tubes, and will provide technical guidance for the proposed (§7.3) sulfur isotope flow tube studies (stanley.sander@jpl.nasa.gov).

Edwin Schauble (Co-Investigator) is an incoming Assistant Professor (from July 1, 2003) in the Department of Earth and Space Sciences who will teach and do research in astrobiology. He proposes exploring the ways (§7.4) in which stable isotopes of metals might be used to track transport between biological and inorganic reservoirs (edwin@gps.caltech.edu).

J. William Schopf (Co-Investigator) is Professor in the Department of Earth and Space Sciences and the Institute of Geophysics and Planetary Physics and a Member of the Molecular Biology Institute. He directs the IGPP's Center for the Study of the Origin and Evolution of Life (CSEOL). Schopf's research deals with evidence for the antiguity of life on Earth (§7.5) and the evolution the biosphere during the Precambrian (schopf@ess.ucla.edu).

Gerald Schubert (Co-Investigator) is Professor in the Department of Earth and Space Sciences and the Institute of Geophysics and Planetary Physics. He is concerned with the formation and evolution of planetary bodies and understanding their physical states. A recent focus has been the structure and evolution of the Galilean moons of Jupiter, work he proposes to continue here (§6.2) (schubert@ess.ucla.edu).

Ralph Y. Shuping (Collaborator) is a Postdoctoral Researcher in the Department of Physics and Astronomy. Shuping has been studying the protoplanetary disks of Orion using near infrared techniques. He proposes to use infrared observational methods to test for self-shielding by CO in protoplanetary disks (§5.4) (shuping@astro.ucla.edu).

Inseok Song (Collaborator) is an Assistant Research Astronomer in the Institute of Geophysics and Planetary Physics and the Department of Physics and Astronomy. He is an observer who has been using spectral features to find the youngest, nearest stars to Earth that are targets for proposed investigations (§5.3) that may lead to the first direct images of planets (song@astro.ucla.edu).

Paul J. Tackley (Collaborator) is Associate Professor in the Department of Earth and Space Sciences and the Institute of Geophysics and Planetary Physics. Tackley uses complex numerical simulations to understand the dynamical and chemical evolution of the interiors of Earth and the other planets and moons. He will work with experimentalists (§6.3) to explore planetary conditions needed for magnetic fields and plate tectonics, both possibly important for habitability (ptackley@ess.ucla.edu).

Ference Varadi (Co-Investigator) is an Associate Research Geophysicist in the Institute of Geophysics and Planetary Physics. Varadi studies the long-term effects of planetary orbits on the evolution of bodies in the inner Solar System as well as problems in solar physics, atmospheric sciences, and applied mathematics. His advanced computational models will be used to investigate the habitability of Jupiter's moons (§6.2), the orbital dynamics of extrasolar planet systems (§6.4), the dynamics of Earth-crossing asteroids (§6.5), and the recent history of climate on Mars (§6.6) (varadi@atmos.ucla.edu).

Ashwin R. Vasavada (Collaborator) is an Adjunct Assistant Professor (Rubey Fellow) in the Department of Earth and Space Sciences. Vasavada is a planetary scientist concerned with the occurrence of volatiles on Mars (§6.6), the Moon, Mercury, and other bodies. (ashwin@ess.ucla.edu).

M. Indira Venkatesan (Collaborator) is a Research Geochemist in the Institute of Geophysics and Planetary Physics who has great experience with the use of organic biogeochemical techniques to understand petroleum occurrence and formation and other paleobiological and environmental aspects of carbon chemistry. Here, she will be involved in the characterization of organic compounds made experimentally (§7.4) (indira@ucla.edu).

John T. Wasson (Collaborator) is Professor in the departments of Chemistry and Biochemistry and Earth and Space Sciences, and a Member of the Institute of Geophysics and Planetary Physics. His principal research interest is the study of meteorites as a tool for understanding the early evolution of the Solar System. He will work with others (§5.4) on the fate of water in protoplanetary systems (jtwasson@ucla.edu).

Thomas J. Wdowiak (Collaborator) is Associate Professor Emeritus, Department of Physics, The University of Alabama, Birmingham (UAB). Wdowiak is affiliated with the UAB Raman imaging facility and will work with Schopf on samples containing ancient fossil microbes (§7.5) (wdowiak@uab.edu).

Mark Webster (Collaborator) is an incoming Assistant Professor (from July 1, 2003) in the Department of Earth and Space Sciences. Webster studies the early evolution of body plans using morphometric techniques applied to fossils, notably Cambrian trilobites. He is part of a proposed collaboration (§8.3) aimed at investigating the origins of animal body plans (websterm@citrus.ucr.edu).

Edward D. Young (Principal Investigator) is a Professor in the Department of Earth and Space Sciences and the Institute of Geophysics and Planetary Physics. Young is an isotope geochemist and cosmochemist whose work is directed towards understanding the geological and astrochemical processes attending the formation of rocky bodies in the early solar nebula (§5.4) and the characterization of isotope fractionation in both inorganic and organic systems (§6.6, 7.4) (eyoung@ess.ucla.edu).

Benjamin Zuckerman (Co-Investigator) is a Professor in the Department of Physics and Astronomy. Zuckerman has a longstanding interest in life elsewhere and has chosen research topics in astronomy that might have a bearing on the question of extraterrestrial life. He proposes (§5.2, 5.3) to continue work on the origins of planetary systems based on the nearby young star database which he and his colleagues have assembled recently (ben@astro.ucla.edu).

Additional UCLA team members: Students, Associates, and Alumni (see §Plan for Strengthening the Astrobiology Community).

3 MAJOR TOOLS TO BE USED BY THE UCLA LEAD TEAM

There are a number of diverse experimental and computational techniques being used by UCLA astrobiologists. In order to facilitate the reading of this proposal, some of the major tools to be used in the coming years are described below and cross referenced to the sections of the text. More detailed descriptions can be found in volume II of this proposal.

The Institute for Genomic Research (TIGR): A non-profit research institute located in Rockville Maryland with laboratories that include large facilities for DNA sequencing, bioinformatics, molecular biology, and biochemistry. UCLA lead-team member Johnson is collaborating with the Institute (§8.2).

The Submillimeter Array (SMA): An imaging array at submillimeter wavelengths consisting of eight 6-meter antennas located on Mauna Kea, Hawaii that is a collaborative project of the Smithsonian Astrophysical Observatory and the Academia Sinica Institute of Astronomy & Astrophysics of Taiwan (http://sma www.harvard.edu/). SMA is scheduled to go into full operation in late 2003. Morris and Shuping propose to use it on a collaborative basis with members of the scientific staff (§5.2, 5.4).

The Combined Array for Research in Millimeter-wave Astronomy (CARMA): An array of radio telescopes (operating at 115 to 345 GHz) located at high elevation (4,000 feet) in California. The facility will be open to the astronomy community on a competitive basis once it is fully operational (expected in 2005). Morris and Shuping propose to use CARMA for measuring carbon monoxide isotopomers in protoplanetary disks (§5.4).

The Space Infrared Telescope Facility (SIRTF): The final mission of NASA's Great Observations Program , SIRTF is an infrared telescope that will be launched in April, 2003. It is the largest infrared telescope ever sent to space. The capacity to see deeply into dense clouds of dust and gas makes SIRTF particularly useful for observing phenomena within the protoplanetary disks that surround young stars where planets are made (§5).

Stratospheric Observatory for Infrared Astronomy (SOFIA): An airborne infrared light observatory aboard a Boeing 747SP aircraft that will be based at Moffett Federal Airfield, California. SOFIA will fly to stratospheric heights in order to avoid interferences from the atmosphere that are especially problematical for infrared wavelengths. It is scheduled to begin observing in late 2004. It is well suited for observations of dense dust clouds such as those found in circumstellar disks. UCLA's Becklin is the Chief Scientist and Director Designate for the project (§5).

W.M. Keck Observatory: Twin telescopes situated at 14,000 feet atop Hawaii's dormant Mauna Kea volcano. The high altitude of the Keck I and Keck II telescopes makes ground-based observations in the infrared possible and addition of adaptive optics (AO) results in images in the near infrared sharper than those from the Hubble Space Telescope. The system is a crucial new tool for studying protoplanetary disks around young stars (§5).

UCLA orbit integrator code: UCLA team member Varadi has developed a specialized code to accurately reconstruct the orbital and rotational history of planets and asteroids for the past 100 million years. The numerical integration scheme is a version of the classical Stormer-Cowell integrator which has been optimized to reduce the long-term effects of numerical round-off errors. This code is used in several studies described herein (e.g., §6.4, 6.5).

The IBM Blue Horizon: Supercomputer installed at San Diego Supercomputer Center in 2000. Blue Horizon has a parallel architecture with 1152 processors distributed over 144 nodes. A fast internode connection makes the configuration capable of a peak performance of 1.728 TFlops per second. The versatility of the nodes, the fairly mature state of processor resource allocation protocols (e.g., Message Passing Interface), and the rapidly increasing amount of parallel numerical software makes this machine accessible for large-scale simulations. Jögi uses Blue Horizon to model stromatolite growth (§7.5).

UCLA stable isotope laboratory: A new stable isotope laboratory is nearly complete at UCLA. It includes two 10 μm (CO_2) infrared lasers for sample heating, a 213 nm (5th harmonic Nd-YAG) ultraviolet laser for in-situ ablation sampling, a Finnigan MAT Deltaplus gas-source mass spectrometer, a Finnigan MAT 253 gas-source mass spectrometer, two gas chromatographs (HP and Varian), two carrier flow interfaces, and two F_2 vacuum extraction lines (one under construction) for O_2 analysis of silicates, oxides, and phosphates. This facility is essential for measurements of oxygen isotopes in meteorites (§5.4).

UCLA multicollector inductively coupled plasma-source mass spectrometer: A new Finnigan MAT Neptune multiple collector inductively coupled plasma-source mass spectrometer (MC-ICPMS) has been installed in the Department of Earth and Space Sciences. This instrument is necessary in order to measure the isotope ratios of elements such as Fe and Mg with high precision (0.1 per mil or better). The high-precision obtainable with this instrument is essential for the proposed studies of how elements move between the organic and inorganic realms (§7.4).

W.M. Keck National Center for Isotope Geochemistry (ion microprobe): The main instrument of astrobiological significance is the CAMECA ims 1270 high-sensitivity, high-resolution ion microprobe, which is a national facility under the direction of Co-I McKeegan. The high spatial resolution of this instrument (1-30 µm) is key to several of the proposed studies (§7, 8).

Raman Imaging Facilities: The University of Alabama (UAB) Laboratory for Paleobiological Chemical Imagery provides images from rastered Raman spectroscopy measurements (§7.5). The UCLA lead team subsidizes this facility by way of a subcontract but plans are being made to construct a new laser Raman imaging facility (Jobin Yvon Horiba T64000 Modular Triple Raman System) in the UCLA Department of Earth and Space Sciences (funds provided by the University). Both the UAB and new UCLA facilities will serve as national resource for the astrobiology community.

4 HIGHLIGHTS OF PREVIOUS ACTIVITIES

Highlights of research conducted in the UCLA Center for Astrobiology over the past several years are listed below. This list is meant to be representative of the types of work completed. It is not a comprehensive publications list (publications lists are available in NAI annual reports).

- A distorted disk of cold dust surrounding the star Fomalhaut (25 light years from the Sun) demonstrates the existence of a large, Saturn-like planet around the star. This is direct evidence for the existence of the types of planets that maybe necessary for life in extrasolar planetary systems (Holland et al. 2003).

- Acquisition of new isotopic and phylogenetic evidence for the anaerobic use of methane by microbial consortia composed of sulfate-reducing bacteria and methane-consuming Archaea (Orphan et al. 2001).
- A model of mass-independent fractionation (MIF) of the three isotopes of oxygen was developed for the modern atmosphere that makes testable predictions about the distribution of MIF effects in different atmospheric molecules (Lyons 2001).
- The catalogue of youngest, nearest stars, such as the Beta Pictoris moving group (Zuckerman et al. 2001) was expanded to ~ 200 members as a result of ongoing observations of the southern skies at the Siding Springs observatory, Eastern Australia. Several of these stars (less than 30 million years old) are expected to have warm Jupiter-class planets that should be visible in the infrared using current technologies (e.g., the Hubble Space Telescope).
- A major survey using the near-infared spectrometer (NIRSPEC), designed and built at UCLA for the Keck Observatory (Mclean), obtained IR spectra of 62 brown dwarfs. The data obtained will provide a wealth of information for modeling the atmospheres of such cool objects.
- Laser-Raman spectral imaging of micrscopic filaments from the 3.5 billion year old Apex chert was used to demonstrate their carbonaceous composition (Schopf et al. 2002). These filaments have been regarded as the world’s oldest microfossils, though controversy surrounds their origin.
- Sulfur isotopic evidence was found for atmospheric but not bacterial processes in the formation of early Archean sedimentary sulfides and sulfates (Runnegar et al. in preparation).
- Reorientation of transfer RNA molecules during protein synthesis may indicate how “proofreading” developed as life emerged from the RNA world (Simonson and Lake 2002).
- All living eukaryotes appear to have mitochondria or to have lost them during the course of evolution. Their last common ancestor must postdate the permanent symbiosis that created the aerobically energized eukaryotic cell from prokaryotic precursors (Roger and Silberman 2002).
- Using genes involved in development, an antecedent of the pituitary gland was identified in early-diverging metazoans (e.g., jellyfish). The pituitary is a relic of a light and gravity detecting structure that may represent the first step in the evolution of the complex sensory and neural organization that characterizes animals (Jacobs and Gates in prep.).
- Calculations showed that a chaotic transition in the dynamics of the inner Solar System around the end of the Cretaceous some 65 million years ago may have disturbed the inner part of the asteroid belt, thus increasing the likelihood of an asteroid hitting the Earth at that time (Varadi et al. 2001).
- Geological mapping of Akilia island, Greenland, confirms an age greater than 3.8 billion years for the oldest sedimentary rocks and the organic material contained within them (Manning et al. 2001).
- Detection of a massive population of asteroids around nearby star ζ Leporis (Jura and Chen 2001).
- Ocean-continental crust interactions approximately 4.3 billion years ago on Earth are evidenced by the isotopic compositions of very old zircon crystals from Western Australia (Mojzsis et al. 2001).

- Horizontal gene transfer is limited by the complexity of gene product interactions (Lake et al. 2000).

- Planetary atmospheres may not be significantly eroded by giant impacts (Newman et al. 1999).

5 GAUGING THE POTENTIAL FOR TERRESTRIAL PLANETS IN EXTRASOLAR PLANETARY SYSTEMS

5.1 OVERVIEW

Observations and models for extrasolar planet formation can be compared with clues about planet-forming processes in the Solar System to answer the question: how typical are the processes that formed our Solar System? By addressing this question one gains insight into the likelihood of Earth-like planets elsewhere in our Galaxy. Collaborations between researchers studying conditions in nearby stellar systems (astronomers Becklin, Ghez, Hansen, Jura, Morris, Shuping, and Zuckerman) and those focused on the history of our Solar System as revealed through the study of meteorites (cosmochemists Lyons, McKeegan, Wasson, and Young) pave the way for new research opportunities related to terrestrial planet formation. These opportunities arise as a result of consultation between workers in fields that have been historically distinct in their approaches to elucidating how planets form.

The 2002 assessment of the NASA astrobiology program by the National Research Council's Committee on the Origins and Evolution of Life noted the weak level of interaction between research in the Astronomical Origins and the Astrobiology programs relative to analogous interactions between the astrobiology community and, for example, the geobiology community. The research outlined in Section 5 addresses this general shortcoming by strengthening, specifically, links between the Astronomical Origins and Astrobiology programs at UCLA.

One area of astrobiology where collaboration between UCLA astronomers and cosmochemists is proving fruitful is description of the first few million years of planet formation. Through studies of young stars surrounded by gas and dust, in the form of “protoplanetary” rings and disks, that could coalesce to form planets, Ghez, Jura, Morris, McKeegan, Shuping, and Young plan to evaluate the time scales over which such structures evolve, and perhaps infer time scales over which planets form.

It has been suggested that the presence of a Jupiter-like (giant) planet in orbit well outside the conventional habitable zone is a requisite for sustaining life on rocky planets similar to Earth. The gravitational field of a giant planet can relatively quickly cleanse a planetary system of the numerous planetesimals that must be part of the planetary formation process and can shield rocky planets from catastrophic impacts. Searches for giant planets orbiting many astronomical units (AU) from their star are therefore relevant to the problem of identifying planetary systems with favorable habitable zones. The most successful technique used to detect extrasolar planets – measuring the wobble of a star due to the pull of an orbiting planet (Marcy et al. 2000) – has revealed mostly giant planets that reside far closer to their central star than does Jupiter. Notwithstanding an occasional exception, it is recognized that systems containing such proximal giant planets are, in general, unlikely to harbor planets that can sustain life. Members of the UCLA lead team are engaged in development and application of new techniques geared to image detection of giant planets located in orbits resembling those of the giant planets of our Solar System.

Advances in astronomy that utilize ground-based telescopes equipped with adaptive optics systems (Beckers 1993), as well as an infrared camera on the Hubble Space Telescope (HST), make it possible to image directly Jupiter mass planets (Macintosh et al. 2001). But a caveat is that such detections must be of thermal emission from young, warm planets rather than of reflected starlight from old, cold planets like Jupiter. For this reason, imaging of giant planets in systems resembling the Solar System requires finding stars within about 50 parsec of Earth and not older than a few tens of millions of years. Recent work on isotopes in the hafnium-tungsten system in chondritic meteorites and in terrestrial samples indicate that Earth’s core formed in <30 Myrs (Fitzgerald 2003). Thus, to identify optimum stars at which to image cooling giant planets and to match the timescale for terrestrial planet formation, Zuckerman and Song will continue their compilation of very young stars close to Earth. Identification and cataloging of young, close, solar-like stars was a major part of the CAB activities over the past several years and will continue, with more of a focus on faint, low-mass stars, during the next five years.

Studies of the origins of meteorites can be used to deduce the processes by which Earth-like planets are formed. Although cosmochemistry is concerned with the origins of planets in the Solar System, the relevance of these studies to astrobiology is enhanced considerably if they are informed by astronomical evidence for analogous processes occurring around other stars. Cosmochemists Lyons, McKeegan, Young and Wasson propose to continue their studies of how rocks and water coalesced to form terrestrial planets in our Solar System, but in a manner that makes better use of astronomical information. Their approach will depart from the more traditional research programs in cosmochemistry in that they will use astronomical measurements obtained by other team members to compare and contrast constraints on planet formation in our Solar System with those seen elsewhere. This cooperation has already resulted in new insights into the significance of some vexing features of meteorites in understanding planet-forming processes (see Section 5.4.2).

UCLA astronomers Morris and Shuping propose a new observational program designed to test results from investigations of photochemistry in the early solar nebula (the Sun's protoplanetary disk, extant 4.6 Gyr ago) that may generally occur during rock formation in young circumstellar disks. Such observations are a direct manifestation of the synergy between the astronomical and cosmochemical communities being cultivated in the UCLA Center for Astrobiology.

Some details of the Center's research programs directed towards understanding the potential for terrestrial planets and Solar System-like planetary systems in our Galaxy are described below.

5.2 ROCKS AND ICES IN THE GALAXY- STUDIES OF HOW AND WHEN ROCKS AND ICES ARE MADE THAT COULD COALESCE TO FORM PLANETS (BECKLIN, GHEZ, JURA, MCLEAN, MORRIS, SHUPING, ZUCKERMAN)

5.2.1 Grain growth in young stellar systems

Most, if not all, young solar-like stars are surrounded by circumstellar disks prior to planet formation. Indeed, it is these disks that provide the basic building blocks for future planetary systems. The ways in which sub-μm size particles of dust in the interstellar medium eventually accumulate into kilometer sized, asteroid-like, planetesimals, which in turn aggregate to form rocky planets, are poorly understood. The process starts in the disks. Understanding the time scales and regions of significant grain growth in disks that surround young stars would enhance our understanding of how rocky planets form, and might be used as a tool for identifying those systems with proclivity for terrestrial planet formation.

Some observational and theoretical research on grain growth from sub-micron specks to millimeter size particles has been carried out (e.g., Pollack et al. 1994). But many more direct measurements of circumstellar disks are needed. Ghez and others are engaged in identifying the earliest stages of planet formation (i.e., dust coagulation) in regions surrounding million year old T Tauri stars. Their search for grain evolution focuses on infrared thermal emissivities and scattering/polarization properties which change as grains grow in size. By comparing infrared images between 1 and 10 μm, obtained with the Keck telescope and Hubble Space Telescope, Ghez has recently demonstrated the existence of grains substantially larger than interstellar in the disk that encircles the T Tauri star GG Tau (McCabe et al. 2003).

During the coming years Ghez and coworkers will build on this early success by performing similar observations at mid-infrared wavelengths of disks surrounding T Tauri stars of various ages. By correlating the extent of grain growth with age, this program of observations should paint a clearer picture of time scales for grain growth around solar-like stars. The program will require observing sessions at the Keck observatory extending at least for the next few years.

Ghez's research focuses on the nearest regions of current star formation such as the Taurus dark clouds. While proximity is obviously a virtue when one is investigating planetary system size phenomena, study of more distant youthful star clusters also has advantages. For example, most stars are thought to form in clusters containing many hundreds of stars, including some that are much more massive than our Sun. The closest, well studied, such region is the Orion Nebula Cluster.

Grain growth up to a few μm has been inferred from studies of transmitted light through a circumstellar disk seen in silhouette against the Orion Nebula. But, unlike forming stars in Taurus which are far from any massive, luminous stars, disks in Orion are being evaporated by intense ultraviolet light from four high-mass stars at the cluster's center (Figure 5.2.1). Models indicate that these disks can be evaporated away on timescales of about a million years. The key question is whether or not planets can form before the disks are destroyed by the UV radiation field. Evidence of grain growth in the Orion disks is especially important in addressing this question.

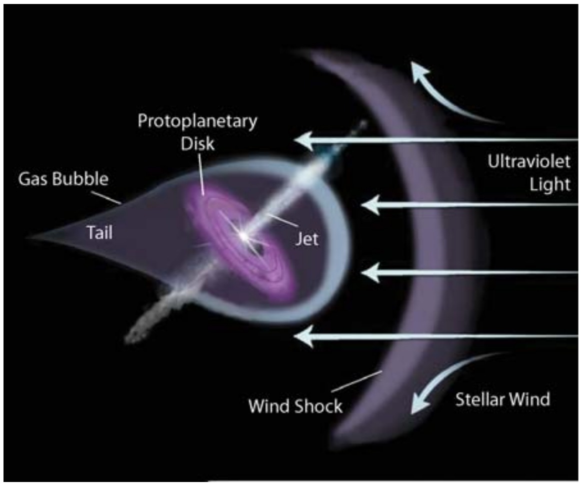

Figure 5.2.1. Schematic of a typical protoplanetary disk in Orion. Ultraviolet (UV) radiation from a nearby massive star eats away at the protoplanetary disk surrounding a young star creating a bubble of warm gas. The outer portions of the gas bubble are then heated and removed by energetic UV radiation. Material falling from the disk onto the central protostar fuels twin gas jets. Artwork: Space Telescope Science Institute.

Silhouette and scattered light images reveal the nature of grains in the outer edges of the protostellar disk while thermal radiation from the mid-infrared through radio wavelengths traces grains in the midplane. Morris and Shuping plan to continue their studies of Orion using existing data available from HST archives coupled with new observations of: (1) silhouettes and scattered light in the near- and mid-IR (at Keck Observatory); and (2) thermal emission from the mid-IR through the far-IR, sub-millimeter and radio wavelengths (using Keck, SIRTF, SOFIA, and various radio observatories). The planned observations will require approximately five to 10 nights to complete, and a few years to analyze and publish.

5.2.2 Detecting asteroids and comets in extrasolar systems – precursors to rocky planets elsewhere in the Galaxy

Asteroids and comets are composed of rocks and volatile ices. Since cosmochemical studies of meteorites demonstrate convincingly that planets of the inner Solar System were made from similar objects, the presence of asteroids and/or comets in other stellar systems may point toward the existence also of rocky planets. Although the asteroidal and cometary building blocks of planets are too small to be directly detected around other stars, their presence can be inferred indirectly, and we propose a program of astronomy-based research that will permit indirect detection of these objects.

In our Solar System, asteroids are eroded by mutual collisions while comets disintegrate by passing near the Sun. Microscopic dust particles from these disrupted parent bodies are subsequently distributed throughout the inner solar system. The zodiacal light is produced by sunlight scattering off these dust particles while absorption and reemission of sunlight by this material generates infrared emission. Dust particles near Earth have a typical lifetime of about 100,000 years before spiraling into the Sun under the operation of the Poynting Robertson effect (photon drag).

In 1983, the IRAS satellite discovered dust orbiting many main sequence stars, including the very bright star Vega. Analogous to our own Solar System, it is thought that this dust results from the disruption of parent bodies (e.g., Zuckerman 2001). Within 2 AU of the Sun, the total mass of dust is about 2×10^{17} g (Ney 1982). Around stars like β Pictoris (age ~12 Myrs) and Fomalhaut (age ~200 Myr), the total mass of dust may be 10^{25} g (Zuckerman and Becklin 1993), but as shown by direct imaging in infrared, optical and submillimeter wavelengths and as illustrated in Figure 5.2.2, dust in some systems is detected as far as 100 AU from the central star (Holland et al. 1998, Weinberger et al. 1999, Weinberger et al. 2002). Typically, this corresponds to location in the Kuiper Belt of comets and large icy bodies in our Solar System. At least one star, ζ Lepus, appears to be encircled by an asteroid belt with about 200 times the mass of the asteroids in the Solar System (Chen and Jura 2001).

One of the most significant consequences of the initial IRAS discovery, is the realization that the dusty disks around main sequence stars usually show non-axisymmetric structure (e.g., Zuckerman 2001, Holland et al 2003 and Figure 5.2.2). The submillimeter SCUBA camera at the James Clerk Maxwell Telescope (JCMT) at Mauna Kea Observatory has been the most successful instrument in imaging non-axisymmetric disks around main sequence stars including some of the best known (e.g., Vega and Fomalhaut). The most plausible cause of such structure is the gravitational field of planets of substantial mass with semi-major axes as large as that of Neptune and even larger (e.g., Ozernoy et al 2000). This is the first observational evidence, albeit somewhat indirect, for the existence of planets in such wide orbits. During the coming years, Zuckerman expects to continue his fruitful SCUBA collaboration with astronomers from the United Kingdom.

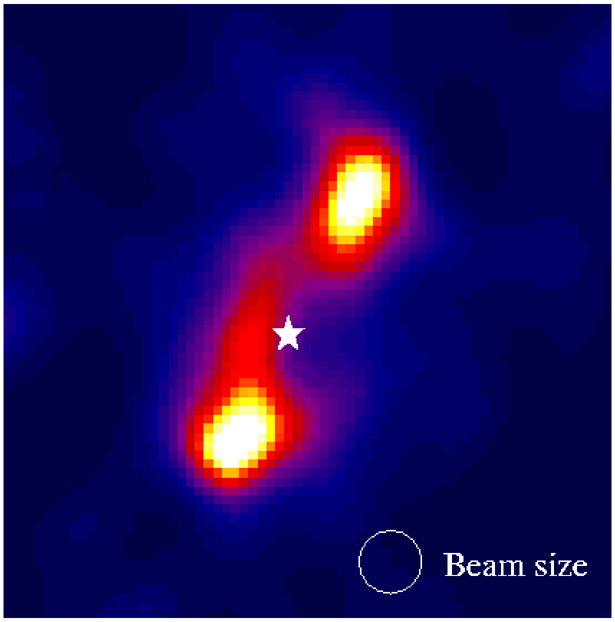

Figure 5.2.2. Image of a dusty debris disk around the bright star Fomalhaut obtained by lead team member Zuckerman and outside collaborators using the SCUBA camera at JCMT, Mauna Kea Observatory . The image, at 0.45 mm wavelength, shows a non-uniform distribution implying the existence of a planet that shepherds the debris.

With a variety of instruments, including the 10 meter Keck telescopes, the HST, SIRTF (launch April 2003) and SOFIA (first light late 2004), Jura, Zuckerman, Becklin, and Hansen propose further studies of debris dust derived from comets and asteroids around main sequence stars with the specific goal of learning more about the formation and evolution of planets in the context of what we know about our Solar System.

For example, for comparisons with the Solar System, the minimum mass, M_{PB}, of the parent bodies of debris can be obtained with the expression,

$$M_{\mathrm{PB}} = \frac{4L_{\mathrm{IR}}t_{\mathrm{age}}}{c^2}$$

where L_{IR} is the observed infrared luminosity of the dust, t_{age} is the age of the star, and c is the speed of light (Chen and Jura 2001). Observation of stars with different ages enables study of parent body mass as a function of time (see Spangler et al. 2001), thus enabling a comparison with what is known about evolutionary time scales in our Solar System as derived from studies of meteorites.

With low resolution spectra obtainable with SIRTF, Jura and colleagues expect to learn about the origin and evolution of the particles that comprise the debris. Grains spiraling inwards under the action of the Poynting Robertson effect produce a spectrum which varies as ν^{-1} independent of the grain size (Jura et al. 1998). Comparison of the data with simple models based on this result will enable Jura et al. to infer where the particles are formed (perhaps in the equivalent of our Kuiper Belt) and whether they spiral all the way into the star or are stopped - as might occur if there is accretion onto a Jovian-mass planet.

New observations made by the UCLA lead team relating to the mass and dynamics of dust vs. central star age will be compared with models for early Solar System evolution by consultations between Jura and colleagues and lead-team cosmochemists McKeegan, Wasson, and Young. The result will be a synthesis of what is known about our Solar System formation in the context of the formation of rocky materials around other stars.

Comparisons between the evolution of our Solar System and that of debris disks around other stars can be taken further. For example, we have the capacity to search for the equivalent around other stars of the era of the Late Heavy Bombardment inferred to have occurred within the Solar System within the first ~800 million years. The development of life in the Solar System is thought to have been delayed by this bombardment. Are such events common in planetary systems? Elsewhere, are they comparable in magnitude to the event(s) recorded in the inner Solar System?

IRAS could only begin to address such questions because its sensitivity limited meaningful observations mostly to stars with twice or more the mass of the Sun. Soon SIRTF will enable astronomers, including Jura and Zuckerman, to investigate stars with masses comparable to that of the Sun. Also, in the Solar System, comets and asteroids produce about 10^6 g s^{-1} of dust which then spirals into the Sun under the operation of the Poynting Robertson effect (Ney1982). SIRTF will be sufficiently sensitive that Jura and coworkers will be able to search for similar dust-production rates around nearby, low mass, main sequence stars of various ages. Do such stars experience asteriodal grinding and comet disruption at the same rate as in the Solar System? Through a new program of SIRTF observations of debris disks, the lead-team members propose to determine whether there are similarities between our Solar System and other regions where tell-tale signs (albeit indirect) of rock and ice formation are present.

5.2.3 Searches for signs of life's essential chemical constituents surrounding young stars

The importance for astrobiology of debris disks surrounding other stars goes beyond garnering indirect evidence for planet-forming processes; the nature of disk material can be constrained from its spectroscopic features. Are there signatures of organics that potentially could be precursors to life? Major organic spectral features are seen in comets in the infrared at 3.3 to 3.4 μm and 5.5 to 8 μm. The former can be studied from the ground with, for example, the Keck telescope. The latter feature must be studied from space (with SIRTF) or from the stratosphere (with SOFIA).

Because of his position as Chief Scientist and Director Designate for SOFIA, lead team member Becklin will concentrate his future efforts on SOFIA. He is currently working with the NASA Ames

Astrobiology lab group to assure that the correct filters and spectrometers become available soon after initiation of SOFIA flights. In addition, UCLA is building a camera and spectrometer for the 1 to 5 µm region. This camera, called FLITECAM (lead team member McLean is the FLITECAM PI), is missing GRISM (GRISM stands for "grating prism") spectrometers in the critical region from 3.0 to 5.0 µm. With these GRISMs we will be able to investigate organic spectral features around 3.3 µm with greater sensitivity than from ground-based telescopes. In addition we will be able to observe the primary carbon containing molecules CO and CO_2, which together with H_2O, are essential to the chemistry that could lead to life.

Becklin proposes as part of this work to purchase the appropriate GRISMs that will enable him to utilize SOFIA for observations relevant to astrobiology. McLean has obtained price quotes from three US vendors for the two necessary GRISMs in the 3 to 5 µm range; typical costs are included in the budget.

5.3 IMAGING EXTRASOLAR PLANETS – REMOVING THE BIAS TOWARDS DETECTION OF GIANT PLANETS CLOSE TO STARS (GHEZ, HANSEN, SONG, ZUCKERMAN)

5.3.1 Development of the youthful star target data base: identification of nearby, youthful stars offers the best nearterm opportunity for imaging Solar System-like planetary systems

The past few years have seen the discovery of numerous massive extrasolar planets (Marcy et al. 2000). All have been detected indirectly, by virtue of their gravitational tug on the star about which they orbit. Only when planets are imaged directly will it be possible to measure their spectra and thus their compositions. Advances in astronomy from the ground, specifically adaptive optics (AO; Beckers 1993), and the employment of an infrared camera on HST, now enable imaging detection of planets with masses comparable to that of Jupiter (Figure 5.3.1; Macintosh et al. 2001). But such detections must be of thermal emission from young, warm planets rather than of reflected starlight from old, cold planets, such as Jupiter. At wavelengths near a few µm, thermal emission from a giant planet not older than tens of millions of years can be hundreds of times brighter than reflected starlight; the latter

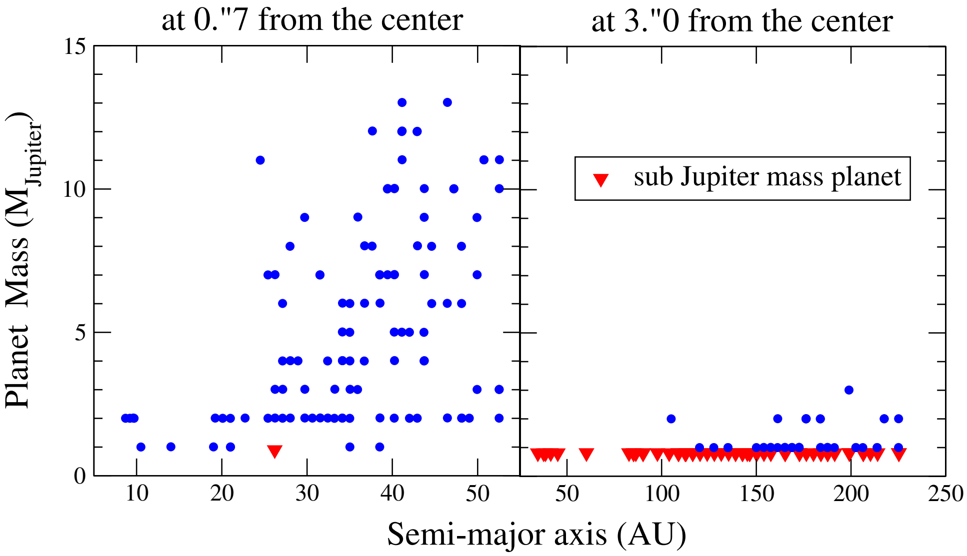

Figure 5.3.1. Plot of masses and star-planet distances for warm, giant planets that would be observable if they were to be in orbit around the 112 stars identified by Zuckerman and Song as very young and near to Earth. The plot shows the minimum masses that should be detectable using the near-infrared camera aboard the Hubble Space Telescope.

is still much too faint to be detected with any existing imaging system.

The giant planets of our Solar System are 5 to 30 times more distant from the Sun than is Earth. Given the diffraction and instrumental scattered light properties of AO and of HST, imaging of Solar Systemanalogs requires finding stars within about 50 pc of Earth and not older than a few tens of millions of years. During the past few years, Zuckerman and his group have carried out a long term project to find the youngest, closest stars to Earth. Using all-sky survey data in X-rays (ROSAT) and major astrometric catalogs (Hipparcos, Tycho-2, and SuperCOSMOS), they have generated a list of a few 1000 very young star candidates within 60 pc of Earth. This project has been very successful. During the course of our present NAI award, Zuckerman and Song have observed about one thousand stars from which they have identified about 200 young nearby stars including the nearest young stellar association, the β Pictoris moving group (Zuckerman et al. 2001; Song et al. 2003).

5.3.2 Infrared searches for Jupiter-mass planets around low-mass stars

Encouraged by the success of the above project, Zuckerman proposes to continue the search for young nearby stars during the period of CAN-3 with greater emphasis on lower mass stars. This is of special interest for two reasons. First, for imaging faint planetary companions around stars, one can detect lower mass planets around low mass stars. For example, at 10 pc from Earth, with AO or HST, it is possible to detect a Saturn-mass planet at an orbital separation of 20 AU around a 10 million year old M-type star. On the other hand, around a 10 million year old A-type star, only planets with masses of about ten Jupiter masses or higher are detectable at the present state of the art. Second, there are many more less-massive stars than massive stars. In fact, regardless of age, there are fewer than 300 A-type stars within 50 pc of Earth while we expect 100,000 or more M-type stars in the same volume.

Various international teams of astronomers have been imaging young stars with AO and/or HST for evidence of cooling planets. But it is generally impossible to know at which nearby star to search without a preceding survey (like that of Zuckerman and Song) to identify "young stars" and to classify them according to mass and age. Thus, all competing planet hunting groups are dependent in various ways on the results of Zuckerman and Song's search. For example, stars identified in the beta Pictoris moving group will be observed early-on with SIRTF by a variety of teams. Indeed the young stars identified by Zuckerman and Song will be re-observed again and again in coming years, each time a more sensitive spaced-based telescope becomes available to astronomers. Young nearby stars from the UCLA survey will be obvious targets for upcoming NASA missions such as Space Interferometry Mission (SIM, lead team member Ghez is a Co-I), James Webb Space Telescope (formerly NGST), and SOFIA.

With compilation of a young nearby stars catalog, members of the UCLA lead team will contribute to the astronomy/astrobiology community by providing a set of valuable targets while maintaining a leading position in an ongoing race for imaging detection of cooling extrasolar planets.

5.4 COSMOCHEMISTRY IN AN ASTROPHYSICAL CONTEXT– RELATING THE ORIGIN OF THE SOLAR SYSTEM TO PROCESSES OF PLANET BUILDING ELSEWHERE (HANSEN, LYONS, MCKEEGAN, MORRIS, SHUPING, WASSON, YOUNG)

5.4.1 The distribution of H_2O in protoplanetary systems

A key question related to the origin and evolution of terrestrial life is that of how water was accreted to Earth and, more generally, how rocky planets acquire their water. There are two main possibilities. One, the endogenous origin, is that the water accreted together with the planetesimals (ranging from asteroid to Mars in size). The other is that water present on Earth’s surface today is exogenous, having been delivered by comet impacts (e.g. Morbidelli et al 2000). At present there is skepticism about the cometary origin of water because the ratios of the heavy isotope of hydrogen to the light isotope, D/H, in the three comets measured thus far (Halley, hyakutake, and Hale-Bopp) are on the order of 2 times higher than in Earth's oceans (Bockelee-Morvan et al. 2000). On the other hand, D/H would most likely have varied with radial distance from the Sun in the early Solar System, making the arguments based on D/H uncertain.

One way to distinguish between the exogenous and endogenous origins of water in rocky planets is to characterize the amount of water that was present in planetesimals. Lead-team investigators McKeegan, Wasson and Young have been studying the role that water played in the evolution of rocky precursors to planets in the Solar System through studies of the ways in which carbonaceous chondrite meteorites, vestiges of the planetesimals, have been altered by reactions with liquid and/or vaporous water (Choi et al. 1997; Choi et al. 1998; Young et al. 1999; Young 2001). This work builds on years of studies pertaining to the role of water in the evolution of planetesimals (asteroid-like precursors to planets) as evidenced by these primitive meteorites (e.g., Kerridge and Bunch 1979; Clayton and Mayeda 1984; Clayton and Mayeda 1999).

It is clear that the bodies from which at least some carbonaceous chondrites come from (now represented by the C-type asteroids) had significant amounts of water within them early in the history of the Solar System, but exactly how much water existed in primitive meteorite parent bodies depends on how the data are interpreted. This is an important question because if objects represented by the C-type asteroids had uniformly large amounts of water (as suggested by some workers, e.g. Young et al. 1999), then the implication is that water was plentiful in the building blocks of the planets in the Solar System (C-type asteroids are the most abundant type of primitive rocky body and the largest asteroid 1 Ceres is such an object). In this case, the origin of water in and on the terrestrial planets need not have been exogenous (i.e., from late introduction by comets) but instead could be the residues left over from much larger amounts of water that existed prior to melting and differentiation of the bodies (i.e., endogenous). Alternatively, if large amounts of water were present in only a small fraction of the primitive building blocks of the planets (as implied by other interpretations of the meteorite data, e.g. Clayton and Mayeda 1984), then water would not have been nearly as plentiful during the planet building process and would not be expected to have survived the planet-forming processes in sufficient quantity to explain present-day abundances (on and within Earth and perhaps Mars).

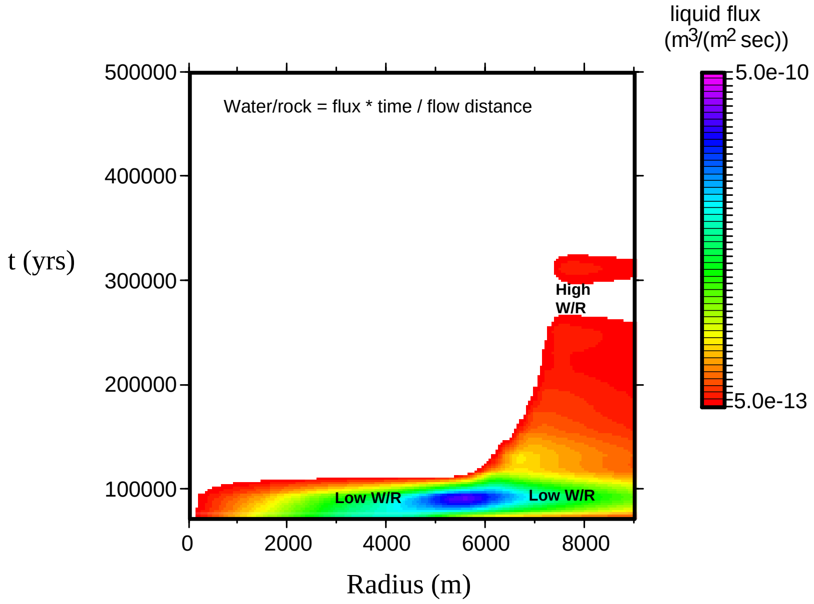

Figure 5.4.1. Results of finite difference model for water flow through an asteroid-like body in the early Solar System (after Young 2001) as a function of radius and time. Colors show intensity of water flux in the body (m^3/(m^2 s) as it evolves with time. Where water/rock recorded by isotopes and mineralogy is high, flux was protracted. Where water/rock is low, flux was fleeting. The total water content of the original body was uniform at 20 volume % but the water/rock preserved in a rock would depend on the original location it occupied in the body rather than the total water content of the body.

There are two models put forward to explain the mineralogical and oxygen isotopic effects of reactions between water and rocks as evidenced in carbonaceous chondrite meteorites. One, the closed-system model put forward by Clayton and Mayeda (1984), states that the amount of water evidenced by the altered rock materials in a meteorite is an expression of the amount of water that existed in the entire parent body (that is to say, the "water/rock ratio" is a characteristic of the object). The implications of this interpretation of the data is that while a few carbonaceous chondrite parent bodies had on the order of 50 volume % water, most had substantially less(< 10%). The other model, the open-system put forward by Young et al. (1999) and Young (2001) is that the amount of alteration of the meteorite depended upon where the particular sample came from in the parent body (Figure 5.4.1). In this model, the parent bodies were heterogeneous in mineralogy and oxygen isotopic characteristics but they all could have had on the order of 20 to 30 volume % water to begin with. If the open-system model is correct, it implies that water was a major constituent of proto-planets prior to their melting and differentiation.

Distinguishing between open-system alteration and closed-system alteration of a chondrite, and thus between large amounts of water in all bodies and large amounts of water in just a few bodies, requires analysis of $^{17}O/^{16}O$ ($\delta^{17}O$) and $^{18}O/^{16}O$ ($\delta^{18}O$) by ultraviolet laser ablation combined with gas-chromatography isotope ratio mass spectrometry (Young et al. 1998). This novel technique is time-consuming but provides a combination of spatial resolution and precision that can not be obtained by any other method. Young and others will carry out oxygen isotope ratio analyses of carbonaceous chonderite meteorites to search for signals that can be used to distinguish between open and closed-system reactions between the rocks and waters. Collection of data for characterization of a reasonable sampling of carbonaceous chondrite meteorites will take several years. The analyses will be carried out in Young’s stable isotope laboratory at UCLA.

Another way to examine the likelihood for exogenous and endogeous sources of water is to study the ways in which giant planets affect the delivery of water to regions where habitable, terrestrial-like planets are likely to form. Planetesimals formed beyond the “snow line” where water is in the solid state in a planetary system are harbingers of water (e.g., comets). Planetesimals formed inside of the snow line may be relatively dry. Giant planets interact gravitationally with planetesimals, in effect stirring them up. What is more, it is now clear that some giant planets in extrasolar systems may have migrated radially with respect to their stars, and it has been suggested that early on gaseous and icy giant planets in the Solar System may also have moved closer or further from the Sun (e.g., Thommes et al. 2002). Indeed it has been suggested that a mechanism for stopping the migration of a giant planet towards its central star is for it to encounter a sufficient number of asteroid-like or comet-like planetesimals (Murray et al. 1998). Giant planets are therefore expected to regulate the distribution of water-bearing planetesimals into regions of terrestrial planet formation.

The consequences of this new paradigm of moving giant planets for terrestrial planet formation are poorly understood. Hansen, in collaboration with Young, plans to perform a detailed investigation of giant planet-planetesimal interactions and the implications for the development of solar-like planetary systems. The challenge will be to cover both the large dynamic range in mass and the large number of particles necessary for a realistic description. The results will be examined in the context of the meteoritic evidence for the early evolution of our own Solar System.

5.4.2 The astrochemistry of protoplanetary systems and the meteorite record

An important step in recognizing signs of life, or the essential precursors to life, is characterization of the various abiotic pathways by which organic molecules are produced in protoplanetary environments, including in our own solar nebula (the protoplanetary disk that surrounded the Sun 4.6 Gyr ago). One potentially important process for forming organic molecules is photolysis. Lyons and Young have begun a program of research devoted to elucidating those characteristics of primitive meteorites that might be explained by photochemistry in the solar nebula. The goal is to get a better picture of the role that photochemistry might have played in determining the inorganic and organic chemistry of the nebula.

One of the most important clues to the origin of the Solar System is the presence of an excess of the ^{16}O isotope of oxygen relative to the two heavier oxygen isotopes, ^{18}O and ^{17}O. This unusual distribution of O isotopes (by terrestrial standards), discovered by R.N. Clayton in 1973, was one of the reasons for suggesting that explosion of a nearby super nova might have triggered the collapse of molecular cloud material to form our Solar System (^{16}O is a product of such an event). However, the connection between an overabundance of ^{16}O inferred to derive from a super nova explosion has not been observed in populations of "presolar" mineral grains that represent pristine ejecta from stars found in meteorites. The variability in ^{16}O apparently has another explanation that remains elusive.

What is clear is that the ^{16}O enrichment is telling us something about conditions that prevailed in the very young solar nebula. Whether these conditions are relevant to the subsequent development of life on Earth is unknown, but they are almost certain to be central to our understanding of other young planetary systems and may be clues to the photochemistry that took place early in the Solar System.

Clayton (2002) made the suggestion that self shielding by CO in the early solar nebula could have been the origin of the anomalous array of $^{18}O/^{16}O$ and $^{17}O/^{16}O$ in primitive Solar System materials (the slope-1 line on a plot of $\delta^{17}O$ vs. $\delta^{18}O$ where $\delta^{17}O$ = per mil deviation in $^{17}O/^{16}O$ relative to standard mean ocean water and $\delta^{18}O$ is defined similarly). The efficacy of the photodissociation of CO as a means for producing slope-1 lines in oxygen three-isotope space is underscored by the detection of slope-1 oxygen isotope ratios in interstellar CO (Sheffer et al. 2002). A major component of the CO self shielding hypothesis is that the starting materials for all solids in the early solar nebula were rich in ^{16}O, with isotopic compositions comparable to the most ^{16}O-rich calcium-aluminum-rich inclusion minerals.

Calculations by Lyons and Young show that self shielding by CO of a stellar flux of UV photons illuminating regions above and below the midplane of the solar nebula (the protoplanetary disk that became the Solar System) should have been sufficient to produce several Earth masses of oxygen with large depletions in ^{16}O relative to the starting over time scales > 10^3 yrs. The most likely sink for the ^{17}O and ^{18}O-rich oxygen liberated by photolysis of CO would have been adsorption onto solid dust grains followed by surface reactions to produce water, as described for molecular clouds by Yurimoto and Kurimoto (2002). Settling of these dust grains and radial transport toward the accreting star (the Sun) brings this source of ^{16}O-depleted oxygen into the nascent inner Solar Systemwhere it can react with gases, minerals, and liquids that form planet precursors.

Experiments show that exposure of ices containing C compounds to UV photons can produce complex organic compounds (Schutte 2002). The model put forward by Lyons and Young implies that ices, primarily composed of water, were important in determining the oxygen isotopic composition of rocky bodies in the Solar System. It also implies that irradiation of condensed materials, including ices, by UV photons could have been an important process, and that the UV photon flux could have come from the central proto-Sun if the ices existed well above the midplane. If shown to be correct, there is the possibility that the origin of organic molecules and ^{16}O anomalies in primitive meteorites are both telling us about the photochemistry of the early solar nebula, and perhaps

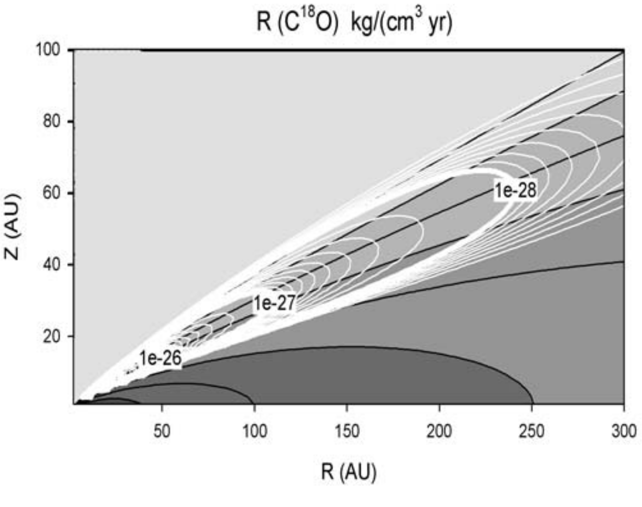

Figure 5.4.2. Calculated rate of $C^{18}O$ photodissociation (white contours) in a protoplanetary disk representing the solar nebula as a function of radial distance from the star (R) and height above the midplane (Z). Grey tones show increasing density in the disk. After calculations by Young and Lyons (2003).

protoplanetary environments in general.

Theoretical tests of this model will be conducted in the next several years. A key refinement will be development of molecular shielding functions. The effects of mutual and self shielding by H, H_2 and CO were included in the original calculations by using the H_2 and CO density-dependent shielding functions of van Dishoeck and Black (1988). These functions were based on calculations appropriate for molecular cloud environments, but should be redone for applications in protoplanetary disks. The calculations will ultimately be extended to investigate the implications for D/H and N isotopes.

If photochemistry at distal regions in protoplanetary disks is common in the Galaxy and recorded in the isotopic compositions of meteorites, then the process should be evident in disks surrounding young low-mass (i.e., solar-like) stars elsewhere. Lead-team members Shuping and Morris propose to test this suggestion by examining the protoplanetary disks in the Orion Nebula. The relative abundances of carbon monoxide isotopomers in the disks can be measured directly using millimeter and submillimeter interferometers. Interferometry is required because the target disks are typically small; spatial resolution on the order of, or better than, an arcsecond is required to match or resolve nearby disks such as those found in Orion and Taurus. Resolution of up to 0.1" is achievable with the Submillimeter Array and with the CARMA array (soon to be in operation).

CO emission has been reported widely in star-forming cores, but only the new generation of interferometers will be capable of measuring the isotopomers of CO in compact protoplanetary disks. By measuring them initially at 230 GHz (the J=2-1 rotational line), where sensitivity is greatest, Shuping and Morris would establish which disks are most promising for measurements of the rarest isotope, $C^{17}O$. Then higher-lying lines would be measured in order to provide information on optical depth and the temperature structure in the disks. The ultimate goal is to determine whether there has been any significant selection, via photodissociative processes, for the more abundant isotopomer relative to the CO abundances in the nearby molecular clouds from which the star and disk formed.

Another approach to take to investigate isotope abundances in disks is to observe the near-infrared (4.6 and 2.3 μm) rotational-vibrational absorption by CO of light from the central star as seen through the disk. While ^{13}CO and $C^{18}O$ are both routinely observed toward protostellar sources at 4.6 μm, the $C^{17}O$ isotope has not yet been detected. Absorption line observations can only be made for protostellar disks with just the right inclination to our line of sight (60 - 80 degrees), and with central stars that are sufficiently bright at 1-5 μm. There are a handful of protostars in Taurus and Ophiuchus which satisfy these conditions. High-resolution near-infrared spectroscopy of the CO lines at both 2.3 and 4.6 μm can be carried out using the Near-Infrared Spectrometer (NIRSPEC) at the Keck Observatory (adaptive optics is not required). In addition to the isotope ratios, these observations will also enhance our understanding of the overall abundance of CO in protostellar disks, both in the gas-phase and as ices condensed onto dust grains (e.g. Shuping et al. 2001, Boogert et al. 2002).

6 CHARACTERIZING THE FACTORS THAT CONTROL THE HABITABILITY OF PLANETS AND PLANETARY SATELLITES

6.1 OVERVIEW

Here we describe research plans in those areas that pertain to the habitability of planets, including Earth. The five areas of proposed research include assessments of the habitability of icy bodies within our Solar System, the potential links between planet-scale dynamics and long-term habitability, the influences of orbital dynamics on prospects for habitable planets in extrasolar planetary systems, the role of impacts on survival and evolution of life, and the evolution of climate on Mars.

The most direct means for investigating the habitability of planets and their satellites is through the study of bodies in the Solar System. Lead-team members Schubert, Moore, Veradi, and Nimmo will examine the potential for sustaining life within the Galilean moons of Jupiter. Two of these bodies, Europa and Ganymede, may owe their potential for habitability to the immense tidal forces they experience by virtue of their gravitational interactions with Jupiter and the other Galilean moons. These forces produce heat that may be capable of sustaining liquid water beneath their surfaces. The mere prospect of the existence of these subsurface oceans demonstrates that an Earth-like planet in circumstellar orbit is but one of a large number of possible hosts for life in the Galaxy and underscores the need to study non-Earth-like systems for gauging their habitability. Our group will study the implications of tidal interactions for oceans within the icy satellites Callisto, Europa, and Ganymede. They will also refine estimates of the thicknesses of the icy crusts of these bodies.

Lead team members Lyons, Newman, Paige, Varadi, and Young will study the volatile inventory of Mars and the Martian climate. Emphasis will be placed on linking Martian climate to rotational and orbital dynamics of the planet, interpreting the stable isotope data for Mars, and on shaping future missions to Mars.

The issue of long-term habitability of planets is being addressed through numerical simulations of planetary-scale dynamics by lead team members Tackley and Aurnou. Earth has been habitable for billions of years while Mars may have been so for a much shorter interval. Based on comparisons between Earth, Mars, and Venus, it seems likely that the long-term habitability in general could depend on the dynamics of the host planet. Plate tectonics may be necessary to sustain an appropriate level of carbon in the atmosphere, for example, which in turn influences surface temperatures. The long-term stability of an atmosphere suitable for life might depend on the presence of a magnetic field of sufficient intensity. Tackley and Aurnou envision establishing criteria that will afford predictions about the likelihood for plate tectonics and magnetic fields based on size and perhaps ages of extrasolar planets. The result of this research has been likened to a rocky planet analogue to the Hertzsprung-Russell diagram (HR diagram) that summarizes the evolution of stars. The HR diagram is used to portray manifestations of stellar evolution. The rocky planet version of the HR diagram would serve an analogous role and would be a useful tool for assessing the potential habitability of extrasolar rocky planets.

Impacts of asteroids and comets must play a fundamental role in the origin, evolution, and extinction of life. Impacts are a primary mechanism of planetary accretion and are possibly responsible for the delivery of water and organic matter to young planets. Large-body impacts may inhibit the formation of life in the early history of planetary formation. Once life has taken hold, impacts can play an important role in the path followed by evolution, such as the mass extinctions that are now known to be coincident with the Chicxulub impact event at the Cretaceous-Tertiary (K-T) boundary. This is not just a terrestrial problem. If life exists on Mars, Europa, or other planets outside our Solar System, impacts must have played a fundamental role there as well. Impacts may even play a role in transporting organisms between planetary objects.

Orbital and rotational dynamics is a central theme in several on-going studies by UCLA lead team members. The factors that cause changes in the frequency of asteroid impacts in the inner Solar System, coupling between Mars' orbital and rotational dynamics and climate, and the influences of giant planet orbital eccentricities on prospects for life in extrasolar planet systems are all being investigated by lead team member Varadi and colleagues using computer codes developed at UCLA. These specialized codes accurately reconstruct the orbital and rotational history of planets and asteroids for up to 100 million years. The physical model is successively refined to take into account small corrections in the equations of motion due to General Relativity, the finite size of the lunar orbit, and so forth. Varadi and Runnegar are using this code to investigate the possibility that impacts that caused mass extinctions might be the result of inner Solar System orbital chaos resulting in asteroid impacts. It might be said, albeit with a hint of frivolity, that because the dynamics of the inner Solar System depend on subtle interactions involving relativistic effects, the extent to which the geological record of extinctions on Earth can be explained by changes in planet orbits serves as a test of General Relativity.

The details of these habitability-related research plans are described below.

6.2 HABITABILITY OF JUPITER'S GALILEAN MOONS (MOORE, NIMMO, SCHUBERT, VARADI)

6.2.1 Tidal forces and the implications for oceans within the icy satellites

There is strong evidence for the existence of a subsurface liquid water ocean on Europa and evidence for the existence of oceans buried in the deep interiors of Callisto and Ganymede as well. A liquid water ocean, at least near the surface of Europa, is a possible habitat for life. It is important therefore to understand how liquid water oceans can exist on Jupiter's icy moons in spite of the tendency for the satellites to cool and the oceans to freeze. The answer lies in a source of heat that offsets the tendency to freeze. It is possible that this heat source is simply the radiogenic heat supplied by the rocky material in the moons (e.g., Callisto, Spohn and Schubert 2003), but especially in the case of Europa, the crucial heat production might originate in the tidal flexing of the satellite by Jupiter. We are therefore motivated to study the role of tides in establishing and maintaining oceans of liquid water beneath the surfaces of the icy Jovian satellites.

From a more general perspective, it is evident that the large satellites of the giant planets have experienced significant orbital, rotational, and thermal evolution due to tides. Tidal dissipation makes Io the most volcanically active body in the solar system, but at the same time, Io clearly demonstrates that too much tidal heating can desiccate a body and render it inhospitable to life. In order to identify the boundaries of a tidally supported habitable zone we must study the orbital, rotational, and thermal evolution of systems of bodies around giant planets. The need to study giant planet moons as a system, even if interest lies mainly in the icy bodies, is clear from the coupling of Io, Europa, and Ganymede in the Laplace resonance.

Schubert, Moore, Varadi and colleagues are developing a numerical model that will calculate the coupled orbital, rotational and thermal evolution of satellite systems of giant planets and will apply the model to the Jupiter, Io, Europa, and Ganymede system. The orbital and rotational evolution of these satellites is obtained by following the dynamical equations forward in time using both symplectic and traditional integrators. We take a primitive-variables approach that does not arbitrarily restrict the orbits or rotations. Thermal evolution models using parameterizations also lead to differential equations that may also be integrated by these methods.

The key to coupling the orbital dynamical and thermal models is development of a dynamical approach to the tidal and rotational deformation of the satellites that represents the deformation equations within each body as a system of ordinary differential equations in time (Hanyk et al.1996). The entire coupled system can then be advanced forward in time using the same integrator. Novel heat transport parameterizations must be developed to adequately describe the magmatic and convective transport of heat in Io; similar parameterizations are necessary for the rocky mantles and icy shells of the other Galilean satellites. The result will be quantitative estimates for the times and places that sufficient heat and liquid water combine to yield potential habitats for life in the icy Galilean moons. The model includes the tidal interactions among the bodies and the tidal dissipation within them. It accounts for the feedback between tidal heating and heat transport in the bodies through the temperature-dependence of viscosity; this is a fundamental aspect of the dynamics of close satellites. Since tidal heating might be the only heat source capable of sustaining geologic activity on the moons for billions of years, understanding this process will be critical for evaluating their habitability. Tidal dissipation is also the mechanism driving orbital evolution and therefore it connects the interior dynamics to the observable orbital state, allowing precise astrometric measurements to constrain the thermal state of the interior of a satellite using only telescopic observations. Since we will not be able to visit any extrasolar satellite systems directly, the development of this theory will be vital to interpreting observations of such systems in terms of astrobiological potential.

For example, by incorporating the tidal models of Schubert and colleagues into ephemeris computations, these workers will be able to tell how much the orbits of the Galilean satellites have changed over recent decades for different internal satellite structures. These predictions will be compared to past observations of the mutual events of the Galilean satellites. This model will also predict the physical librations of the satellites, i.e., departure from rotation around a principal axis of the moments of inertia tensor. These predictions can be tested against observations of the librations, perhaps by a future orbiter (for example, the planned Jupiter Icy Moon Orbiter) to constrain the interior structures of the satellites.

From results already obtained on the physical librations of the Galilean satellites, it has become apparent that improvements in our understanding of the dynamics of synchronous rotation are necessary. Straightforward numerical simulations of rigid satellites reveal that physical librations can have very large amplitudes, comparable to those of spin axis precession. We expect that tides would damp such motions, but it is not obvious how. Nevertheless, the heating rate implied by this dissipation is potentially significant, and could explain the excess heat flow observed from Io relative to that expected from Keplerian tides alone. Europa may also be subject to this excess tidal heating, and additionally may experience differential rotation between its ice shell and rocky interior. Measuring the amplitude of such librations (from an orbiting spacecraft) would provide an excellent constraint on the thickness of the ice when compared with the predictions of the theory being developed as part of this project.

6.2.2 Estimating the thickness of Europa’s icy crust

The thickness of the icy crust of a Galilean satellite has major implications for its thermal history, habitability, and suitability for future missions. On Ganymede and Callisto, the crust is thought to be O(100 km) thick; on Europa, the crust is perhaps O(10 km) thick or smaller, but there is considerable uncertainty in this estimate (Pappalardo et al. 1999). Some inferences of crustal thickness from interpretations of the surface geology have the crust only a few kilometers thick (Geissler et al. 1998; Hoppa et al. 1999; Greenberg et al. 2000) As discussed more thoroughly in §6.2.3, the thickness of Europa’s crust is key to the transport of nutrients from the surface to an underlying liquid water ocean. So much depends on how close Europa’s ocean is to the surface that it is essential to explore all avenues at our disposal for estimating the thickness of Europa’s icy crust.

One approach to estimating the thickness of Europa’s crust is to construct theoretical models of its internal structure as part of a thermal history investigation. This has been done by Hussmann et al. (2002) and Spohn and Schubert (2003). These models predict ice crusts that are a few tens of kilometers thick. The coupled orbital dynamical, rotational, and thermal evolution models discussed in §6.2.1 contain more physics and will provide improved theoretical estimates of ice crust thickness.

Another way of estimating the crustal thickness is to measure its rigidity, or effective elastic thickness. Ice retains its elastic strength only at relatively cold temperatures. Since the temperature gradient within the ice crust depends on its total thickness, the measured elastic thickness can be used to infer the crustal thickness. The elastic thickness measured is the lowest since the deformation occurred.

On the Galilean satellites, stereo topography and flexural analysis can be used to derive the elastic thickness (Nimmo et al. 2002). This has been done for topographic profiles across two rifts on Ganymede, with the result that both profiles give an effective elastic thickness of about 1 km, implying a total crustal thickness of about 3 km at the time of loading (Nimmo et al. 2002). The crustal thickness at present is much larger. However, these calculations indicate that Ganymede once had an ice crust only a few km thick, probably due to an episode of tidal heating.

Nimmo and coworkers propose to extend this approach to Europa. In a preliminary analysis of several topographic profiles across Europa they find an elastic thickness of 6 km, suggesting that the present-day crustal thickness is at least 15 km. This is larger than some estimates, but it agrees with evidence from impact crater studies (Schenk 2002) and predictions from thermal history models (Hussmann et al. 2002; Spohn and Schubert 2003). Possible links between the surface and the internal ocean through such thick ice will be studied in the project described in the next section.

6.2.3 Transport of nutrients through an icy crust – feeding an isolated world

The ice shell covering Europa (§6.2.2) impedes the transfer of nutrients and energy (e.g., sunlight) from the near surface to the interior ocean that most likely lies beneath. The extent to which material from the surface can be transported to the interior, and vice versa, is crucial for assessing the likelihood for Europan life.

Nutrients could be produced by either ^{40}K decay within the ice shell (Chyba and Hand 2001) or the collision of particles accelerated by Jupiter's magnetic field with the surface (Carlson et al. 1999). the latter may be efficacious because Europa is located at the outer edge of Io's plasma torus. The co-rotating plasma from Jupiter's magnetosphere continually overtakes Europa and bombards it with plasma with energies ranging from 100 eV to several MeV. The particles that have a significant effect on the surface chemistry and morphology have energies exceeding tens of keV.

The chemical products formed from the radiolysis of water and CO_2 ice by charged particles include H, OH, H_2O_2, O_3 and many C-H-O compounds like CH_3OH, H_2CO, and CH_2CO etc (Delitsky and Lane 1998). The yield factors for these chemical products are not very well known but yields of 0.01 for O_2 molecules and 0.2- 0.4 for H_2O_2 molecules for each 100 eV of deposited energy have been reported (Brown et al. 1982; Moore and Hudson 2000). Carlson et al. (1999), using infrared spectroscopy from the Galileo spacecraft, estimate that hydrogen peroxide (H_2O_2) abundance is 0.13% relative to water ice on the surface of Europa.

Because photosynthesis is severely inhibited by the thick ice covering Europa, and because the primary energy from geothermal and chemical weathering processes would be quite limited there, Gaidos et al. (1999) argue that most metabolic pathways that power the life cycle on Earth would be denied to organisms on Europa. Therefore, many authors (Chyba 2000; Chyba and Phillips 2001; Cooper et al. 2001; Chyba and Hand 2001) have considered the potential of the radiolysis-produced oxidants to power life in an oceanic ecosystem. The rate at which the oxidants produced at the surface are transferred to the liquid ocean depends on the primary yield from radiolysis, erosion of surface from sputtering and impact gardening, the ultraviolet processing of the surface and the oxidants, and the overturn rates of the surface material by endogenic geological processes.

The radiation not only creates oxidants, it also destroys them and through sputtering can eject a large fraction of the radiolysis products from the surface altogether. Chyba and Phillips (2001) have analyzed the competition between particle sputtering and impact gardening in creating, destroying and preserving (through regolith burial) oxidants on the surface of Europa and suggest that if the regolith is well mixed and communicating with the deeper layers, as much as 2.5×10^{25} molecules of H_2O_2 would be produced per square centimeter of the surface over a time period of 10 Myr. Depending on the models of ice thickness and subsurface geology a wide variety of scenarios can be supposed for the delivery of these oxidants to the liquid ocean. Using fairly conservative estimates of oxidant creation and transfer to the ocean, Chyba and Phillips (2001) suggest that the ocean would be able to support ~ 10^{23} to 10^{24} prokaryotic-analog cells in the oceanic biomass. However, if the upper layers of ice could be constantly replenished with material exchange from the interior so that a maximum transfer of the oxidants occurs to the subsurface ocean, the biomass estimate would increase by a factor of 10^3 and the level of oxygen in the Europan ocean could be comparable to that in the Earth's ocean (Cooper et al. 2001).

The solid ice shell of Europa consists of two parts, a near-surface cold region in which deformation occurs by brittle processes, and a deeper warmer region in which ductile deformation predominates. The latter region may experience solid-state convection (see below) and is likely to be the area in which heat is generated by tidal deformation of the ice shell.

Nimmo and coworkers propose to investigate possible transport mechanisms in both these regions, and focus in particular on the likelihood of melting the ice. Melting is attractive because it forms an efficient transport mechanism, and there is observational evidence for it, such as the surface chaos regions.

Melting within the brittle near-surface layer is difficult to achieve, but one potential mechanism is shear heating on strike-slip faults (Nimmo and Gaidos 2001). This model suffers some drawbacks, notably its inability to calculate the thickness of the brittle layer self-consistently. We propose to remedy this deficiency in order to better establish the conditions under which near-surface melting can occur. A further consequence of the shear-heating model is that it may produce linear diapirs, which can potentially advect material towards the surface. It is well known that Europan ridges are darker than the surrounding material (Fagents et al. 2000). Nimmo et al. propose to investigate whether this observation is consistent with diapiric activity.

Transport of material within the convective zone of the Europan ice crust is estimated to occur on timescales of about 10^3 yr to about 1 Myr. If nutrients can be transported through the brittle lid, such timescales are probably sufficient to sustain a modest oceanic biosphere (Chyba and Phillips 2001). Previous convection models of Europa have generally assumed Newtonian behavior (e.g., Pappalardo et al. 1998), but the ice may actually be behaving in the non-Newtonian regime. An important consequence of non-Newtonian behavior is episodicity, which means that previously calculated transport timescales could be incorrect. Furthermore, convection might lead to discrete diapirs (e.g., Nimmo and Manga 2002) rather than the steady currents previously envisaged (e.g., Pappalardo et al., 1998). Nimmo and colleagues propose to carry out a suite of convective model calculations that will incorporate non-Newtonian behavior and tidal heating and examine the consequences for material transport and melt generation. While they intend to focus on Europa initially, the equations are general so that one can also investigate convective processes on Ganymede, Callisto and the Saturnian icy satellites.

A key feature of the convection models will be the incorporation of a realistic composite ice rheology (Goldsby and Kohlstedt 2001), including the different creep deformation mechanisms (dislocation, superplastic, and diffusional) that come into play at different stresses and grain sizes. The former two of these are non-Newtonian, which can lead to deformation that is episodic and localized (e.g., Larsen and Yuen 1997), as mentioned above. The models will also include a simple parameterization of brittle failure of the lid using a pseudoplastic yield stress, which can also lead to highly episodic behavior, as well as mobile-lid-like features (Tackley 2000). This modeling can be performed using an existing code, Stag3D, which has previously been used for modeling silicate convection in 2-D and 3-D and already includes the necessary rheological capabilities. Failure of the brittle layer would be especially interesting in this context as it would permit advective transport of materials from/to the surface.

The convection models will be coupled to a tidal dissipation calculation, in order to self-consistently treat the feedback between viscosity variations caused by convection, and tidal dissipation (Sotin et al. 2002). Tidal flexing is a long-wavelength phenomenon so it couples mostly to long-wavelength viscosity variations, and a global treatment is necessary to calculate this correctly. The main interest in such heating is that it is another possible melt-generating (and hence nutrient-transporting) mechanism.

6.3 THE STRUCTURE AND DYNAMICS OF ROCKY PLANETS (AURNOU, TACKLEY)

Cycling of volatiles (particularly water and carbonate) between the interior and surface of a terrestrial planet could play a major role in the evolution of the fluid envelope, and hence the long-term habitability of the surface environment. This cycling is strongly influenced by tectonic mode (i.e., plate tectonics, rigid lid or episodic plate tectonics). For medium-sized planets, a magnetic field, when present, greatly reduces solar wind-induced escape of the atmosphere, aiding long-term habitability. Previous habitability analyses have included only highly idealized, parameterized models of planet interiors (bringing into question their veracity) and have not included the generation and consequences of a planetary magnetic field. Tackley and Aurnou propose to study the interaction of the interiors of terrestrial planets (mantles and cores) with their fluid envelopes using advanced numerical models, with the goal of formulating predictions for the evolution of habitability of terrestrial planets as a function of size, stellar flux and initial conditions. The assumed criterion for planetary 'habitability' will be the usual: the existence of liquid water at the surface (e.g., Kasting et al. 1993b) which requires a surface temperature of between 273K and 373K (at 1 bar or 10^5 Pa).

Both the mantle and the core of a terrestrial planet play important roles in determining the evolution and composition of its atmosphere. The fluid envelope of a planet in turn influences the dynamics of its interior, resulting in a system of feedbacks that requires careful analysis. Such an analysis requires consideration of coupled mantle-core-atmosphere systems to determine the likelihood of surface liquid water (hence habitability). Habitability is clearly time-dependent, with planets such as Mars possibly passing through a short-lived (e.g., 100s of Myr) habitable phase before reaching a long-term, non-habitable (too-cold) condition, while planets such as Earth experiencing a long-term, slowly-evolving habitable condition. It is notable that the known planets without plate-tectonics-related interior-atmosphere feedback (i.e., Mars and Venus) appear to have undergone a transient one-way evolution to a non-habitable mode.

The mantle of a rocky planet influences the planet's fluid envelope by contributing volatile components (e.g., water, carbon dioxide gas) to the surface by way of volcanic activity, and by as a sink for volatiles from the surface where tectonic processes are capable of delivering surface material to the mantle. Indeed, a long term cycle that moves carbonate to and from the mantle (volcanic outgassing, tectonics) may provide a critical feedback mechanism that maintains surface temperature in a habitable range (Kasting et al. 1993b; Sleep and Zahnle 2001). Volatile recycling also affects the redox (reduction/oxidation) state of the mantle, which in turn, through outgassing, influences the redox state of the atmosphere (Delano 2001; Kasting et al. 1993a; Lecuyer and Ricard 1999), and may have been responsible for the rapid rise in atmospheric oxygen ~2 Gyr ago (Kump et al. 2001).

Plate tectonics appears to be a crucial component of such planet-scale cycles and feedbacks. It is by way of plate tectonics that carbonate, water and other volatiles are returned to the mantle by the process of subduction. Such an efficacious return mechanism is not possible in a planet with a rigid, unyielding outer lid (lithosphere). Apparently, the existence of plate tectonics may be important for long-term planetary habitability. The conditions necessary for plate tectonics to exist as a feature of other rocky planets of variable sizes and distances from their stars, and the scaling of key rates (e.g., outgassing, subduction) associated with plate tectonics on other planets, are not understood. In addition, the details of how recycled water and other volatiles circulate in the mantle to be returned to the shallow melting zones beneath volcanic centers are poorly understood even for Earth. The uncertainties are exacerbated by the fact that the mantle of a planet may be partly stratified in convection or in composition, and this stratification will have evolved with time (Tackely 2000a). Tackley and colleagues propose to study these aspects using numerical models of mantle convection and lithosphere dynamics, as discussed below.

Based on the known terrestrial planets of our Solar System, the core of a rocky planet is responsible for the generation of the magnetic field that shields the planet's atmosphere from the stellar wind emanating from its star, thereby greatly reducing the rate of atmospheric escape (Shizgal and Arkos 1996; Yung and DeMore 1999). Existence of a magnetic field is particularly important for retaining atmospheres around smaller terrestrial planets such as Mars (larger ones such as Venus are more able to hold on to their atmospheres by gravity alone) and is also important for protecting primitive organisms from potentially lethal charged particles (Horneck et al. 1994). Existence of a magnetic field may be important for maintaining a habitable atmosphere over billions of years for smaller planets, but not all terrestrial planets have an internal dynamo of long duration.

Defining those characteristics of a rocky planet that lead to its ability to generate a magnetic field (by virtue of a dynamo in the core) is of the utmost importance for determining the likelihood that the planet could sustain life over the long term. A first-order criterion for the existence of a dynamo is that the heat flux extracted from the core by the mantle must be greater than that conducted down the core adiabat. However, it may be more complicated than this criterion implies. For instance, studies by (Kutzner and Christensen 2002) and (Olson and Christensen 2002) suggest that the existence and behavior of the magnetic field depends strongly on the strength and pattern of core heat loss as well as the planetary rotation rate. Assuming that the heat flux out of the core is sufficient to drive a dynamo (Gubbins 2001; Nimmo and Stevenson 1992), these studies find that generating an Earth-like dipole dominated magnetic field is sensitive to the ratio of buoyancy forces and rotational forces. It is not understood how this ratio evolves over the thermal history of a planet. In addition, the solid inner core tends to germinate and grow outward at the expense of the liquid outer core during the lifetime of a terrestrial planet (Labrosse et al. 1997). It is not well understood how the magnetic field generation process changes as the core solidifies (Al-Shamali et al. 2002). Tackley and Aurnou propose to investigate these aspects using three-dimensional numerical geodynamo models and parameterized models of coupled core-mantle evolution, as discussed below.

Tackley, Aurnou and lead-team colleagues propose to investigate the coupled system comprising the fluid envelopes, mantles and cores of terrestrial planets by first performing fundamental research on key aspects of the problem (e.g., magnetic field generation, generation and scaling of plate tectonics convection) using multidimensional numerical models and planetary evolution calculations using either numerical modeling of the mantle with parameterized core and atmosphere models, or fully parameterized models. This improves on previous research which has used only simple parameterizations, about which there is considerable uncertainty, for planetary interior behavior. The new models will be applied to known terrestrial planets prior to extrapolating to all possible terrestrial planets. Terrestrial planets from Mars size to ~10 Earth masses will be considered, with the core making up different proportions of the total mass.

A key output of this will be to establish a predicted domain diagram of exoplanet habitability as a function of size, incident stellar flux (related to steller brightness and distance from the star) and time. The sensitivity of this to initial conditions (e.g., initial concentration of carbon dioxide in the atmosphere) will also be investigated. A preliminary example of a hypothesized domain diagram at a time corresponding to the present-day Solar Systemis shown in Figure 6.3.

Numerical modeling (in two- and three-dimensions) of mantle convection in a plate tectonic regime will be performed. The models will include chemical transport and differentiation associated with crust production. This numerical modeling is necessary because there is considerable doubt as to how convective quantities scale with convective vigor in a plate tectonic regime due to the dissipation associated with subduction (Conrad and Hagar 1999), to the changing compositional buoyancy of oceanic plates (Davies 1992), and to changes in internal dynamics associated with phase transitions (Christensen and Yuen 1985; Davies 1995; Tackley 1995). The basic modeling technology already exists (Tackley 2000b; Tackley and Xie 2002) but will be expanded to include tracking of the subducted volatiles carbonate and water. Tracing these key volatiles will permit Tackley to monitor the evolution of the redox state and water-dependent viscosity of the mantle.

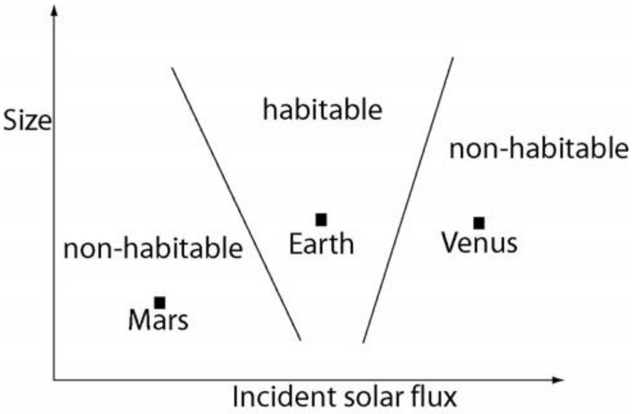

Figure 6.3. Plausible domain diagram of present-day planetary habitability (i.e., after billions of years of evolution) as a function of planet size and solar flux. Domain boundaries will be time-dependent.

A parameterized atmosphere-ocean 1-D radiative model will be overlain on these calculations in order to account for feedbacks between the two systems. A parameterized model of core heat loss (e.g., Labrosse et al. 1997) will also be included to evolve the lower boundary condition and determine core heat loss. Key goals are to establish the regions in parameter space where plate tectonics is expected when the fluid envelope of the planet is taken into account and to establish how feedbacks between the fluid envelope and the interior affect the time-dependent dynamics of the planet interiors.

Fundamental research into core dynamics of prospective terrestial planes will be performed via 3-D numerical dynamo simulations (Wicht 2002) to understand the effect of the main parameters on the type and strength of dynamo generated. The main parameters are the size of the core, the size of the solid inner core, cooling rate, and rotation rate. These experiments will give us a systematic understanding of how a planetary dynamo is likely to vary in strength and form (e.g, the relative importance of quadropole and higher components) for different sized planets at different stages of their evolution. Using these results, the rate of escape to space of different atmospheric species can be calculated, and this will form an important component of the atmosphere evolution model.

The abundances of the main atmospheric and oceanic constituents will be tracked over a planet's evolution, with inputs coming from mantle outgassing, and outputs to rock formation and subduction, and escape to space. A parameterized, 1-D atmospheric model will be used (as in e.g., Kasting et al. 1993b) to determine surface temperature and any other necessary quantities. Tackley and Aurnou do not plan to develop more sophisticated atmospheric models because this is being done by other NAI groups (e.g., Meadows et al. at JPL-2) and thus Tackley and Aurnou will collaborate with them if more sophistication is required. The initial condition (after major impacts, etc.) may have an important influence on subsequent planetary evolution, and this will be a major focus. Clearly, if life starts it will also exert a major influence, so the parameterized models will also include this possibility and compare the signature of planets with and without life.

6.4 ORBITAL DYNAMICS OF HABITABLE EXTRASOLAR PLANETS (VARADI, RUNNEGAR)

The known giant extrasolar planets have wide ranges of orbital semi-major axes and eccentricities. A giant planet with even moderately large eccentricity encounters a wide section of space. Accordingly, such planets can affect perturbations in the orbits of smaller bodies. Can habitable terrestrial planets survive in such orbital environments? Varadi et al. have unique capabilities to locate orbitally stable regions in extrasolar planetary systems. As opposed to the straightforward trial-and-error numerical simulations, they map out the stable regions of orbital resonances by computing the location and stability of resonant periodic orbits. They already have extensive results for the 2:3 (Varadi 1999; Figure 6.4) and the 1:2 (Haghighipour et al. 2003) orbital resonances. In the case of the former, they find stable, nearly circular orbits for small planets which cross the highly eccentric orbit of a giant planet. The configuration is the reverse of the Neptune-Pluto system. Their technique will also be used to find stable planetary orbits in multiple-star

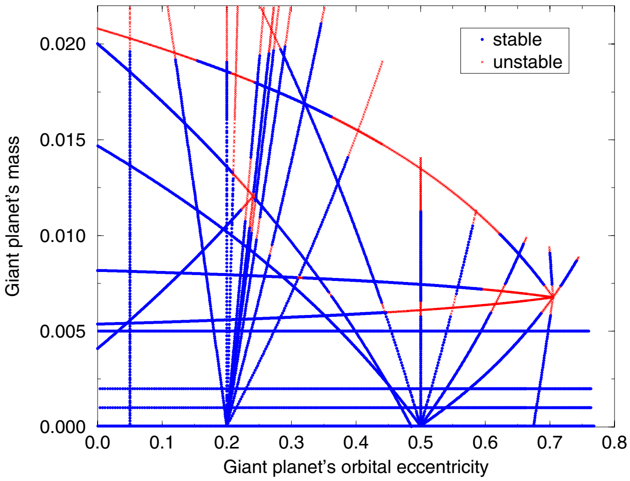

Figure 6.4 The stability of orbits of hypothetical small planets in 3:2 orbital resonance with a giant planet. Each dot represents a particular resonant periodic orbit found by varying the mass and orbital eccentricity of the giant planet. The results define paths along which resonant periodic orbits of small planets were determined.

systems and to constrain the evolutionary path of multi-planet systems in orbital resonances. Varadi and colleagues collaborate in this onging project with the Carnegie Institution of Washington NAI lead team.

6.5 STUDIES OF ASTEROIDS, IMPACTS, AND THEIR EFFECTS ON THE DEVELOPMENT OF BIOSPHERES AND THEIR PLANETARY ENVIRONS (BYERLY, KYTE, LOWE, NEWMAN, VARADI)

Members of the UCLA Center for Astrobiology are directly involved in exploring several areas of this important subject. This work involves direct studies of terrestrial impact events and critical events in Earth history, analytical studies of the evolution of planets and asteroids through time to explore the possibility of planetary forcing of clustered impacts, and modeling large impacts to understand their influence on the evolution of planetary volatile inventories (i.e., oceans and atmospheres).

6.5.1 Extraterrestrial impact history on Earth

This area of research is led by Frank Kyte, an established expert on the study of sediment deposits formed by large-body impacts and co-chair of the NAI Impact Focus Group. Kyte plans to engage in collaborative research with several research groups to expand our understanding of the impact history on Earth and potential links to perturbations in the Earth's evolutional history. This research involves Kyte's expertise in characterizing an impact signature using chemical and mineralogical analyses, in collaboration with experts in diverse fields ranging from sedimentology to isotope geochemistry. Several of the collaborations are described briefly below.

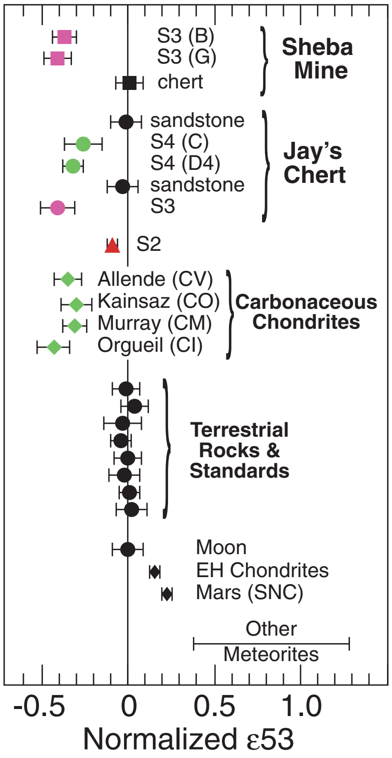

Figure 6.5.1. Cr isotope data for terrestrial rocks, carbonaceous chondrite meteorites, with ε 53 < 0, and K-T boundary, and Archean spherule beds (S2-S4). The spherule beds have isotopic compositions similar to the carbonaceous chondrites.

Early Archean (3.5 to 3.2 Gyr) impact deposits that were first reported by Lowe and Byerly (1986) in sedimentary rocks from the Barberton Greenstone Belt are now clearly established as derived from mega-impacts, based on their anomalous Cr-isotopic compositions (Figure 6.5.1, Kyte et al. 2003b). These rocks provide the earliest confirmed record of impacts on Earth, and provide a link to the Late Heavy Bombardment impacts that were recorded on the Moon. This research includes field and laboratory studies with UCLA lead team members Lowe (Stanford) and G.R. Byerly (LSU), as detailed below.

The Triassic-Jurassic boundary is one of the "Big Five" mass extinctions in the Phanerozoic. Detailed studies of new stratigraphic sections have demonstrated a significant stable isotope shift (Ward et al. 2001) and a small Ir anomaly (Olsen et al. 2002), suggesting a possible impact link to these extinctions. Kyte and the rest of the impact lead team members are engaging in analyses of new sections with P.D. Ward (University of Washington lead team) and other workers, to further examine this record.

Multiple Late Eocene impacts might be caused by a comet shower, according to Farley et al. (1998) who reported an increased flux of ^{3}He to sediments at that time. Kyte and colleagues are using chemical, mineralogical, and isotopic studies of these ejecta deposits to sort out the provenance (e.g., cometary, impact plume, interplanetary dust?) of various physical components at several sites around the world. This work should help to constrain the comet shower hypothesis.

The late Pliocene impact of the Eltanin asteroid is the only known deep-ocean (5 km) impact (e.g., Gersonde et al. 1997) and is characterized by high-energy deposits with high concentrations of meteoritic materials (Kyte et al. 2002a-c). A recent oceanographic expedition to the impact site recovered 17 new sediment cores with ejecta deposits. This unique deposit might be used to constrain models of impacts on early Earth that are proposed as a potential source of organic matter for the origin of life (Pierazzo and Chyba 1999; Kyte et al. 2003a). Kyte and colleagues are also attempting to obtain precise ages on this impact to link it to the climate record at 2.4 Myr before present, a time of rapidly deteriorating climate.

6.5.2 Exploring the early Archean impact record and the consequences for early life

Over the next few years, the UCLA lead team plans to investigate three main aspects of the Barberton Greenstone Belt (BGB) impacts: (1) Archean impact rates; (2) the effects of large impacts on surface environments; and (3) the effects of impacts on putative biological materials and communities.

Lowe (Stanford), Byerly (LSU), and colleagues propose to constrain the Archaean frequency of impacts by providing additional geochronological constraints on critical sections within the BGB, especially within the upper Onverwacht, which is composed of over 100 million years of sedimentary and volcanic rock with no internal age dates. The Stanford-USGS SHRIMP (ion microprobe) will be used on several samples previously collected from the upper Onverwacht. Within the upper Onverwacht they will also collect closely spaced samples, and in places obtain continuous cores, from the condensed sedimentary sections. Preliminary analyses for chromium anomalies will be used to screen for possible impact layers. Subsequent analyses for iridium anomalies and possibly chromium isotopic anomalies will be used to distinguish chondritic impact materials from the very similar komatiitic volcanic materials.

In shallow-water and shelf environments, impact spherules have generally been extensively reworked by impact-produced tsunamis and, in some areas, subsequent environmental currents and waves. In deeper-water settings, the spherules accumulated as direct fall deposits (Lowe and Byerly 1986; Lowe et al. 2003). By tracing beds along individual outcrop belts and among the various structural belts, it will be possible to document the effects of tsunamis and fall-deposition of enormous volumes of impact-produced debris on local environments and to determine how new environmental conditions that were established following the impacts differed from those prevailing before the impacts. The latter should provide key evidence regarding the long-term effects of such large impacts. Lowe and Byerly will also examine the sedimentary record immediately above well documented impact layers for indications of major compositional anomalies that might be associated with impact-induced modifications of the atmosphere and shallow hydrosphere.

It has been suggested that impacts that deposited some BGB spherule-containing layers were large enough to boil away the surface layer of the oceans (Sleep and Zahnle 1998). Such a profound environmental effect may be reflected in the character of organic matter across the impact horizons. In a number of localities, black organic chert occurs below and immediately above impact layers. The types, abundances, distribution, and isotopic composition of organic grains and mat-like layers (e.g., Walsh and Lowe 1999) should provide clues about the changes in organic materials and perhaps the organisms that produced them across the impact layers.

Lowe and Byerly will spend approximately 3 weeks each summer conducting field studies in the Barberton and other Kaapvaal greenstone belts, South Africa, and/or the greenstone belts of the Pilbara, Western Australia. One week each summer will be spent with analytical studies. Byerly will visit Stanford for one week each summer to do geochronology in the SHRIMP Lab. The initial two years will focus on Barberton, and subsequent years will be spent in the Pilbara looking for correlative impact layers.

6.5.3 Solar-System chaos and the frequency of asteroid impacts

Chaos in the motions of the inner planets of the Solar System causes episodic transitions in the way their orbits interact. While chaos makes it difficult to reconstruct or predict these transitions far from the present, state-of-the-art simulations indicate that a major transition took place about 65 Myr ago, coinciding approximately with the Chicxulub asteroidal impact (Kyte, 1998) that is believed to be responsible for the Cretaceous-Tertiary (K-T) mass extinction event. So the question is: was chaos in the inner Solar System the ultimate cause of the extinction of the dinosaurs? Or, more generally, can chaotic disturbances of inner Solar System dynamics lead to an increased probability of a sizeable asteroid hitting the Earth?

These questions have to be considered in the general framework of asteroid orbital dynamics. The largest changes in the orbits of the major planets and asteroids are regular rather than chaotic. From time to time, the orbits of some asteroids (e.g., 1750 Eckert) are strongly perturbed by the major planets due to certain orbital alignments (see Williams and Hierath 1987). Furthermore, some regions of the asteroid belt are chaotic independently of chaos in the motions of the major planets (Lecar et al. 2001). The result may be collision with another body, ejection from the Solar System, or scattering within the asteroid belt. Most of the current asteroids are the survivors of this constant perturbative erosion. However, chaotic transitions in the motions of the inner planets may change the locations of regions of strong erosion in orbital parameter space (Figure 6.5.3) and, as a result, long-term survivors may become vulnerable.

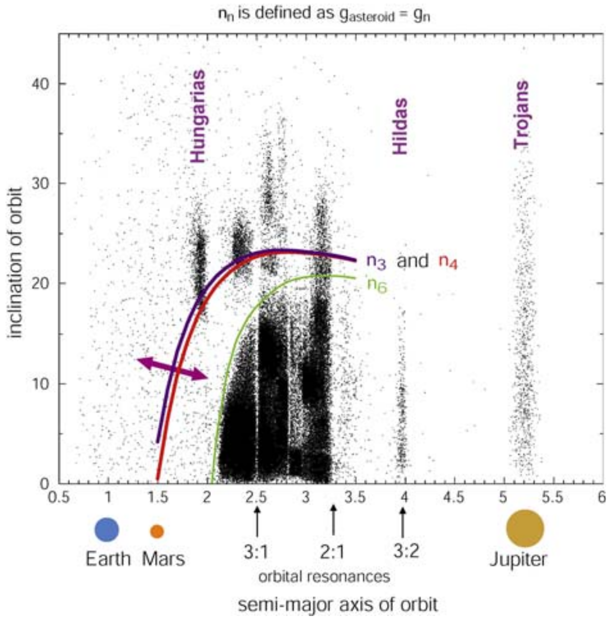

Figure 6.5.3. Plot of asteroids (dots) as a function of distance from the Sun (semi-major axis) and inclination of orbits. The n_3, n_4, and n_6 refer to secular resonances resulting in very large perturbations of the asteroid orbits. As the rates of Earth's and Mars'orbits change due to chaos, so too do the locations of these unstable orbits of the asteroids depicted by n_3, n_4, and n_6.

In order to determine the magnitude of any chaos-induced increase in asteroid impact probability, Varadi and colleagues propose to carry out a variety of long-term numerical simulations. First, they will determine the types and ranges of possible chaotic transitions by simulating only the motions of the major planets. Next, they will add thousands of randomly placed hypothetical asteroids into the model in order to locate regions in parameter space which enable the test asteroids to survive. Finally, Varadi will drive the survivors through regime transitions. One way to approach this problem in the shorter term (which we shall also use) is to take a set of the most vulnerable existing asteroids - those which are already or nearly planet crossing, such as 433 Eros and 1750 Eckert - and simulate their behavior both backwards in time through the observed major transition near the K-T boundary and through an equally sizeable transition that is expected to occur about 30 Myr from now.

Varadi will use a numerical integration scheme that is a version of the classical Stormer-Cowell integrator but optimized to reduce the long-term effects of numerical round-off errors. The UCLA lead team has obtained an improved analytical representation of the lunar orbit which is a significant step toward increased accuracy. The simulation results are used not only to investigate a possible connection between inner Solar Systemorbital chaos and asteroid impacts, but also to couple the orbital and rotational dynamics of Mars in order to understand long-term changes in Martian climate (§6.6.1).

6.5.4 Impacts and the evolution of atmospheres

Newman and colleagues will consider the energetics of large bolide impacts (10 times the K/T event and greater) on atmosphere-free planets to determine whether such impacts will contribute to the planet's volatile inventory.

It appears that it is possible to acquire volatiles through very large impacts even in the absence of degassing of surface volatiles and mantle outgassing. This is evident by considering an impactor that strikes a planet at 20 km/s and vaporizes approximately three times its own mass in target (i.e., surface) material (O'Keefe and Ahrens) (O'Keefe and Ahrens 1977). The vapor cloud has, therefore, four times the mass of the impactor. Excluding all other sinks of energy (i.e. the impact has perfect conversion of kinetic energy from bolide to vapor cloud), the mean speed of the cloud will be reduced to 10 km/s, less than Earth's gravitational escape velocity. If one adds more realistic sinks of energy (i.e., latent and sensible heat, seismic radiation, etc.), the expansion velocity of the cloud will decrease further, and more vapor will be retained. Newman et al. are therefore calculating a strict lower bound on retained material. More inclusive representations of energy sinks will increase the amount of vapor retained.

Newman and coworkers have created a simple, physical model derived from the self-similar model of vapor cloud density of Zel'dovich and Raizer (1966) for expansion of gas in a vacuum, the model used previously by Vickery and Melosh (1990). They also assume the amount of target material excavated by an oblique impact based on the findings of O'Keefe and Ahrens (1977) as well as Pierazzo and Melosh (2000). By considering both the expansion speed of the cloud and the bulk drift of the cloud due to lateral motion of the oblique impactor, they solve for the fraction of the expanding cloud for which the total (vector) velocity is less than the escape velocity of the planet. They have observed (Mischna and Newman, in prep) that most impact events on airless worlds provide substantial inventories of volatiles, thereby producing the atmospheres and hydrospheres necessary for life.

Newman et al. propose to perform first-principles hydrodynamic simulations of oblique impacts for a variety of impact speeds (i.e., Solar System positions of origin), target planet, impact angles, crustal volatile content (ranging from ocean-impacts to dry, Venus-like lithospheres). The simulations will be performed in collaboration with Los Alamos National Laboratory (LANL) collaborator Eugene Symbalisty using LANL and Sandia National Laboratory codes, some of which have now been ported to desktop workstations, to develop more accurate quantitative estimates of the efficiency of the volatile retention process. Finally, Newman will consider how these results can be applied to extrasolar planetary systems.

6.6 MARTIAN CLIMATE AND VOLATILE INVENTORIES THROUGH TIME (LYONS, NEWMAN, PAIGE, VARADI, VASAVADA, YOUNG)

In the search for life on Mars, either present or past, it is necessary to develop comprehensive understanding of the inventory and behavior of Martian volatiles and the Martian climate. Volatiles and climate on Mars are intimately linked to a wide range of dynamical phenomena, including: (1) the dynamics of the Solar System and Mars' spin axis; (2) the dynamics of impactors and their interaction with the Martian surface and atmosphere; (3) the dynamics and chemistry of the Martian crust and interior; (4) the dynamic interaction between the Martian atmosphere and the space environment; and (5) the dynamics of the Martian atmosphere and polar caps. During the next five years, the UCLA NAI Mars Volatiles and Climate subgroup will address four focused problems directly relevant to Mars volatiles and climate studies.

6.6.1 Orbital and axial dynamics of Mars

Varadi, Paige, Vasavada and colleagues proposes to develop new, state-of-the-art models for orbital and rotational dynamics and couple them to low-dimensional climate models to better understand how large-scale quasi-periodic variations in Mars orbital and axial elements are coupled to Martian climate change. Successively refined numerical simulations of the orbits of the planets are expected to provide a more accurate orbital history of the Solar System for the past 70 million years (see §6.5.3). Beyond this time scale, the uncertainties due to chaos make the results of individual simulations unreliable. They are still meaningful, however, in terms of understanding the general features of orbits over hundreds of millions of years. Rotational dynamics, on the other hand, needs to be fundamentally reconsidered.

According to the conventional view, planets rotate around a principal axis of the moments of inertia tensor and the spin axis precesses in space due to torques by the Sun, other planets, and also satellites. This is a convenient approximation which is not consistent with the equations of rotational dynamics. The torques responsible for spin axis precession also cause the planet to deviate from exact principal-axis rotation. Our recent results demonstrate that the deviation can be comparable to the amplitude of spin axis precession in the case of synchronously rotating satellites (§6.2.1). Could similar phenomena be important for Mars? Once the body is allowed to deviate from principal -axis rotation in our models, there can be a number of resonances between the period of the wobble and short-period orbital forcing from other planets.

UCLA lead team members are already developing new analytical machinery in the form of perturbation theory, to obtain accurate equations for the long-term behavior of obliquity. While rotational variations can affect climate, the reverse is also true. The seasonal deposition and sublimation of large polar caps on Mars perturbs the moments of inertia (as measured by Mars Global Surveyor through the gravity field) of Mars, providing a means for feedback between climate and rotation. Other internal processes such as the formation of Tharsis also modify the inertia tensor and therefore influence the rotational state of Mars. The team is developing a model for following the time-dependent deformation of Mars under various loads. This model will be coupled to both the climate model (through the polar cap loading/unloading) and the orbital and rotational dynamics through the time-dependent inertia tensor. The dynamics of such a system have not been analyzed, and this feedback may have a significant effect on the obliquity history of Mars.

The orbital and rotational dynamics will be coupled with simplified models of the behavior of the Martian climate system that will calculate the state and mass distribution of the polar caps and atmosphere. Such models will be used to understand potential coupling between the dynamics and of the Solar Systemand the Martian climate, which may be recorded in the Martian layered deposits. We will develop and use sophisticated time series analysis techniques based on Singular Spectrum Analysis to extract potential climate signals that can be compared to observations of Martian layering patterns as demonstrated by Laskar et al (2002). Our studies will include polar layered deposits as well as mid-latitude layered sedimentary deposits recently identified in Mars Global Surveyor Images (Malin and Edgett 2000). The analysis will employ a recently-developed "denoising" technique called Random-Lag Singular Cross-Spectrum Analysis. This technique provides not only cleaned-up signals, but also cross-filters with phase information between signals to detect time lags between astronomical forcing and changes in the rates of deposition.

6.6.2 Oxygen isotope fractionation and the crysosphere of Mars

The ratios of the isotopes of oxygen in Earth's atmosphere reveal much about the functioning of our planet. In particular, the fact that the $^{18}O/^{16}O$ of oxygen in tropospheric air is grossly out of equilibrium with $^{18}O/^{16}O$ in the oceans is a first order consequence of the existence of a biosphere; disequilibrium in oxygen isotopes between air and oceans is the result of respiration, a phenomenon known as the "Dole effect" (Dole 1935). Similarly, the oxygen isotope ratios of the various oxygen-bearing reservoirs on Mars are potentially useful as first-order indicators of processes that operate in the outer, volatile-rich envelope of the planet. Lead team investigators Young and Lyons propose to investigate oxygen isotope fractionation processes applicable to Mars with an eye towards elucidating the meaning of the measurements that exist for that planet.

Oxygen represents a major component of the Martian atmosphere, cryosphere, lithosphere, and perhaps its biosphere if it exists. With respect to the ^{16}O, ^{17}O and ^{18}O isotopic system, data from Martian meteorites (SNC meteorites) suggest unusual fractionation patterns that have yet to be fully explained. Clues come in the form of similar, though far from identical, effects in Earth's troposphere.

Oxygen in Earth's troposphere has $\delta^{17}O$ values ($\delta^{17}O$ = per mil deviation in $^{17}O/^{16}O$ relative to standard mean ocean water) that are ~ 0.3 per mil lower than rocks and waters at the same $\delta^{18}O$ value. Differences in $\delta^{17}O$ relative to $\delta^{18}O$ values are referred to as differences in $\Delta^{17}O$ where $\Delta^{17}O = \delta^{17}O - 0.52\ \delta^{18}O$. This definition of $\Delta^{17}O$ is based on the assumption that the so-called mass-dependent fractionation among the three isotopes of oxygen follows the relation $\delta^{17}O = 0.52\ \delta^{18}O$. In fact the "slope" factor 0.52 is actually an exponent in a fractionation law and takes on a range of values from about 0.53 to 0.51depending upon the physicochemical process involved (Young et al. 2002). This factor, referred to as β, is predicted to be lower for kinetic processes than it is for equilibrium processes (Young et al. 2002), though only a few direct measurements to confirm or contravene this assertion have been made to date. The convention of assuming that $\beta = 0.52$ for the purpose of defining $\Delta^{17}O$ values is well ensconced in the literature and is retained.

Luz et al. (1999) attributed the $\Delta^{17}O$ value of tropospheric O_2 to photochemistry in the stratosphere. Young et al. (2002) suggested that the $\Delta^{17}O$ value of tropospheric O_2 is instead an expected consequence of the Dole effect; it represents a steady state between two processes acting with near constant rates. The two processes are photosynthetic production of O_2 and extraction of O_2 by respiration. Although the control that these competing biological processes exert on $\delta^{18}O$ in atmospheric oxygen is well known, until recently there had been no characterization of β values for respiration (photosynthesis results in O_2 with the same $\Delta^{17}O$ as ocean water because the fractionation associated with the process is small). Young et al. (2002) made the prediction that the β value for the kinetic process of respiration should be close to 0.508, and that this value is sufficient to explain the $\Delta^{17}O$ of tropospheric O_2 with out the need to invoke mixing with photolysis products from the stratosphere. The competing-rates hypothesis has gained momentum with new measurements showing that β values attending photorespiration and dark respiration are 0.506 and 0.518, respectively (Luz et al. 2002). The measured values are close to the predicted value of 0.508.

From the preceding discussion it is clear that the cause of the measured $\Delta^{17}O$ of O_2 in the troposphere is uncertain but the existence of the $\Delta^{17}O$ difference between rocks ($\Delta^{17}O \sim 0$ similar to waters) and tropospheric O_2 means that there are two distinct reservoirs of oxygen maintained by some phenomenon that affects the lower atmosphere but not the rocks. The phenomenon is either a steady state imposed by the relative rates of O_2 consumption (respiration) and production (photosynthesis) or it is photochemistry that occurs elsewhere in the atmosphere. It is likely that both explanations are valid. In any case, before we can use $\Delta^{17}O$ as a tool for tracing material transfer to and from different near-surface reservoirs on Earth, it will be necessary to understand all of the factors that can influence $\Delta^{17}O$ values, both mass dependent (variable β) and mass independent (photochemistry).

Similar arguments pertain to Mars. The atmosphere of Mars is dominated by CO_2, making the oxygen isotopic compositions of carbonates from the planet especially useful tracers of atmospheric processes there. Carbonates from one SNC meteorite (apparently formed on Mars approximately 3.6 billion years before present near the Hesperian time interval, McKay et al. 1996) have $\Delta^{17}O$ values ~ 0.5 per mil higher than the igneous minerals from all measured SNCs. The difference between the two mineral types suggests that just as on Earth, there are, or were, at least two oxygen reservoirs on Mars. One in the atmosphere (sampled by SNC carbonate) and the other represented by the regolith (sampled by the

SNC igneous minerals). This is an important clue to the way that the Martian atmosphere behaved in Hesperian time, but the cause of the observation is uncertain.

Farquhar et al. (1998), the workers who made the measurements of $\Delta^{17}O$ in carbonate from SNC meteorite ALH 84001, suggested that the difference in $\Delta^{17}O$ between carbonate and igneous minerals was the result of exchange between CO_2 and electronically excited O liberated by photodecomposition of ozone. Another possibility is that the $\Delta^{17}O$ in the carbonates reflects an anomalous, partly non-mass dependent fractionation caused by gravitational separation of the isotopes above the homopause and isotopically selective escape of isotopomers at the exobase (Jakosky 1993).

Yet another explanation for the difference in $\Delta^{17}O$ between ancient Martian carbonate and igneous minerals is that competing processes with different mass-dependent β values, analogous to the situation that controls $\Delta^{17}O$ of tropospheric O_2 on Earth, are operating near the surface. In this case (Young et al. 2002) a steady state between sublimation of CO_2 ice with a low value for β, consistent with a kinetic process, and condensation of CO_2 with a higher β value approaching equilibrium values (since condensation implies partial pressures approaching equilibrium), might be the cause of the disparate carbonate $\Delta^{17}O$ values, as shown in Figure 6.6.2.

Young and Lyons propose to test the hypothesis that $\Delta^{17}O$ can be affected by passage of CO_2 between the cryosphere and the atmosphere on Mars through a program of experiments that will characterize the β values attending condensation and sublimation. The first experiments will be on O_2 liquid and vapor (since the three isotopes of oxygen are readily analyzed in this system). Young and Lyons will freeze O_2 in a vacuum line and analyze the residual gaseous O_2 as a function of fraction of gas frozen. Techniques will be similar to those described by Eiler et al. (2000) but with the exception that $\delta^{17}O$ as well as $\delta^{18}O$ will be measured using the stable isotope laboratory at UCLA. These early studies of O_2 will serve as the basis for new experiments on CO_2 in which fluorination will be used to liberated O_2 from C for isotopic analysis.

Lyons will simultaneously reexamine the suggestion by Jakosky (1993) that escape from the top of the Martian atmosphere could have caused significant shifts in $\Delta^{17}O$ in CO_2. He will evaluate the mass

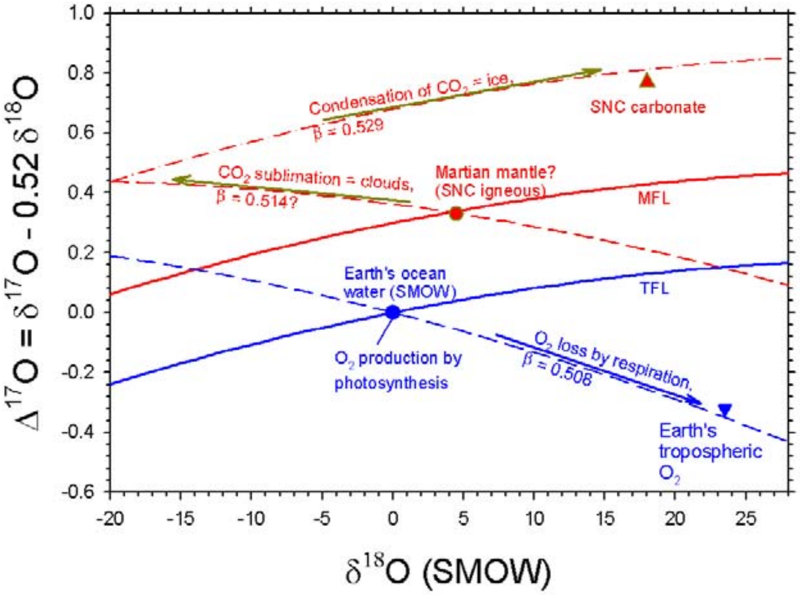

Figure 6.6.2. Oxygen three isotope plot showing the mass-dependent isotope fractionation mechanisms that may have caused negative $\Delta^{17}O$ values for O_2 in Earth's troposphere and positive $\Delta^{17}O$ in Martian carbonates.

independent component of diffusive escape processes in the Martian homopause. The problem requires examination of how O, CO, and CO_2 behave above the homopause and the physics of escape of O from the exobase. These processes will be examined in the context of the competing processes of non-mass dependent photochemical reactions that liberate electronically-excited oxygen.

The product of this research will be a better understanding of the meaning of variable $\Delta^{17}O$ values (at the ~ 0.5 per mil level) both on Earth and on Mars.

6.6.3 Liquid water on Mars

Understanding when and where liquid water may have existed on Mars is crucial for assessing the biologic potential of the planet, as well as for guiding our efforts to explore Mars with robotic spacecraft. The selection of promising landing sites is of particular importance for future missions in order to maximize their potential scientific return.

Paige and Shebenski have developed a new approach for studying the distribution and stability of Martian near-surface ground ice by observing the thermal effects of the presence of ground ice on diurnal and seasonal surface temperature variations using Mars Global Surveyor Thermal Emission Spectrometer data (Shebenski and Paige 2002). This approach can produce maps of the spatial distribution of ground ice at much higher spatial resolution than has been possible with the gamma ray data, while simultaneously providing key constraints on the depth, temperature and thermal properties of the ice itself. With these new data, Paige and colleagues can study correlations between the present distribution of Martian ground ice and geological and topographical features, as well as construct detailed models for the distribution and behavior of ground ice through time. Of particular interest are periods during the past 50 million years when the obliquity of Mars' spin axis has increased to as high as 45 degrees. During these high obliquity periods, the high latitude regions of Mars experience much higher summertime temperatures that could result in the transient melting of near-surface ground ice deposits (Costard et al 2002). Paige and coworkers propose to use their new constraints on ground ice distribution to map the most favorable regions for ice melting and correlate these with high-resolution imaging and topographic data. The results of this work will provide an important test of the notion that aspects of the geomorphology of Mars can be understood through models of past thermal and hydrologic behavior. It will also identify promising landing sites for future exploration.

7 EARLY EARTH'S ATMOSPHERE, OCEANS, AND LIFE

7.1 OVERVIEW

Knowledge of Earth's earliest life, and the environment in which it evolved, is incomplete and controversial at the present time. Here, cutting-edge, microscale, isotopic geochemistry ($^{131}Xe/^{136}Xe$, $\delta^{18}O$, $\Delta^{33}S$, $\Delta^{36}S$) of Earth's oldest materials (>4.0 Gyr-old zircon crystals) and Archean (3.9-2.5 Gyr-old) sulfur minerals (sulfides and sulfates) will be used to explore early atmosphere-ocean evolution and sulfur cycling. In addition, proposed theoretical and experimental studies are aimed at understanding the extraordinary gas-phase chemistry responsible for mass-independent isotope effects in oxygen and sulfur compounds. Other advanced geochemical techniques (laser Raman and optical tomography, in-situ carbon isotopic analysis) are to be used to scrutinize the microfossil evidence for Earth's earliest life. The complementary macrofossil evidence (stromatolites) will be assessed through the use of numerical simulations based on the mathematics of condensed matter physics. The pooled results from these disparate studies will provide new information about the antiquity of life on Earth and provide a firm basis for life-detection on other bodies in the Solar System.

7.2 WHEN DID EARTH BECOME SUITABLE FOR HABITATION? (HARRISON, MCKEEGAN, MOJZSIS)

The earliest evidence of life on Earth comes from graphitic inclusions within >3.83 Gyr marine sediments from West Greenland that were found by ion microprobe analysis to contain isotopically light carbon (Mojzsis et al. 1996; cf. Fedo and Whitehouse 2002). As this places the emergence of life prior to the end of a period of intense bombardment in the inner Solar System (3.8-3.9; Ryder 1990), this result raises the possibility that life originated during the Hadean Eon (4.5-4.0 Gyr) – a period of Earth history for which there is no known rock record. That being the case, how can we determine whether the criteria thought necessary for biopoesis (i.e., energy source, organic molecules, liquid water) were extant during this time? Since the necessary energy sources and molecular building blocks for life were surely available during the formative stages of planetary evolution (Chyba and McDonald 1995), our question reduces to: When did suitably quiescent conditions and liquid water first appear at the Earth's surface?

Attempts to trace Earth history back in time via the rock record reach an impasse around 4 billion years ago. However, the discovery of detrital zircons (Compston and Pidgeon 1986) from the Jack Hills, West Australia, as old as 4.3 to 4.4 Gyr offers the prospect of gaining unprecedented insights into surface environmental conditions during the earliest phase of Earth evolution (Mojzsis et al. 2001, Wilde et al. 2001; Peck et al. 2001). For example, oxygen isotope compositions of these ancient zircons suggest the presence of a terrestrial hydrosphere and stable continents only 200 Myr after accretion (Mojzsis et al. 2001). These preliminary results challenge the traditional view that continental formation and development of a hydrosphere were frustrated by meteorite bombardment and basaltic igneous activity until ~4.0 Gyr. We propose to utilize these ancient zircons – the only tangible record of the Hadean Eon – to seek insights into the origin of the atmosphere, hydrosphere, and the geodynamo during the earliest stages of Earth evolution.

7.2.1 The age of the atmosphere

The Earth's atmosphere is thought to have been derived from mantle degassing (Brown, 1952). Although cometary water has more recently been suggested as a possible source (e.g., Delsemme 2001), D/H measurements of comets Halley, Hyakutake, and Hale-Bopp are inconsistent with this hypothesis (Bockelee-Morvan et al., 2000). While comets formed in the Jovian region might have a similarly low D/H ratio to the Earth's oceans (Mumma et al. 2001), this idea remains untested.

Excesses of ^{129}Xe in mantle-derived samples relative to the atmosphere have been interpreted to indicate the presence of live parent ^{129}I in the deep Earth following early degassing of the atmosphere (e.g., Staudacher and Allegre 1982; Allegre et al. 1983) since ^{129}I decays to ^{129}Xe with a half life ($t_{½}$) of only 16 million years. If true, then it is argued that the present atmosphere and hydrosphere must have formed by ~4.4 Gyr (Podosek 1970).

However, the isotopes of Xe offer additional constraints on the age of the atmosphere. The plutonium isotope ^{244}Pu has a short half life of 82 million years ($t_{½}$=82 Myr). Spontaneous fission of ^{244}Pu produces ^{131}Xe, ^{132}Xe, ^{134}Xe, and ^{136}Xe in characteristic relative abundances. The component of mid-ocean ridge basalts associated with fission decay of ^{244}Pu implies a source that is 100 times lower than the chondritic plutonium/uranium ratio of 0.007 (it is assumed that Pu/U ratios equivalent to chondrites should be "primordial", i.e. solar) (Kunz et al. 1998). This appears paradoxical as other noble gas isotopic data are interpreted to indicate the presence in the deep Earth of a primitive reservoir of solar composition (e.g., Honda et al. 1991) that presumably would be associated with chondritic Pu/U (Azbel and Tolstikhin 1993). In the absence of a mechanism to fractionate Pu from U during planetary formation, the possibility remains that ^{129}Xe differences simply reflect inherited heterogeneities in the I/Xe ratio of terrestrial reservoirs. If this is the case, then the atmosphere and hydrosphere could be substantially younger than ~4.4 Gyr (Caffee et al. 1999). Alternatively, since the absolute amounts of ^{129}Xe excess to fissiogenic ^{136}Xe (fission of both ^{244}Pu and ^{238}U produces ^{136}Xe) in the atmosphere and their relative proportions are comparable to what would be left behind in the Earth after an early outgassing, such as that resulting from a Giant Impactor event, xenon isotope systematics may carry little information regarding the age of the atmosphere.

The place to begin to address this issue is to determine the terrestrial Pu/U. There are no firm constraints on this parameter, but existing data are suggestive of a chondritic Pu/U for the Earth (e.g., Caffee et al., 1999; Honda et al., 2000). The fundamental problem in elucidating this parameter is illustrated in Figure 7.2.1, which shows the expected ^{131}Xe/^{136}Xe due to Pu and U fission during the first 900 Myr of Earth history. Clearly, zircons <4 Gyr in age contain very little signal of ^{244}Pu (i.e., ^{131}Xe). Materials formed between 4.4-4.1 Gyr provide the best opportunity to characterize terrestrial Pu/U and thus better utilize Xe isotope studies to understand the evolution of the atmosphere.

Harrison and his colleagues in Manchester, England (outside collaborators I. Gilmour and G. Turner) have recently discovered the very first evidence for extinct ^{244}Pu in individual 4,150 Myr old zircons from Jack Hills and propose to carry out a research program to determine the Pu/U ratio in the Earth and the early crust and investigate the implications for the earliest differentiation of crust and atmosphere. Their ability to analyze the isotopic composition of xenon in individual zircons relies on the development in Manchester of a uniquely sensitive mass spectrometer based on the principle of laser resonance ionization (Gilmour et al. 1994). The instrument, RELAX (Refrigerator Enhanced Laser Analyser for Xenon), is capable of analyzing samples of only a few thousand atoms, some two orders of magnitude smaller than conventional noble gas mass spectrometers, permitting single zircons to be measured. In the first four RELAX analyses one has a ^{131}Xe/^{136}Xe composition consistent with a chondritic Pu/U ratio, but three others have lower values. The preliminary interpretation of this result is that the lower ratios reflect partial xenon degassing subsequent to the extinction of ^{244}Pu. What this means is twofold: analysis of an aggregate of old zircons would lead to a highly ambiguous result due to mixing of degassed and un-degassed populations, and assessment of the terrestrial Pu/U will require a large number of measurements using single crystals varying in age from 4.1 to 4.4 Gyr to define the upper bound of the population thus far discovered.

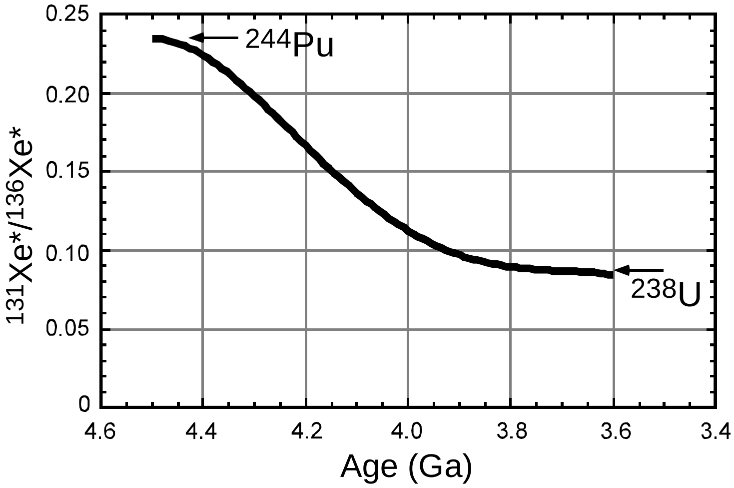

Figure 7.2.1. The changing ^{131}Xe/^{136}Xe due to fission of ^{244}Pu and ^{238}U over the first 900 Myr of Earth history. >4.1 Gyr zircons are ideal to assess the initial terrestrial Pu/U ratio.

7.2.2 The age of the hydrosphere (and redox state of Earth's surface)

Oxygen isotopes in rocks and minerals provide a means to discriminate among possible sources (i.e., mantle, metasedimentary, hybrid) of granitoids (Taylor and Sheppard 1986). Zircon appears promising in this role as exchange rates for O are very slow (Watson and Cherniak 1997), potentially permitting preservation of the protolith signature through high-grade metamorphism (Valley et al. 1994). For this reason Mojzsis et al. (2001) and Wilde et al. (2001) used the δ^{18}O values of Jack Hills zircons to infer crust-hydrosphere interactions at ca. 4.3 Gyr. These preliminary results warrant further study because of the surprising conclusion that a liquid hydrosphere (as opposed to steam atmosphere) was in place by ~4.3 Gyr. We propose to expand the approach to focus also on the "microrock" (i.e. polymineralic inclusion) environments encapsulated within the zircons.

Igneous zircons typically contain inclusions that reflect the parent melt (Chupin et al. 1988). 10-100 μm-sized inclusions have been found in >4 Gyr zircons from Jack Hills quartzites (Maas et al. 1992; Wilde et al. 2001), including assemblages of quartz, K-feldspar, biotite, chlorite and muscovite. One inclusion containing quartz, feldspar, apatite, and monazite (Maas et al. 1992) is significant as it is typical of S-type granitoids (Rapp and Watson 1986) where S-type refers to granitic rocks derived ultimately from sediments. Mojzsis et al. (2001) noted that peraluminous inclusions (those with high Al concentrations relative to alkali elements) encapsulated in zircons enriched in ^{18}O are suggestive of the melt having originated from rocks at the Earth's surface. This is because Al-rich compositions occur today by virtue of weathering and so indicate early development of a sedimentary cycling environment, and because high δ^{18}O (relative to mantle rocks, for example) is also an indication of interactions with a hydrosphere. While specific circumstances could be convolved to create this signal in the absence of surficial processes, they would be exceptional.

In rare cases, melt inclusions are also preserved in zircon. If the encapsulating zircon shielded a melt inclusion from changing external conditions since formation, then it may be feasible to extract information regarding the fO_2 (fugacity of oxygen) of the melt from which the zircon crystallized. If the melt protolith originated at the Earth's surface (e.g., normative corundum, meaning Al-rich and so having experienced a weathering cycle, and heavy ^{18}O), then it remains possible that a faint record of life at the Earth's surface might be detectable. As an example of how this might be inferred, consider why I-type granites are pink in color and garnet-bearing S-type granites are white. In a subduction environment where I-type (I for igneous) granitic rocks are made beneath island arcs, fO_2 is maintained above the hematite-magnetite buffer (Zen 1988) and Fe^{3+} is soluble in K-feldspar, leading to a pink coloration (Zen 1985; Zen 1988). In S-type granitoids (again, S for sedimentary) of SE Australia, the rocks are white because graphite in the Paleozoic source rocks controlled the fO_2, producing more reducing conditions that stabilize Fe^{2+} in the evolved magmas that derive from them. The ultimate source of reduced C responsible for lowering fO_2 in S-type granitoids is fossil biomass within sediments that formed at the rock-hydrosphere or atmosphere interface. While a surprising concept, the color of a granitoid can relate to the presence or absence of reduced C at the Earth's surface!

In the microrock environment, the intrinsic fO_2 of melt inclusions can be determined via knowledge of the Fe^{3+}/Fe^{2+} ratio (Delaney et al., 1998) and a thermodynamic model (Kilinc et al. 1983). The μXANES (X-ray absorption near edge structure) method is capable of determining Fe^{3+}/Fe^{2+} on a 3 μm spot with ±5% accuracy (Bajt et al. 1994). Because zircon solubility in melts (i.e., melt inclusions trapped within zircon are zircon saturated) is both a function of Fe^{3+}/Fe^{2+} (i.e., network former vs. network modifier) and temperature (Baker et al. 2002), both fO_2 and peak melting temperature can in theory be determined by knowing Fe^{3+}/Fe^{2+} and dissolved Zr. Thus it may be possible to assess whether conditions consistent with the presence of reduced carbon at the Earth's surface – potentially bearing on the presence of life – were extant between 4.4 to 4.0 Gyr.

7.2.3 The initiation age of the geodynamo

The earliest evidence for geodynamo activity comes from the intrinsic magnetism of 3.5 Gyr volcanics in southern Africa. Because Jack Hills zircons are hosted in low grade sediments, they could retain the oldest record of the Earth's magnetic field. Preliminary measurements using an ultra-sensitive SQUID magnetometer (Baudenbacher et al., 2002) show that a Jack Hills zircon carries a weak (10^{-13} Am^{-2}) intrinsic remanent magnetism (J.L. Kirschvink pers. comm.). Provided the detrital grains were not remagnetized, the presence or absence of intrinsic magnetism could be our only signal of geodynamo activity during the earliest period of Earth history. For example, should Harrison discover that all zircons younger than, say, 4.2 Gyr are magnetic but that all older zircons are not, this could be evidence that the terrestrial geodynamo initiated at ca. 4.2-4.3 Gyr. While admittedly a long shot, a positive result could potentially place a profound constraint on the dynamical evolution of the planet.

Harrison and colleagues will provide an outside paleomagnetics laboratory (Kirschvink's laboratory at Caltech is the lead candidate at this writing) 4.0-4.4 Gyr zircons that have been dated without exposure to strong magnetic fields. If age analysis is found to remagnetize the grains, the grains will be characterized before dating (this is feasible as ~100 grains can be measured in a 24-hour period). It may be necessary to undertake limited drilling in the Jack Hills quartzites to obtain unweathered cores. ^{40}Ar/^{39}Ar dating of inclusions and single crystal xenon isotopic may analyses may be useful in establishing zircon thermal histories and thus age of magnetization.

7.2.4 Measurements of ancient zircons- building the database

While the discovery of >4.3 Gyr Jack Hills zircons provides unique new opportunities to gain insights into the earliest evolution of the atmosphere, hydrosphere, and continents, zircons older than 4.2 Gyr make up only ~0.5% of the detrital population (Amelin 1998). To overcome this hurdle, Harrison and coworkers have refined a method to survey ^{207}Pb/^{206}Pb ages of large numbers of zircons. Using a high-resolution ion microprobe in multi-collector mode, an age with ±1% precision can be obtained in less than one minute. In this way, these workers have thus far analyzed a total of 15,000 grains thereby increasing the number of dated Jack Hill zircons by a factor of 15 (Compston and Pidgeon 1986; Maas et al. 1992; Amelin 1998; Mojzsis et al. 2001; Wilde et al. 2001). Two clear age peaks are evident at ~3.3 Gyr and ~4.0 Gyr (Figure 7.2.4) tailing off at older ages. From this population, Harrison and others have thus far identified 105 zircons in the age range 4.1 to 4.2 Gyr and 31 >4.2 Gyr including three that are >4.35 Gyr. One ~8 μg zircon is 4.37 Gyr. We are confident that we know the yield of the most ancient zircons and therefore can predict the quantities required for future experiments from the database statistics.

Harrison estimates that the experiments proposed above require about three times the present complement of >4.1 Gyr zircons and thus he will need to age characterize another 30,000 zircons. The approach will be to rapidly survey large numbers of zircons using our established multi-collector approach at UCLA. However, this effort is coordinated with the group at the Research School of Earth Sciences at the Australian National University who will undertake about half the analyses. When sufficient quantities of the old zircons have been acquired, they will be disbursed to our collaborators

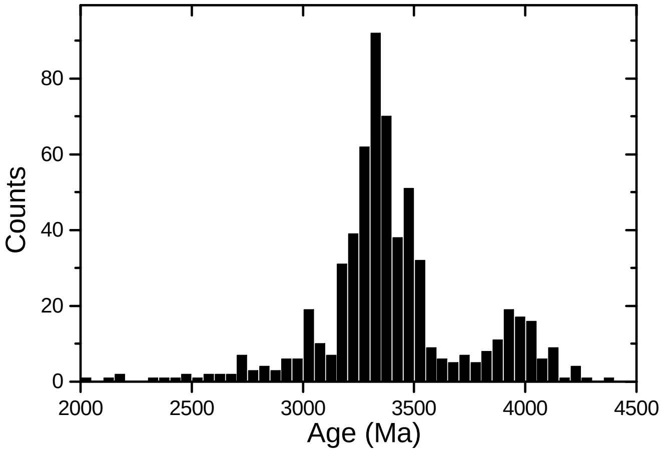

Figure 7.2.4. Historgram of lead-lead ages for ancient zircons from Jack Hills sample 634. Two peaks are evident at ~3.1 Gyr and ~4.0 Gyr, tailing to ages as old as 4.37 Gyr.

for xenon isotopic and magnetic measurements. Oxygen isotopic and inclusion studies will commence at UCLA immediately with material already in hand.

7.3 Sulfur cycling on the early Earth (Farquhar, Fitz-Gibbon, Lyons, Marcus, McKeegan, Mojzsis, Rubin, Runnegar, Sander)

The recent discovery by Farquhar et al. (2000) and Bao et al. (2000) that mass-independent isotope effects (§7.3.1) may survive in terrestrial geological materials has invigorated sulfur and oxygen isotope geochemistry. As these effects are thought to be solely due to gas-phase reactions (Gao and Marcus 2001), their geological record provides an unprecedented source for atmospheric history. Most obviously, the anoxic atmosphere of the early Earth (older than ~2.2 Gyr) promoted UV-induced sulfur photochemistry whereas the subsequent oxygen-rich atmosphere was, and is, one in which ozone is a principal photochemical product of UV radiation (Lyons 2001). The “Great Oxidation Event” (Holland, 2002), which took place about 2.2 Gyr ago, is believed to represent the transition between these two states and is recorded by the sudden disappearance of mass-independently fractionated (MIF) sulfur compounds (principally $BaSO_4$ and FeS_2) from the geological record. In contrast, the preservation of the MIF sulfur signal in rocks older than ~2.2 Gyr results from the fact that there were at least two main products of the atmospheric reactions, elemental sulfur particles and sulfate aerosols, each having a different MIF signature (Figure 7.3). As the elemental sulfur particles were insoluble in surface waters, these two components did not mix, and their positive and negative MIF signatures were transmitted to minerals formed from them in sedimentary environments.

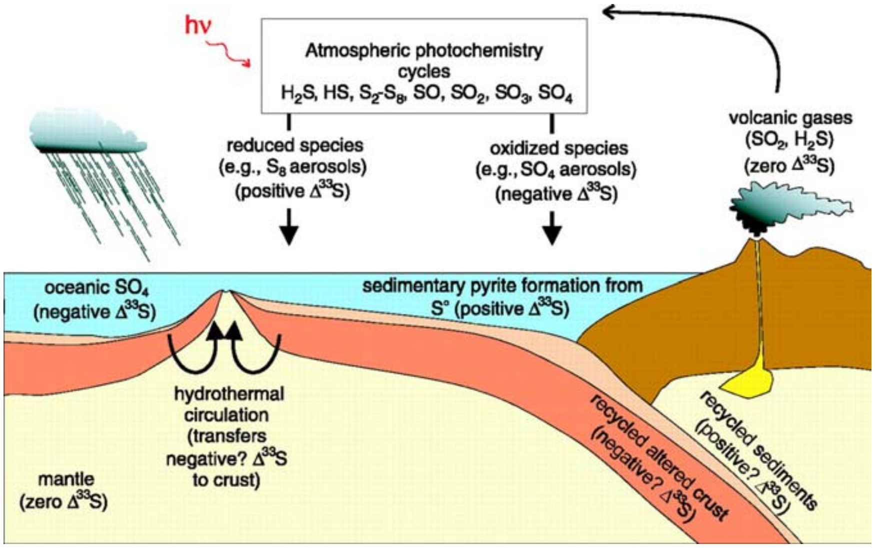

Figure 7.3. The Archean sulfur cycle (Farquhar et al. 2002). The principal products of atmospheric chemistry were ultimately pyrite (positive $\Delta^{33}S$) and sulfate (negative $\Delta^{33}S$) as shown in Fig. 7.3.2. The atmospheric photochemistry (box) is one target of the research proposed here.

7.3.1 Ion microprobe measurements of the four stable isotopes of sulfur

Our role in the development of this fruitful area of research has been the following: (1) The demonstration that the effect is real, and not an artefact of sample preparation as had been argued by Ohmoto (2000), by making $^{33}S/^{32}S$, $^{34}S/^{32}S$, and $^{36}S/^{32}S$ measurements in a completely different way using the UCLA Cameca ims 1270 ion microprobe in monocollector and multicollector modes (§3; Runnegar et al. 2002); (2) The development of new sulfide (FeS, FeS_2, $CuFeS_2$) and sulfate mineral

($BaSO_4$) standards for ion microprobe analysis (Greenwood et al. 2000; Runnegar et al., in prep.); (3) Evidence that early Archean sulfate minerals traditionally regarded as barite ($BaSO_4$) replacements of primary gypsum ($CaSO_4.2H_2O$) evaporites were, in fact, originally hydrothermal barite; this bears on the composition of the Archean ocean (Runnegar et al., 2001b, in preparation); (4) The recognition of three different sulfur reservoirs in Archean sedimentary rocks based on their three and four sulfur isotope compositions (Figure 7.3.1), results that argue against widespread microbial sulfate reduction during the Archean (Runnegar et al. 2001a, in preparation) in contrast to work based on only the two most common isotopes (Shen et al. 2001); (5) The use of MIF sulfur signatures as tracers of base metal sources and hydrothermal fluid circulation in Archean ore deposits (Runnegar et al. 2002); (6) A survey of Precambrian and Phanerozoic sulfates and sulfides of many different ages and environments to provide a background for the interpretation of MIF sulfur signatures throughout Earth history (Runnegar et al., in preparation); (7) The development of a quantitative understanding through numerical modeling, of the role that ozone plays in acquiring and transmitting a substantial MIF signature to oxygen-bearing compounds at all levels in the modern atmosphere (Lyons 2001); and (8) Application of the photochemical understanding gained in (7) to the important problem of self-shielding and the production of MIF oxygen in the solar nebula (§5.4).

Given these discoveries, and the excitement of complementary studies by our NAI colleagues (Hiroshi Ohmoto, Pennsylvania State University; Douglas Rumble, Carnegie Institution of Washington; Andrey Bekker, Harvard University), we propose to proceed over the next five years on the following fronts:

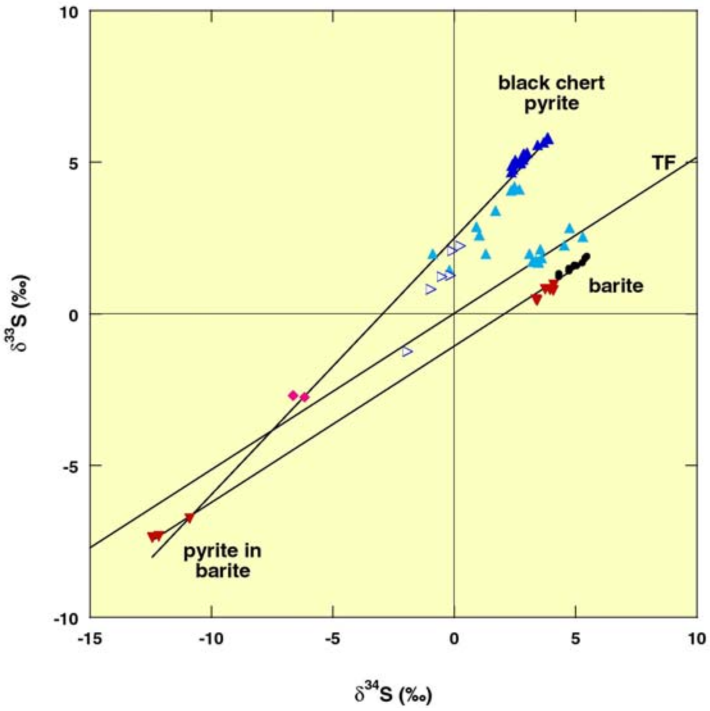

Fig. 7.3.1. Sulfur isotopic compositions of 3.5 Gyr-old sulfides and sulfates, North Pole area, Western Australia. Pyrite in organic-rich cherts are enriched in ^{33}S relative to normal terrestrial materials ($\Delta^{33}S > 0$), indicating their orign from the reduction of elemental sulfur (Fig. 7.3.1). Pyrites that are intimately associated with bedded and cross-cutting sulfates (barites) are depleted in ^{33}S ($\Delta^{33}S < 0$), as are the sulfates. The 15‰ difference in δ^{34}S between the barite and the barite-associated pyrite has been regarded as evidence for bacterial sulfate reduction (Shen et al. 2001). However, in the expected setting for sulfate-reducing bacteria (black cherts and shales) the pyrite has a Δ^{33}S signature which cannot have come from sulfate.

(1) Explore sulfur cycling during and following the Archean by investigating key sedimentary environments in greater detail than has been done in our current survey that involved approximately 300 multiple sulfur isotope measurements on ~50 samples ranging in age from 3.85 Gyr to the Miocene. We are particularly interested in syngenetic pyrite in organic-rich shales and banded iron formation, in sulfates and sulfides associated with volcanic-hosted massive sulfide (VHMS) deposits and ancient "back smokers", and sulfate evaporites. Each of these environments, if tracked through time, has great potential for the preservation of sulfur isotope biosignatures.

(2) Investigate the disappearance of MIF sulfur from the sedimentary cycle at or after the Great Oxidation Event (GOE). Although this problem is being explored effectively by others in a primary stratigraphic context, there is the need to consider other avenues of investigation that involve the recycling of previously MIF sulfur compounds. These include ore deposits formed by meteoric hydrothermal actvity (Runnegar et al. 2002) and material recycled mechanically from older terrains. A combination of geochemical exploration and numerical modeling will be used to investigate the history of sulfur cycling on a global scale during the GOE transition.

(3) We have preliminary data, that needs to be confirmed and supports an earlier report (Rees and Thode 1977), of a small MIF effect in sulfide-bearing phase in the Allende carbonaceous chondrite. Rubin and McKeegan propose to explore this anomaly using the numerous Allende and other carbonaceous chondrite samples in the UCLA meteorite collection maintained by Wasson.

7.3.2 Laboratory experiments and theoretical analysis of the kinetics and photochemistry of mass-independent sulfur isotope effects

The chemical origin of the MIF in sulfur is still unclear. Farquhar et al. (2001) have shown in laboratory experiments that photodissociation of H_2S, SO_2, and $SO_2/CO_2/H_2O$ mixtures all produce elemental sulfur with a wavelength-dependent MIF signature. However, the experimental results that best reproduce MIF in sulfur-bearing rocks older than ~2.2 Gyr involve photodissociation at *single* wavelengths < 200 nm. In a real atmosphere, MIF would not be produced at a single wavelength, since solar radiation is broadband. Instead, we believe that MIF in sulfur arises, at least in part, from the reaction $S + S_2 \rightarrow S_3$. It has been clearly shown (Mauersberger et al. 1999) that MIF in O_3 is produced during the ozone formation reaction, $O + O_2 \rightarrow O_3$. Because O and S are isovalent atoms, the ozone formation reaction and the S_3 (thiozone) formation reactions are also isovalent. It is therefore likely that formation of S_3 isotopomers occurs in a mass-independent manner, just as is true for the isotopomers of O_3. We propose experiments to test this hypothesis and to determine the rate coefficients for formation of several isotopomers of S_3.

The first experiment we propose is to pass an electrical discharge through flasks of H_2S and SO_2. Elemental sulfur has been observed previously in such experiments. We will collect elemental sulfur and SO_2, and measure ^{32}S, ^{33}S, ^{34}S, and ^{36}S relative to the initial gas isotope values. The measurements will be done in collaboration with Farquhar. Although very simple, the discharge experiments are an essential first step. If MIF is observed in the collected SO_2 and elemental sulfur residue, then we have demonstrated that an inherently broadband process (discharge) can produce MIF of sulfur. Conversely, if no MIF is observed, then it is likely that photodissociation alone (and not subsequent reactions of photoproducts) is the principal cause of the MIF.

Assuming that MIF is observed in the sulfur residue collected in the discharge experiments, then flow tube experiments will be undertaken to determine the isotope-specific rate coefficients for the formation of several S_3 isotopomers, for example:

$$^{32}S + ^{34}S^{34}S \rightarrow ^{32}S^{34}S^{34}S$$

$$^{33}S + ^{32}S^{32}S \rightarrow ^{33}S^{32}S^{32}S$$

We shall also determine the rate coefficient for sulfur atom exchange with S_2,

$$^{34}S + ^{32}S^{32}S \rightarrow ^{32}S + ^{32}S^{34}S$$

It may also be necessary to measure isotope-specific rate coefficients for the S_4 formation reaction, $S_2 + S_2 \rightarrow S_4$, and for the SO dimer reaction, $SO + SO \rightarrow (SO)_2$, since these are important pathways to elemental sulfur and sulfate formation (Kasting et al. 1989).

A flow tube will be used because the variable-length reactant port allows for the determination of accurate rate coefficients. Additional ports are for reactant S_2 and the He flow gas. Atomic sulfur will be generated by microwave discharge of isotopically-pure carbonyl sulfide (OCS). Diatomic sulfur will be generated by heating isotopically-pure solid sulfur. The flow tube will be quartz (~1 meter in length), and will be heated to > 150 ºC to prevent condensation of S_2 and S_3. Neutral products will be converted to positive ions by electron impact ionization and will be detected with an Extrel MAX 500 quadrupole mass spectrometer purchased for this purpose. Flow tube measurements will be done in collaboration with Sander.

Lyons also proposes to investigate the kinetic theory of the thiozone formation reaction in collaboration with Marcus. This will be an extension of the non-RRKM (i.e., non-statistical) unimolecular dissociation theory developed for the $O + O_2 \rightarrow O_3$ reaction by Marcus and his colleagues (Gao and Marcus 2001). The sulfur kinetic theory will provide an important link to the much better understood chemistry of gas-phase oxygen isotopes, and may be applicable to higher-order polysulfur compounds such as S_4 and S_8. With knowledge of the isotope-specific rate coefficients for thiozone isotopomers, full photochemical models of Archean sulfur chemistry can be developed.

7.3.3 Genomic approach to understanding of the evolution of sulfur metabolisms

Easily cultured organisms are estimated to constitute a small fraction of all microbial species and are rarely numerically dominant in the communities from which they were obtained (Hugenholtz 2002). Thus, much remains to be learned about the distribution and diversity of microorganisms and their geobiological activities. This can be overcome by purifying total DNA from environmental samples, constructing random DNA fragment libraries, and then using random sequencing or probing for genes of interest. Fitz-Gibbon and colleagues propose to use these exploratory methods to search for novel genes and novel genetic settings for sulfur metabolism.

Genes involved in dissimilatory sulfate reduction (ATP sulfurylase, APS reductase and sulfite reductase) are known from a wide range of Bacteria. Phylogenetic trees based on these genes tend to follow conventional taxonomic groupings (Wagner et al. 1998; Friedrich 2002). On the other hand, few of these genes have been identified from members of the Archaea, hampering efforts to determine whether the ability to reduce sulfate was a property of the last common ancestor of Bacteria and Archaea. Dissimilatory sulfate reduction is well studied in the euryarcheal genus *Archaeoglobus* but may be more widespread within the Archaea. For example, growth with sulfate as an electron acceptor has been reported for *Caldivirgas* (Itoh et al. 1999) and possibly also *Thermocladium* (Itoh et al. 1998), both members of the Crenarchaeota. Moreover, a set of sulfate reductase genes was found in the genome of the crenarchaeote *Pyrobaculum aerophilum* (Fitz-Gibbon et al. 2002), although frameshift mutations have made some of the genes non-functional.

The identification of a small number of novel archaeal sulfate reduction genes would be sufficient to determine whether they will produce phylogenetic trees follow the 16S rRNA pattern. If so, and if the genes were broadly distributed across the Archaea, it would be likely that sulfate reduction had been present in the common ancestor of Bacteria and Archaea. Conversely, the novel archaeal genes may show a clear pattern of more recent horizontal transfer from the Bacteria, and thus the possibility that sulfate reduction postdates the Archaea-Bacteria divergence. Sulfur metabolism genes tend to cluster in many genomes (Fitz-Gibbon et al. 2002). For example in *Pyrobaculum* a 26.5 Kb-long section of the genome carries approximately 35 genes, eleven of which are clearly involved in sulfur metabolism. Some of the other 24 genes appear to be in operons that also contain the sulfur metabolism genes, suggesting that they may also be involved in sulfur biochemistry. Thus, the identification of one sulfur metabolism gene by random sequencing can be followed by further sequencing along the clone (BAC clones are ~250 Kb in length) in the expectation of discovering additional genes for sulfur metabolism.

7.4 GEOCHEMICAL CONTEXT FOR EARLY LIFE (HOUSE, KAPLAN, KAVNER, MANNING, SCHAUBLE, VENKATESAN, YOUNG)

7.4.1 Chemical feedbacks

Hydrothermal systems in the early Earth were likely hosted by olvine-rich ultramafic igneous rocks. In such systems, the most important silicate-hydrolysis reaction is the conversion of the mineral olivine to serpentine and magnetite (serpentinization). Because this reaction produces large amounts of H_2 gas, CH_4 gas, and basic solutions (e.g., Janecky and Seyfried 1986; Coveney et al. 1987; Abrajano et al. 1988; Rona et al. 1992; Charlou and Donval 1993; Kelley 1996; O'Hanley 1996; Kelley et al. 2002), sites of active serpentinization should have been favorable environments for chemotrophic organisms on the early Earth. Manning and coworkers are testing this hypothesis by conducting experiments on serpentinization in the presence of microorganisms.

Manning and House propose an experimental program that will investigate model ecosystems involving primitive microorganisms, olivine, and hot seawater. Preliminary experiments have been conducted using the hyperthermophilic methanogen *Methanopyrus kandleri* in 100 °C solutions with olivine, serpentine, and magnetite. *M. kandleri* is used because its molecular phylogeny suggests minimal evolution away from the hypothesized universal ancestor of life on Earth, it thrives at 100 ˚C in oceanic hydrothermal vents, and its metabolism utilizes H_2 during chemoautotrophic production of CH_4. *M. kandleri* also facilitates reduction of aqueous Fe(III)-bearing organic compounds, which could release O_2 and create positive feedback for additional olivine-sourced Fe(II) oxidation.

Results at 100 °C, 3 bar H_2+CO_2, show that *M. kandleri* is readily cultured during hydrolysis of olivine (Herrera et al. 2003). Concentrations of Fe, Mg, and Si in solution were higher in the presence of *M. kandleri* than in abiotic systems, implying enhanced olivine dissolution rates and strong chemical feedback. The olivine-rich ultramafic-hosted hydrothermal systems that were abundant in the early Earth are favorable environments for this microorganism. Further experiments are planned, including those involving isotopically-doped Mg and Fe for tracing the exchange of Mg and Fe between phases in the system using the isotopes of these elements using multiple-collector inductively coupled plasma-source mass spectrometry (MC-ICPMS, see next section).

7.4.2 Abiotic pathways to complex organics

The prebiotic Earth contained abundant organic matter that was produced by abiotic chemical pathways. The standard model for the origin of life hypothesizes that the earliest organisms arose from this complex, abiotic, organic brew. Careful assessment of this hypothesis relies on two factors: (1) completeness of the inventory of the prebiotic organic mix, and (2) development of appropriate tests to assess the contributions of different pathways. We are conducting studies in both these areas. To address the completeness of the hypothesized organic inventory, we are exploring alternative pathways for abiotic organic production. Numerous mechanisms have been proposed for abiotic organic production, including electrical discharge, cometary and meteorite delivery, and production in early surficial hydrothermal systems. However, a major additional pathway in the early Earth that has not been considered is the generation of methane, n-alkanes, and potentially simple organic acids and N-bearing compounds at elevated pressure and temperature during tectonic burial of nascent hydrated ultramafic plates in Hadean time. Substantial amounts of organic compounds are produced by this process in the modern Earth. The larger volumes of ultramafic material at the surface of the early Earth motivate chemical reactive flow modeling to investigate organic production by this mechanism.

7.4.3 Role of metals in early biology

A second line of investigation involves using intermediate-weight stable isotopes (e.g., isotopes of Mg, Fe, Cu, and Si) to investigate the role of metals in the early organic chemistry of the Earth. The first application is as tracers of biologically and non-biologically mediated reactions between rocks and waters relevant to organic synthesis. Manning and Young will investigate the partitioning of the stable isotopes in laboratory simulations of water-rock reactions in the presence and absence of microbes to establish isotopic criteria for distinguishing biologically from non-biologically mediated reactions. The other line of study focuses on isotope fractionation attending fundamental physicochemical processes, with the goal of understanding the extent to which stable isotopes of transition metals and alkali metals might be used as biomarkers. In particular, transition metal isotope fractionation attending redox reactions will be monitored using electrochemical techniques. Kavner and Young plan to use potentiostatic techniques to study the fractionation of iron, nickel, and chromium isotopes during redox processes relevant to organometallic chemistry. Studies by Kavner and Young will focus not only on the magnitude of the partitioning of the isotopes, but also on the "slopes" defined by three-isotope systems (see § 6.6.2). The slopes, under favorable circumstances, can be used to distinguish equilibrium steps from kinetic steps in a fractionation process. The expected outcome will be a quantitative tie between the driving potential for chemical oxidation/reduction processes, and corresponding isotope fractionation signatures. This will help elucidate the mechanism by which microorganisms generate specific isotope signatures and allow us to isolate discrete fractionating steps in both biological and non-biological redox systems. The results can be used for comparisons with fractionation in more complicated systems.

7.4.4 Equilibrium Fe isotope fractionation between Fe^{2+} and Fe^{3+} - an experimental approach

Mass-dependent fractionations of the stable isotopes of iron have recently been discovered, and it is observed that large isotopic fractionations are largely restricted to precipitates formed in low-temperature natural and laboratory environments. This property of the Fe-isotope system suggests that it may be ideally suited for the identification of ancient low-temperature environments on Earth and other planets. Major unanswered questions remain, however, regarding the causes of environmental Fe-isotope fractionations and the possibility of using observed signatures in rock samples to unequivocally identify ancient biological activity. There is evidence to suggest that the largest fractionations (1‰ to 3‰) typically occur when iron is partially oxidized or reduced in the presence of liquid water. These fractionations are preserved in the rock record when the different oxidation states (Fe^{3+} and Fe^{2+}, typically) are separated, for instance by precipitation of $Fe^{3+}O(OH)$. Fe-redox transformations are commonly mediated by microorganisms, and it has been suggested that the biological redox fractionation (~1.5‰) is characteristically smaller than the inorganic fractionation (~3‰). Significant uncertainty in the equilibrium organic fractionation persists, however, due to the difficulty of separating Fe^{3+} and Fe^{2+} reversibly. One way to avoid this problem is to allow an easily separable phase (an immiscible organic solvent such as diethyl ether) to equilibrate with mixed solutions with a range of Fe^{3+}/Fe^{2+} ratios. Such a technique can, in principle, be applied to many exchange-labile chemical species in aqueous solutions.

Schauble and Young propose fundamental laboratory studies to develop techniques for determining Fe-isotope fractionations between different species in aqueous solutions. The project will examine the potential of using an immiscible organic solvent phase (diethyl ether) as a rapidly equilibrating and easily separable reservoir of dissolved iron. In Fe^{3+}-Fe^{2+}-HNO_3-HCl solutions, $[FeCl_4]^-$ is the only ether-soluble species. It is expected, therefore, that the isotopic partitioning behavior of iron in the ether phase will be nearly constant over a range of aqueous Cl^- activities, Fe^{3+}/Fe^{2+} ratios, and pH. Measured fractionations between the iron dissolved in this organic reservoir and aqueous solutions of varying chemistry (for instance, a series of increasing Fe^{2+}/Fe^{3+} ratios) will reflect changing isotopic behavior in the aqueous phase, allowing indirect measurement of fractionations between ether-solvated $[FeCl_4]^-$ and aqueous $[Fe(H_2O)_6]^{3+}$, Fe^{2+} (i.e. $[Fe(H_2O)_6]^{2+}$), Fe^{3+}-chloro complexes such as $[Fe(H_2O)_5Cl]^{2+}$, and

Fe^{3+}-hydroxyl complexes. Relatively fast equilibration (~minutes to hours) between ether and aqueous phases is expected, based on bulk iron partitioning experiments from the literature.

7.5 DETECTION AND GEOCHEMICAL CHARACTERIZATION OF EARTH'S EARLIEST LIFE (AGRESTI, HOUSE, JÖGI, KUDRYAVSTEV, MCKEEGAN, RUNNEGAR, SCHOPF, WDOWIAK)

Although the fossil record of Archean (>2,500-Myr-old) life is notably sparse (Schopf and Walter 1983; Schopf 1992a), it is both better known and biologically more diverse than is generally appreciated. Indeed, from even among the oldest deposits of the Archean, rocks ~3,200 to ~3,500 Myr in age, eight fossil-bearing units have been described (by some 40 workers from 7 countries), containing *in toto* both stromatolites and spheroidal and filamentous microfossils backed both by laser-Raman and carbon isotopic analyses of their kerogenous components. Despite this body of evidence, however, the biological origin of the most thoroughly documented of these assemblages - fossils from the second oldest of the eight units, the ~3,465-Myr-old Apex chert of Western Australia (Schopf and Packer 1987; Schopf 1992a, 1993) - has been questioned (Brasier et al. 2002), doubt that has recently been extended to include *all* reports of particularly ancient evidence of life, anything "older than, say, 3.0 billion years" (M.F. Brasier, quoted in the NASA-sponsored *Astrobiology Magazine*, January 2003).

Such doubt raises a severe problem for Astrobiology. If current techniques are inadequate to establish the existence of early life on Earth, how can we expect them to uncover evidence of ancient life on other worlds? Research proposed in the following sections addresses this issue.

7.5.1 How can biogenicity be established?

In a general sense, the answer to the question of biogenicity was shown decades ago when early workers in the field (Barghoorn and Tyler 1965; Cloud 1965; Barghoorn and Schopf 1965) first demonstrated that "Precambrian microfossils" are, indeed, true fossils. Namely, the biological origin of fossil-like microscopic objects can be established by demonstrating that they possess a suite of traits that are unique to life, traits that taken together are shared by fossils and living organisms but not by inanimate matter. Thus, the solution to the problem is to insist that claims of ancient fossils be backed by data that show what the fossil-like objects actually *are* – rather than what they seemingly might be or apparently are not – positive lines of evidence that when considered as a whole comprise a signature unique to living systems.

Of the various traits thus used, three have been shown to be particularly useful: (1) the μm-scale morphology of the objects in question; (2) the carbon isotopic composition of organic matter associated with and/or comprising the fossil-like structures; and (3) the chemical (molecular) makeup of the fossil-like objects. In the case of organic-walled fossils, this is particulate carbonaceous kerogen. Each of these factors can yield strong evidence consistent with a biogenic interpretation. Yet none of them, if considered alone, has proven definitive and use of morphology alone has led to numerous errors of interpretation (Schopf and Walter 1983; Mendelson and Schopf 1992). Reliance on carbon isotopic evidence, by itself, has proven inconclusive (van Zuilen et al., 2002); in and of themselves, analyses showing that such objects are composed of geochemically mature organic matter establish only their carbonaceous makeup, not their biological origin (Schopf et al. 2002a).

Nevertheless, other than biology, no mechanism is known that can yield communities of fossil-like objects that have cellular morphologies, exhibit a biologically distinctive carbon isotopic signature, and are themselves composed of particulate carbonaceous matter. Thus, if the three factors are taken together, as a suite of biologically indicative traits, the lines of evidence become mutually reinforcing and a biogenic interpretation, compelling.

In principle, therefore, the question of biogenicity can be easily answered. But in practice, the answer has proven elusive, primarily because of a lack of analytical techniques having sufficient power to provide the high resolution three-dimensional morphological information needed to definitively address the question, and an absence of means by which to directly link, in individual microscopic specimens, morphological information to elemental-isotopic and structural-molecular compositions. Means are now at hand to solve this problem, due primarily to advances pioneered during the past three years by UCLA astrobiologists (House et al. 2000; Kudryavtsev et al. 2001; Kempe et al. 2002; Schopf et al. 2002b). Exploitation of these advances, coupled with development of the new analytical techniques outlined below, will provide a firm basis by which to establish or to refute the biogenicity of putative ancient fossils.

7.5.2 Microbial morphology as evidence for early life

The fossil record of life's early microbial history is based primarly on "morphology," a term that subsumes a great many variables: organismal shape (e.g., coccoid or filamentous); cell shape, size, and surface ornamentation; structure and thickness of an encompassing sheath, if present; and many others (Schopf 1992b), and in taxonomic studies, routinely includes quantitative (morphometric) analyses of intra-taxon variability and population structure. But interpretation of morphology is notoriously subjective; a microscopic object regarded as a good fossil by one investigator may be considered to be a nonfossil artifact by another. Clearly, there is a need for hard and fast criteria by which to separate the *bona fide* from the bogus. For three-dimensionally permineralized (petrified) organic-walled fossils, the most life-like of all types of structurally preserved microscopic biologic remnants, a prime criterion is the mineral-infilled spheroidal or tubular structure defined by their enclosing carbonaceous cell walls, a character by which they differ decisively from solid mineralic pseudofossils (Ruiz et al. 2002). Backed by analyses establishing the chemical composition of the enclosing walls, such cellularity, combined with other morphologic features, can be used to unambiguously distinguish true fossils from mineralic look-alikes.

At the current state of the science, high-resolution optical microscopy can demonstrate the requisite three-dimensional cellularity. In a fossil microbial trichome, for example, the presence of surrounding cell walls and regularly spaced transverse septa that enclose mineral-infilled cell lumina. But, because of the shallow depth of field of the high magnification (e.g., 100x) required to obtain such information, and the limitations imposed by scientific journals on space allotted for illustrative figures, the existence of such cellularlity cannot be effectively conveyed in published form without use of interpretive drawings (e.g., Schopf 1993). This is an unacceptably subjective means of data presentation. To remedy this deficiency, Schopf and coworkers plan to generate high resolution three-dimensional optical images of individual petrified microscopic fossils, an easily achievable technological advance that, combined with the chemical analyses outlined below, will provide data crucial to answering the question of biogenicity.

7.5.3 In-situ isotopic analysis

The carbon isotopic composition of microfossil-associated Precambrian organic matter is known from thousands of measurements in hundreds of Precambrian deposits (Strauss and Moore 1992), studies that have traced isotopic signature of microbial photosynthesis to at least 3,500 Myr ago (Hayes et al. 1983; Strauss et al. 1992). Such analyses of bulk samples, however, yield average isotopic values of carbon derived from a mix of sources, including microfossils of diverse types and states of preservation as well as sapropelic carbonaceous particles of multiple origins. By making use of the spatial resolution afforded by ion microprobe mass spectrometry (e.g., the Cameca 1270 at UCLA), isotopic analyses have now been extended to the kerogenous materials comprising specific microscopic fossils (House et al. 2000; Ueno et al. 2001), an analytical advance that links morphology and carbon isotopic composition in individual fossil microorganisms. The potential of this technique has been barely tapped, and the analytical advance first developed at UCLA (House et al. 2000) has yet to be applied to all but one of the eight earliest fossil assemblages known. Schopf and colleagues therefore plan to combine this newly established method with three-dimensional optical and Raman imaging techniques to evaluate the putative biogenicity of ancient microscopic fossils in rock samples already on hand.

These samples represent some of the oldest reputed fossiliferous units known and include those of the ~3,375 Myr old Kromberg and ~3,465 Myr old Apex deposits.

7.5.4 Molecular composition and geochemical alteration of organic matter

Another important key to establishing the biological origin of ancient microscopic fossil-like objects is to link their morphology to their chemical composition. Studies of the molecular-structural makeup of the organic matter comprising such fossils have only recently begun, most effectively by laser-Raman imagery and atomic force microscopy (Kudryavtsev et al. 2001; Kempe et al. 2002; Schopf et al. 2002b). These analytical techniques have only just recently been applied to the kerogenous components of Precambrian organic-walled microfossils and associated sapropelic debris, yet they hold great promise. In particular, Raman imagery provides the means to correlate optically-discernable morphology with molecular structure in individual carbonaceous microfossils (Figure 7.5.4, Kudryavtsev et al. 2001; Schopf et al. 2002b). Atomic force microscopy studies of carbonaceous microfossils permit visualization of the sub-μm-scale micromorphology of their preserved kerogenous constituents (Kempe et al. 2002). Results thus far have demonstrated a one-to-one two-dimensional correlation between cellular morphology and chemical composition. But to answer the question of biogenicity unambiguously and to rule out the possibility that fossil-like objects represent some sort of solid mineralic (e.g., graphitic) sports of nature, these composition and structure-dependent visualization techniques must be extended to three dimensions. This will be achieved by the installation of a new, state-of-the-art laser Raman imaging facility at UCLA.

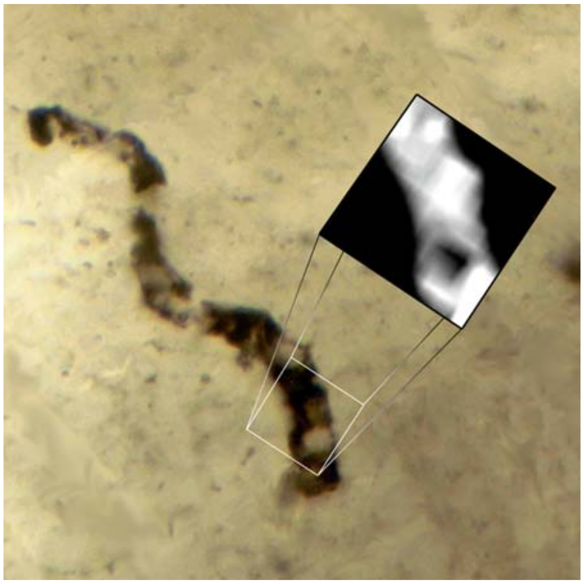

Figure 7.5.4. Photographic image and laser Raman image (inset) of ~3.47 billion year-old microfossil from the Apex chert of Western Australia. Dark material is demonstrated to be carbonaceous by the laser Raman image.

Schopf and colleagues recently used laser-Raman imagery (Kudryavtsev et al. 2001; Schopf et al. 2002b) to conduct a comprehensive study of the chemistry of carbonaceous microscopic fossils permineralized in 25 fine-grained chert units ranging in age from Devonian to Archean. Results demonstrate that the structure of the spectra acquired varies systematically with the metamorphic grade of the fossil-bearing rock units sampled, the fidelity of preservation of the fossils studied, the color of the organic matter analyzed, and with both the H/C and N/C ratios measured in kerogens isolated from bulk samples of the fossil-bearing cherts (Schopf et al. in press). To compare quantitatively the systematic variations observed among the various spectra, this work introduces the concept of the Raman Index of Preservation (RIP), an approximate measure of the degree of geochemical alteration of the 25 kerogens analyzed. Deconvolution of the various spectra, facilitated by comparisons with spectra obtained from experimentally heated fossil specimens, has provided insight into the molecular and chemical makeup of ancient kerogens and the changes that accompany organic metamorphism. To refine and extend this work, arrangements have been made to obtain additional samples of kerogens that are well characterized as to maximum temperature (by vitrinite reflectance, palynomorph color, H/C ratios, etc.), from U.S. petroleum companies (via Dr. W. Dow) and from the Institut Français du Pétrole (via Dr. Mireille Vandenbroucke). Schopf and collaborators proposes to analyze these ~400 specimens by Raman spectroscopy in order to provide a firm basis for calibrating the thermal (catagenic) history evidenced by their RIP values and to determine the activation energies that have resulted in loss of various chemical moieties as a function of their geologic (or laboratory-simulated) thermal histories.

7.5.5 Quantitative methods for evaluating the biogenicity of fossil stromatolites

Spectacular, conical stromatolites arranged in egg carton-like arrays were reported recently from 3.45 Gyr-old Warrawoona Group strata in Western Australia (Hofmann et al. 1999). These stromatolites are arguably the best evidence for the nature of early life on Earth because they may record some aspects of the behavior and ecology of early Archean microorganisms. However, it is first necessary to be convinced that these structures are, at least in part, biogenic constructions. Understanding their morphogenesis also serves as a prelude to lander and rover explorations of the ancient terrains of Mars because distinctive, large, and widely-distributed sedimentary structures of this type are an obvious target for astrobiological missions.

The case for an abiotic origin for at least some Precambrian stromatolites was advanced by Grotzinger and Rothman (1996), who used a power spectral analysis to quantify the three-dimensional shape of some Paleoproterozoic stromatolites as observed in outcrops and in sawn sections. They believed that the stromatolite growth process could be modeled in 2+1 dimensions by the classic KPZ interface equation of condensed matter physics (Kardar et al. 1986). Although numerical show that this is not correct (Jögi and Runnegar 2002), Grotzinger and Rothman made a very important advance by showing how the terms in the KPZ equation (upward growth, surface-normal growth, diffusion, gaussian noise) can represent processes that are meaningful in sedimentological and biological contexts (sediment fallout, spherulitic crystallization, downslope movement, and environmental fluctuations, respectively).

Simulations are carried out in 1+1 and 2+1 dimensions using code written by Jögi over the past three years. For small problems (say, 256 x 256 grid points), the calculations are performed locally on Sun workstations; larger arrays have been run using parallelized code on the San Diego Supercomputer Center's IBM "Blue Horizon" (§3).

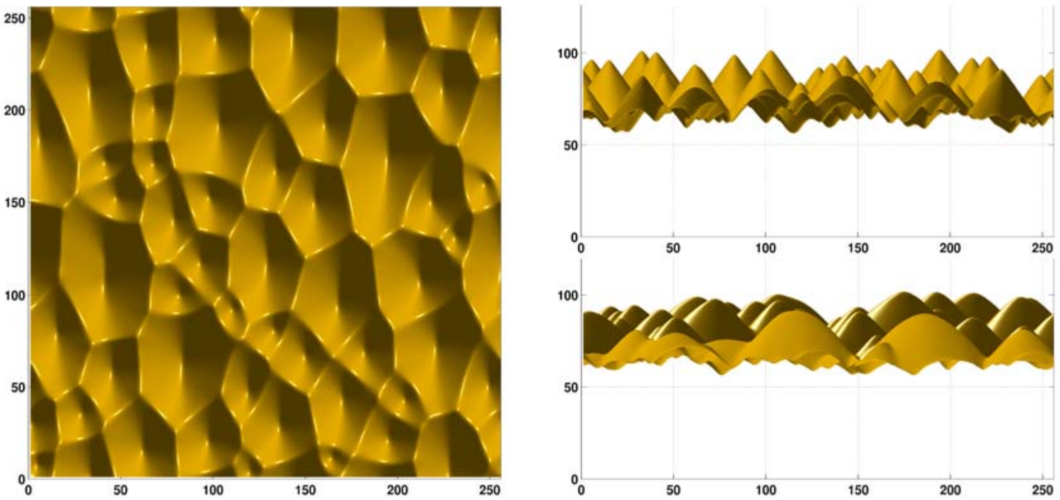

Fig. 7.5.5. Simulation of 3.45 Gyr-old coniform stromatolites, Warrawoona Group, Western Australia using a 256 x 256 grid with periodic boundary conditions (600 timesteps). Left image is a plan (Z) view; note asymmetry and preferred orientation parallel to Y; right images represent views parallel to the Y and X axes.

Results to date have shown conclusively that the KPZ equation, and others like it (EW; Edwards and Wilkinson 1982) are incapable of producing simulated structures that resemble the Archean coniform stromatolites from Western Australia. On the other hand, an equation that is important in the physics of metal atom sputtering (Smilaeur et al. 1999) simulates conical structures effectively (Figure 7.5.5). The reason is that the process being modeled (electron beam epitaxy) has an uphill component caused by an edge effect at the atomic scale. Thus, models constructed using this equation (SRK) incorporate an upslope diffusion term that is not present in KPZ-based models. As upslope diffusion is a process that is easily attributable to life but not to other non-vital environmental agents at anything larger than atomic scale, this parameter may provide a definitive test for biogenicity.

There are other features of the Warrawoona stromatolites that need to be explored mathematically. The SRK equation produces cones that either slowly coalesce ("coarsen") or exhibit rounded tops and froth-like behavior in long simulations. Similar behaviors are seen in experimental and industrial settings when metals are deposited using these methods. Jögi and Runnegar have discovered that there is a narrow zone of stability between these two realms that corresponds to a phase transition between regimes controlled by the endmember EW (frothy) and SRK (coarsening) equations. Simulations that occupy this transition zone generate suitably conical structures (Figure 7.5.5) that do not coalesce. After numerous experiments of this kind, it is now possible to accurately specify the slope angles (in two orthogonal directions as in the stromatolites; Figure 7.5.5) and grow cones to a specified size. It should be emphasized that the only "environmental" input to these simulations is uncorrelated random noise. This and the values given to the various diffusion terms are the controlling parameters. They provide the beginnings of a precise understanding of the physical and biological factors that may have generated these ancient structures.

The next step is to try to incorporate features not captured by the current model (down-dip asymmetry, higher-frequency wrinkles, etc.) and then to make careful, quantitative comparisons between the modeled stromatolites and the field exposures. This will require the development of more sophisticated metrics than the method used by Grotzinger and Rothman (1996), the production of 3D physical models using rapid prototyping technology, and additional analysis of the natural objects using digital images of outcrop and sawn sections, and, possibly, computerized X-ray tomography. Ultimately, the goal is to extend this approach to other distinctive stromatolite types.

7.6 GENOMICS, GEOLOGY, AND THE TREE OF LIFE (AWRAMIK, FITZ-GIBBON, HOUSE, LAKE, RIVERA, RUNNEGAR)

Phylogenetic trees can serve as DNA-derived windows into Earth's past. They offer a framework upon which one can map the atmospheric, paleontological, geological, and climatological records and thereby test scenarios for evolution on a planetary scale. Here, phylogenetic reconstructions will be used to address a central set of questions relating to life's early history: What were environmental conditions like early in the evolution of life on Earth? Did life start in a hot environment? What compounds were being made in the first half billion years of life on earth? What was the role of horizontal gene transfer during these early times? Was methanogenesis developed quickly and only once? How did environmental variables such as temperature, pH, sulfur availability, and oxygen affect the evolution of life? Did heterotrophy evolve before autotrophy, or *vice versa*? The research proposed in this section will focus on these, and related, questions using a combined geological and genomics approach.

7.6.1 Mapping microbial metabolisms on to the tree of life

Parsimony analyses of phylogenetic trees, can allow one to extrapolate from the environments in which extant prokaryotes are currently living to the environments in which their distant ancestors lived. This process (Williams and Fitch 1989) is illustrated in Figure 7.6.1 using a standard reference tree of eight prokaryotes of diverse ancestry. Six environmental parameters of present day organisms are indicated by the colors at the tips of the branches and the inferred parameter values are shown by colors continuously distributed across the trees. This example is inconclusive because few taxa have been sampled, but serves to illustrate the method. Using trees constructed in this way, but which contain many prokaryotic taxa, it will be possible to trace back the evolution of different environmental parameters into the interior of the tree and thereby relate the tree of life to the geological record.

Phylogenetic reconstruction is central to interpreting the geological record, but obtaining realistic reconstructions of the prokaryotic branches of the tree of life is a daunting task. At present, prokaryotic relationships remain poorly resolved. There is now an emerging consensus that prokaryotic trees, whether based upon ribosomal RNA gene sequences or upon other molecules, fail at depths greater than the "phylum" level (Garrity and Holt 2001). Although it is usually known to which phylum any particular bacterium belongs, it is generally not known how the various phyla are related to each other. This deficiency has obvious implications for understanding the origins and evolution of planetary-scale metabolic activities such as, for example, oxygenic photosynthesis. For example, at present, the relationships among the various kinds of photosynthetic prokaryotes are unknown. Solving this problem is important if we are to understand fully the early evolution of life on Earth. Here, several steps towards obtaining better, more robust trees are proposed.

New computational tools and approaches for genome analysis, that specifically address horizontal gene transfer, have and are being developed (Lake and Moore 1998). HGT can distort phylogenetic relationships since different genes within a given genome will have different histories and therefor give rise to different trees when compared across organisms. Thus, gene trees do not necessarily correspond to organismal trees (Brown and Doolittle 1997; Feng et al. 1997; Koonin et al. 1997; Rivera et al., 1998). However, more recent studies suggest that horizontal gene transfer, while rampant, is not random, since it predominantly affects only "operational" genes, those primarily involved in housekeeping functions (Lake et al. 1999). By using only "informational genes", which are less affected by horizontal gene transfer (e.g., those involved in protein synthesis and RNA transcription), one should be able to derive correct organismal trees and also resolve deep phylogenetic divergences among prokaryotes. Ribosomal RNA genes belong to the informational class, but because they are short (2,000 to 4,000 nucleotides) they cannot accurately place prokaryotic phyla relative to each other. However, sequences constructed from concatenated informational protein genes (>100,000 nucleotides) obtained from public genome databases, are expected to be able to resolve these deep prokaryotic divergences. Lake and Rivera propose to use these methods to greatly refine the prokaryotic (bacterial and archaebacterial) sectors of the tree of life and then to use these refined trees to explore the history of environmental tolerances, as described above. This information will be integrated with the results of geological and geochemical studies (§7.4, 7.5, 8.2) that provide evidence for the time of appearance

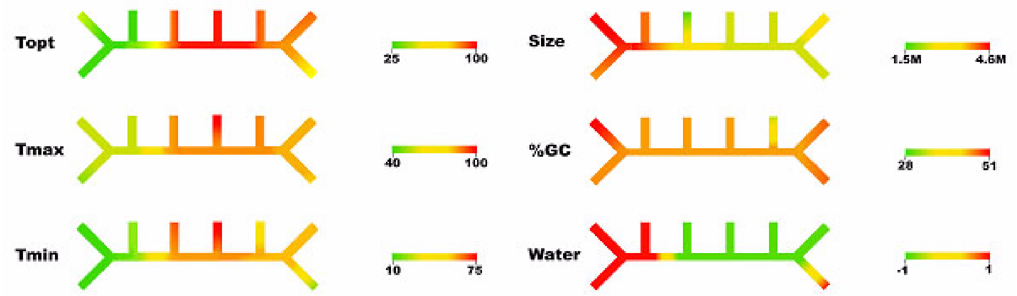

Figure 7.6.1. The distribution of environmental and genomic parameters during prokaryotic evolution as calculated from extant taxa. The parameters illustrated include minimum (Tmin), optimal (Topt), and maximum (Tmax) growth temperature, genome size, genome composition (%GC), and salinity (Water). Clockwise from lower left to lower right, the taxa are: *Escherichia coli* (g proteobacterium), *Bacillus subtilis* (gram positive eubacterium), *Synechocystis* (cyanobacterium), *Aquifex* (eubacterial extreme thermophile), *Pyrococcus* (archaebacterial extreme thermophile), *Methanococcus* (thermophilic methanogen), *Methanobacterium* (moderately thermophilic methanogen), and *Archaeoglobus* (a thermophilic archaebacterium).

of key metabolic activities.

8 EVOLVING COMPLEXITY

8.1 OVERVIEW

Progress in the evolution of life on Earth is measured by an increase in biological diversity (biodiversity), by an increase in morphological disparity, and by progress towards increasing complexity. This are presumably general principals which apply to any living system and so studies of the processes that result in these advances should have universal application. Of the three metrics for evolutionary progress, complexity is the most difficult to define, measure, and understand. In this section, biologists and paleontologists attempt to grapple with this difficult issue by focusing on two outstanding biological events: The origin of eukaryotes and the radiation of animals during the "Cambrian Explosion".

8.2 Origins of eukaryotes (Fitz-Gibbon, House, Johnson, Lake, Porter, Rivera)

Szathmáry and Maynard Smith (1995) identified eight major milestones in the history of life on Earth: cells (compartments), chromosomes (genomes for cells), nucleic acids and proteins (separation of function at the molecular level), endosymbiosis (combination of function), sexuality (genetic recombination), multicellularity (separation of function at the cellular level), social organization (separation of function at the organismic level), and civilization (communication via language). The rise of eukaryotes began before the fourth of these thresholds was crossed, but eukaryotes progressively passed all of the other milestones and are the only branch of terrestrial life to have done so. Understanding the early part of this progressive history may therefore reveal general principles that are applicable to the growth of complexity in any living system. In this section, biologists and geologists propose to study early evolution of eukaryotes using information from molecular biology and the fossil record. The goals are to better understand the order in which important universal properties of eukaryotes (nucleus, sterols, cytoskeleton, endoplasmic reticulum, organelles, multicellularity, etc.) were acquired, and to try to time these events using both the fossil record and molecular clocks.

Unless ongoing horizontal (lateral) gene transfer has completely obliterated deep historical information from modern genomes (§7.6.1), one clear possibility is that the last common ancestor of the primary line of descent leading to eukaryotes – the so-called eukaryote “host” – was also the last common ancestor of the Archaea (Cavalier-Smith 2002; House et al., submitted) or, perhaps, some members of the Archaea, if the Archaea is not a monophyletic group (Rivera and Lake 1992). In this scenario, this event (the origin of the eukaryote total group) would be unrecognizable in the microfossil and biomolecular fossil records because both descendant species would have been essentially identical at the time of divergence. Only subsequently, did they independently acquire those metabolic and other attributes that allow them to be differentiated into distinct biological categories.

A second class of hypotheses for the origin of eukaryotes invokes biological convergence – an amalgamation of two or more fundamentally different kinds of organisms instead of an ordinary evolutionary divergence (Gupta et al. 1994; Lake and Rivera 1994; Martin and Müller 1998; Horiike et al. 2001; Hartman and Federov 2002). If this were true, the originating event would represent a genomic singularity in the tree of life and, perhaps, also be visible in the fossil record. In terms of molecular sequence comparisons, the amalgamation event can, in principal, be seen as a time when a signifcant number of foreign genes entered the genome of the “host” organism.

The nature of the “host” organism and the source of the prokaryotic “donations” to the genome(s) of the last common ancestor of all living eukaryotes are outstanding problems in evolutionary biology that will be addressed by the research proposed here. There are obvious contributions from the endosymbiotic events that gave rise to mitochondria and plastids (chloroplasts etc.), but it is still not clear whether mitochondria and other similar energy-producing organelles known as hydrogenosomes were incorporated before the origin of the crown group (Roger and Silberman, 2002), and have been lost subsequently in some members (notably *Giardia* and its relatives), or are characteristic of only some groups of eukaryotes. It is even more uncertain whether the "host" organism was a stem or crown group archaebacterium (A), an unusual primitive bacterium (B; Philippe 2002), or a member of an extinct lineage (C) that diverged prior to the universal last common ancestor of all life on Earth (Hartman and Federov 2002).

When these relationships are better understood, it should be possible to use the major amalgamation events as timelines across the tree of life. For example, if all mitochondria are derived from a unique obligate endosymbiosis between a *Rickettsia*-like a proteobacterium, and if mitochondria were acquired by stem group eukaryotes, then the last common ancestor of all living eukaryotes must postdate the differentiation of the proteobacteria (Gray et al. 1999). Combining this approach with molecular clock estimates of divergence times and evidence from the fossil record will ultimately lead to an understanding of the early history of eukaryotes in a planetary context.

8.2.1 Investigating the prokaryotic sources of eukaryotic genes

The increasing availability of eukaryotic and prokaryotic genomes, and of new phylogenetic methods, promises to help understand which prokaryotic groups are the antecedents of eukaryotes. Knowledge of eukaryotic ancestors and their metabolisms, may in turn tell us about the environment in which eukaryotes arose and suggest what conditions on Earth facilitated their evolution. Furthermore, knowing whether eukaryotes are descended from anaerobes or from aerobes may greatly constrain possible scenarios for their evolution. At present, there is increasing interest in proposals that eukaryotes are chimeric and have multiple origins (Gupta et al. 1994; Lake and Rivera 1994; Martin and Müller 1998). Evidence from whole-genome analyses indicates that those eukaryotic genes coding for translation and transcription have come from archaebacterial hyperthermophiles whereas genes used for amino acid biosynthesis and other cellular processes have come from several different groups of eubacteria (Koonin et al. 1997; Rivera et al. 1998; Martin et al. 2002).

Johnson and her collaborators will focus on the steps by which eukaryotes have obtained and lost their genes and organelles (mitochondria and hydrogenosomes). Using methods developed previously, Lake and Rivera will will search for those prokaryotic "phyla" (Garity and Holt 2001) that have made the largest genetic contributions to the eukaryotic genome. In preliminary studies, it was found that several prokaryotic genomes have made significant contributions to eukaryotes. However, by using representative members of the ~80 currently available prokaryotic genomes and procedures similar to those used for studies of horizontal gene transfer (§7.6.1; Jain et al. 1999), they expect to determine which of the major bacterial groups have been the sources of the eukaryotic genes. The plan then is to identify which classes of genes (e.g., amino acid biosynthesis genes, cell envelope protein genes, energy metabolism genes) have come from which prokaryotes. These will then be compared with the metabolic properties of the contributing prokaryotes in order to test existing hypotheses for the origins of eukaryotes.

In a complementary study, Fitz-Gibbon and House propose to carry out additional whole genome comparisons in order to obtain more fully resolved phylogenetic trees. They score individual genes as being either present or absent, just as any particular nucleotide is scored as being in one of four possible states (A, G, C or T) in DNA sequence comparisons. This method of whole genome comparison has been successfully applied previously (House and Fitz-Gibbon 2002; House et al. submitted).

Since the method of whole genome analysis is in its infancy, Lake and Rivera propose to investigate some of the potential problems. When genomes differ considerably in size, whole genome analyses tend to put adjacent taxa together even if the organisms are not closely related. This effect, "big genome attraction", is similar to the long branch attraction artefact of gene and protein sequence comparisons (Philippe 2002). It can become important because eukaryotic genomes differ so greatly in size. For example, trees were constructed using the following eukaryotes, listed according to increasing genome size: *Saccharomyces cerevisiae*, *Schizosaccharomyces pombe*, *Drosophilia melanogaster*, *Caenorhabditis elegans*, *Arabidopsis thaliana*, and *Homo sapiens*. Invariably, the taxa clustered together according to the size of their genomes as expected from the “big genome attraction” concept. This problem needs further exploration.

8.2.2 Origin and evolution of eukaryotic respiratory organelles

Modern eukaryotes are viewed as a consortium of ancient associations between the nucleus plus cytoplasmic “host” and endosymbiotic bacteria that gave rise to energy-generating organelles, the mitochondria, chloroplasts, and hydrogenosomes. Competing hypotheses speculate about the role these ancient endosymbioses had in shaping the early eukaryotic cell. One view, the “hydrogen hypothesis” (Martin and Müller 1998), suggests that it was an association between a methanogenic host and a hydrogen-producing bacterial symbiont that led to the establishment of mitochondria in extant eukaryotes. Other theories hold that the mitochondrial symbiosis occurred substantially after the origin of the eukaryotic nucleus, pointing to the existence of ancestral amitochondriate eukaryotes (Andersson and Kurland 1999). Each of these hypotheses implies a different time of origin and selective force for the establishment of symbiont-derived organelles and has implications for the origins of anaerobic and aerobic eukaryotes and their metabolic pathways.

The credibility of various hypotheses concerning eukaryotic organellar origins depends upon knowledge of hydrogenosomes (complex organelles involved in anaerobic carbohydrate metabolism) and mitochondria, the relationships between these organelles, and the origin of their protein components (Roger 1999; Dyall and Johnson 2000). To better understand the origin and nature of the hydrogenosomes, Johnson and her collaborators will probe the evolutionary and biochemical properties of this organelle in the anaerobic protist *Trichomonas vaginalis*, using a combination of genomics, proteomics and phylogenetic approaches. They propose to identify all genes encoding hydrogenosomal proteins by scanning the soon-to-be-completed genome using a highly conserved part of all matrix protein-coding genes. A proteomics approach, using mass spectrometry and genome sequence mining, will also be used to directly identify organellar proteins. Proteins identified by both methods will be subjected to phylogenetic analyses and their presence in the hydrogenosome will be confirmed using a variety of cell biological techniques. By combining genomics, proteomics, molecular evolutionary and cell biological approaches, they will attempt to elucidate the ancestry of the trichomonad hydrogenosome, an organelle that is central to energy metabolism in diverse anaerobic, and possibly other primitive, eukaryotes. The data generated will be used to assess alternative hypotheses for the origin and evolution of energy-generating organelles in early eukaryotes.

Only six proteins from hydrogenosomes have been subjected to phylogenetic analyses and the results are ambiguous (Dyall and Johnson 2000; Horner et al. 2000). While the analyses of four of these genes are consistent with a common ancestry for hydrogenosomes and mitochondria, the other two genes suggest an ancestry from certain kinds of anaerobic bacteria. Whether any or all of these genes arose via an endosymbiotic event or via lateral gene transfer is unclear. The central aim of the proposed work is to identify most, if not all, proteins that are targeted for import to the hydrogenosomes. In brief, it is proposed: (1) to identify genes encoding hydrogenosomal matrix proteins as described above; (2) to identify all proteins in the hydrogenosome; (3) to test whether the putative hydrogenosomal proteins found are localized to the organelle *in vivo*; and (4) conduct phylogenetic analyses on newly-identifed hydrogenosomal proteins. Johnson’s laboratory is currently collaborating with TIGR (The Institute of Genomic Research) to obtain the complete genome of *Trichomonas vaginalis*. The sequencing is expected to be completed by July, 2003.

These studies, which directly test whether hydrogenosomes and mitochondria arose from a common endosymbiont, will improve understanding of how organelles and eukaryotic cells first arose, and shed light on ancestral metabolic associations that led the evolutionary specialization and complexification of eukaryotic cells. They will explore the ancestry of organelles which are central to energy metabolism in eukaryotes, and will highlight processes by which cells gain complexity and evolve. If hydrogenosomes arose from an ancestor different from the mitochondrion, then hypotheses concerning the nature of living eukaryotes will be narrowed to those postulating endosymbiotic associations among a consortium of eubacterial and eukaryotic progenitors. The proposed combination of phylogenetics, genomics and proteomics to assess homologies among organelles sets this part of the proposal apart. However, Johnson's work and that proposed by Lake and Rivera (§8.2.1) are intimately related as they both address the potential contribution of bacterial consortia in the formation of the eukaryotic cell.

8.2.3 The fossil record of eukaryotic diversification

The diversification of eukaryotes coincided with dramatic changes in Earth's climate, ocean chemistry, atmospheric oxygen levels, and tectonic configuration. Mechanisms that link eukaryotic diversification to changes in the physical environment have recently been proposed (e.g., Brasier and Lindsay 1998; Anbar and Knoll 2002), but, with a few notable exceptions (Javaux et al. 2001), the stratigraphic and paleontologic datasets needed to test these ideas are not available. Recent work in well preserved, widely separated successions in western North America offers an unparallelled opportunity to gain insight into the interaction between biology and environmental change during the early to middle Neoproterozoic interval of Earth history (1,000 to ~600 Myr ago). Sequence stratigraphic, chemostratigraphic, geochronologic, and tectonic studies are in progress or have already been completed for two basins: the ~770-742 Myr-old Chuar Group, Grand Canyon, and its likely correlative, the Uinta Mountain Group, Utah (Weil et al. 1999; Karlstrom et al. 2000; Dehler et al. 2001; Timmons et al. 2001; Dehler et al. 2002; C. Dehler and L. Crossey, pers. comm. 2002). These studies provide a detailed record of environmental change with which paleobiological studies can be integrated. Initial work in the Chuar Group indicates a tantalizing connection between increasing carbon isotope variability and the first appearance of heterotrophic protists within the basin (Porter and Knoll 2000; Dehler et al. 2001; Porter et al. 2003). This possible causal connection will be explored using studies that investigate the abundance, diversity, and paleoenvironmental distribution of organic walled microfossils (acritarchs), and also the relationship of these variables to environmental parameters. In addition, ultrastructural and ion microprobe analyses of individual acritarchs will help elucidate the affinities of these early eukaryotic fossils, aiding in the calibration of branch points in the eukaryotic tree. Ion microprobe carbon isotope analysis of individual acritarchs may also prove useful for inferring paleoecological or paleoclimatic information; these possibilities and others will be explored in the proposal period. Chuar Group samples have already been collected and processed; funding is requested for fieldwork in the Uinta Mountain Group and for the processing of samples.

8.3 Understanding the assembly of animal body plans in the context of the Cambrian explosion (Gehling, Jacobs, Kouchinsky, Porter, Runnegar, Webster)

The Cambrian Period witnessed one of the most significant events in the history of life: an exponential increase in animal diversity and complexity, commonly referred to as the "Cambrian explosion". Despite recent advances in our understanding of animal relationships (Peterson and Eernisse 2001) and Cambrian geochronology (Bowring and Erwin 1998), important questions remain, perhaps the foremost of which is, what triggered the Cambrian explosion, and what makes it so unusual? Addressing these questions requires that we understand not only the steps by which early animal body plans evolved, but also the extrinsic and intrinsic controls on that evolution. We propose to study four topics that will elucidate these issues: (1) The stratigraphic record of the first multicellular (Ediacaran) animals (Gehling, Runnegar); (2) The nature of the developmental program controlling skeleton formation (Jacobs, Kouchinsky); (3) The evolution of developmental constraints in early Cambrian trilobites (Webster); (4) The sequence of body plan evolution in the lophotrochozoan phyla (Porter, Runnegar). These studies will combine insights from evolutionary developmental biology and data from the fossil record to obtain a clearer understanding of the Cambrian explosion.

8.3.1 Ediacaran biodiversity: Prelude to the Cambrian explosion

Ediacaran organisms have been biologically enigmatic since they were first discovered (and thought to be pseudofossils) in Newfoundland during the 19th century (Gehling et al. 2000). However, recent discoveries of numerous new fossils at remarkably rich sites in the Flinders Ranges of South Australia, in southern Namibia, on the shores of the White Sea, and in Newfoundland have demonstrated that the Ediacaran biotas really do record the initial diversification of multicellular animal life. What is particularly striking, is that the older assemblages (ca. 565 Myr old) lack evidence in the form of body fossils and trace fossils for animals of bilaterian grade (mobile, bilaterally symmetrical, cerebral). In contrast, there is ample evidence for bilaterian grade animals in the younger assemblages worldwide. Ediacaran fossils are no longer limited to single stratigraphic horizons that are isolated by unfossiliferous strata from the succeeding Cambrian explosion. In Newfoundland, for example, Ediacaran fossils have been found beneath virtually every volcanic ash layer (~65 in all) over some 2.5 km of stratigraphic thickness (Narbonne and Gehling 2003). Furthermore, the oldest of these fossiliferous levels is not far above the Gaskiers Tillite, arguably the youngest (580 Myr; Bowring et al. 2002) of the Neoproterozoic snowball Earth glacial events.

The time has come to put all of this globally-distributed paleontologic and biostratigraphic information together in order to: (1) Test the idea that the last one or two Snowball Earth glaciations were implicated in the appearance and diversification of the Ediacaran biota. (2) Document the progressive evolution of biocomplexity through the terminal Proterozoic period (soon to be formally named the Ediacaran). (3) Explore further the connections with the Cambrian explosion. The modest funds requested for this research ($5k/year) will be used by Gehling for field studies of the most important sites outside Australia.

8.3.2 The evolution of mineral skeletons

The evolution of skeletons is thought to have fed back through predator-prey evolution to increase specificity of interactions that contributed to the rapid diversification of Cambrian bilaterian animals. Preliminary work (Jacobs et al. 2000) suggests that aspects of the growth of shells and other mineralized skeletal elements are under common developmental control in a wide range of living animals. Although skeletal ultrastructures and materials in different animal phyla are distinct, common features of organic matrices found with skeletons suggest that the process may have a single common ancestry. Homology of bilaterian skeleton formation, if proven, would suggest that the onset of skeletogenesis played a critical role in the Cambrian radiation.

To better understand the relationship between the evolution of bilaterian skeletogenesis and the Cambrian explosion, we propose to: (1) explore the relationships of developmental genes that appear to be associated with skeletogenesis in unstudied animals; (2) compile all available ultrastructural information pertaining to setae, spicules, and similar skeletal precursor organs in order to develop a model of the evolutionary origin of the simplest skeletal elements; and (3) use this model to choose candidate genes for further study.

The *engrailed* gene, best known for its role in bounding the exoskeletal units of arthropod segments, appears to bound skeletal elements in other invertebrate phyla including shells of molluscs, setae of annelid polychaetes and the arm plates of brittle star echinoderms (Jacobs et al. 2000, Seavers et al. 2002). Thus, the *engrailed* gene is one of several clues linking the process of skeletogenesis across a range of bilaterian animals. To assess the breadth of this phenomenon we propose to measure the expression of *engrailed* in related phyla that have mineralized hard parts, including brachiopods, echiurids, sipunculids, and tube dwelling annelids. The *engrailed* gene has already been sequenced from echiurids and sipunculans.

8.3.3 Role of constraints on animal development through morphometric studies of Cambrian trilobites

The magnitude and rate of evolutionary innovation associated with the Cambrian explosion was not sustained in post-Cambrian times. This implies either ecological constraint, where filled niches limited opportunity, or developmental constraint, where evolution of development limited the ability of organisms to evolve new morphology regardless of ecological opportunity.

Cambrian trilobites are the best group to test competing ecological and developmental explanations for the post-Cambrian decrease in evolutionary innovation. Detailed reconstruction of paleoenvironments across significant Cambrian extinction events permit control for ecological factors and assessment of responses to changes of diversity that reduce the degree to which niches are filled. This, in combination with detailed examination of the developmental series through time, permits a formal comparison of the ecological and developmental limits on morphological diversification. The proposed research will use detailed morphometry (Webster et al., 2001; Webster, 2003) to investigate new collections of high-quality, silicified (uncompacted) trilobites made at high stratigraphic resolution both across and between extinction events. These studies will lead to a greater understanding of the unique patterns of metazoan evolution associated with the Cambrian explosion.

8.3.4 Using stem group taxa to order characters important in body plan evolution

Modern mobile animals, technically known as bilaterians, are characterized by complex, functionally and developmentally integrated anatomies. Insight into how such complexity arose can be gained through study of the Cambrian fossil record, which contains a number of "oddball" animals that have unfamiliar morphologies or lack features found in modern groups. Recently it has been recognized that these problematical animals are not members of extinct phyla (Gould 1989). Instead, they are often stem-group representatives of modern groups. When they are placed within a phylogenetic framework, stem-group taxa can help reveal the evolutionary steps through which modern body plans arose (Budd 2002).

Halkieriids are among the most widespread, diverse, and abundant early Cambrian "oddball" animals. These scaly organisms are either stem-group members of the lophotrochozoans or, more likely, of one of its contituent phyla such as the molluscs, brachiopods, or annelids (Annelida, Brachiopoda, Mollusca; Jell 1981; Bengtson 1992; Conway Morris and Peel 1995; Runnegar 2000; Holmer et al. 2002). Porter and Runnegar propose to study the morphology and ontogeny of halkieriids and their relatives in unprecedented detail. First, ultrastructural studies will be conducted to reconstruct the original composition, morphology, and structure of halkieriid sclerites (Porter 2002; in press); variation within the group necessitates comprehensive representation of halkieriid taxa. Second, 3D models of halkieriid scleritomes, constructed from laser scanned images of well-preserved sclerites (Lyons et al. 2002) and guided by data from articulated specimens (Conway Morris and Peel 1995), will be used to test competing hypotheses of halkieriid ontogeny and skeletal growth. These data, combined with those obtained through similar investigations of fossil and modern lophotrochozoan groups, will lead to a detailed cladistic analysis of selected lophotrochozoans and, hopefully, provide some insight into how complex body plans arose. Halkieriid specimens from Australia and Siberia are in existing collections. Funding is requested for scanning electron microscopy and laser scanning of specimens, and for fieldwork in China to obtain new collections from Early Cambrian horizons known for exceptional preservation of halkieriids and other problematical fossils.

References

Abrajano, T. A., Sturchino, N. C., Bohlke, J. K., Lyon, G. I., Poreda, R. J., & Stevens, C. M. (1988). Methanehydrogen gas seeps, Zambales ophioloite, Philipines - Deep or shallow origin. *Chemical Geology*, 71: 211-222.

Alexander, E. C., Lewis, R. S., Reynolds, J. H., & Michel, M. C. (1971). Plutonium 244: Confirmation as an extinct radioactivity. *Science*, 172: 837-840.

Allegre, C. J., Staudacher, T. H., Sarda, P., & Kurz, M. (1983). Constraints on evolution of Earth's mantle from rare gas systematics. *Nature*, 303: 762-766.

Al-Shamali, F., Heimpel, M. H., & Aurnou, J. M. (In preparation, 2002). Effects of varying spherical shell radius ratio on dynamo generation.

Amelin, Y. (1998). Geochronology of the Jack Hills detrital zircons by precise U-PB isotope dilution analysis of crystal fragments. *Chemical Geology*, 146: 25-38.

Anbar, A. D., & Knoll, A. H. (2002). Proterozoic ocean chemistry and evolution: a bioinorganic bridge?: *Science*, 297:1137-1142.

Andersson, S. G. E., & Kurland, C. G. (1999). Origins of mitochondria and hydrogenosomes. *Current Opinion in Microbiology*, 2: 535-541.

Ash, R. A., Knott, S. F., & Turner, G. (1995). Evidence for the Timing of the Early Bombardment of Mars. *Meteoritics*, 30: 483.

Awramik, S. M., Schopf, J. W., & Walter, M. R. (1983). Filamentous fossil bacteria from the Archean of Western Australia. *Precambrian Research*, 20: 357-374.

Azbel, I. Y., & Tolstikhin, I. N. (1993). Accretion and early degassing of the Earth: Constraints from Pu-U-I-Xe isotopic systematics. *Meteoritics*, 28: 609-621.

Bajt, S., Sutton, S. R., & Delaney, J. S. (1994). X-ray microprobe analysis of iron oxidation states in silicates and oxides using x-ray absorption near edge structure (xanes). *Geochimica et Cosmochimica Acta*, 58: 5209-5214.

Baker, D. R., Conte, A. M., Freda, C., & Ottolini, L. (2002). The effect of halogens on Zr diffusion and zircon dissolution in hydrous metaluminous granitic melts. *Contributions to Mineralogy, & Petrology*, 142: 666-678.

Bao, H., Thiemens, M. H., Campbell, D. A., Lee, C. C-W., Heine, K., & Loope, D. B. (2000). Anomalous ^{17}O compositions in massive sulfate deposits on the Earth. *Nature*, 406: 176-178.

Barghoon, E. S., & Schopf, J. W. (1965). Microorganisms from the late Precambrian of central Australia. *Science*, 150: 337-339.

Barghoon, E. S., & Schopf, J. W. (1966). Microorganisms three billion years old from the Precambrian of South Africa. *Science*, 152: 758-763.

Barghoon, E. S., & Tyler, S. A. (1965). Microorganisms from the Gunflint chert. *Science*, 147: 563-577.

Beckers, J. M. (1993). Adapative optics for astronomy - principles, performances, and applications. *Annual Review of Astronomy, & Astrophysics*, 31: 13-62.

Bengtson, S. (1992). The cap-shaped Cambrian fossil *Maikhanella* and the relationship between coeloscleritophorans and molluscs. *Lethaia,* 25: 401-420.

Bockelée-Morvan, D., Gautier, D., Hersant, F., Huré, J. M., & Robert, F. (2000). Turbulent radial mixing in the solar nebula as the source of crystalline silicates in comets. DPS meeting 32, no. 44.07. *American Astronomical Society*, 1081-1095.

Boogert, A.C.A., Blake G.A., & Tielens A.G.G.M. (2002). High-resolution 4.7 micron keck/NIRSPEC spectra of protostars. II. Detection of the ^{13}CO isotope in icy grain mantles. *Astrophysical Journal*, 577: 271-280.

Boss, A. P. (1998). Protostars and protoplanetary disks. *Astrophysics and Space Science*, 255: 15-23.

Bottke, W. F., Jr., Rubincam, D. P., & Burns, J. A. (2000). Dynamical evolution of main belt meteoroids: Numerical simulations incorporating planetary perturbations and Yarkovsky thermal forces. *Icarus*, 145: 301-331.

Bowring, S. A., Landing, E., Myrow, P., & Ramenzani, J. (2002). Constraints on terminal Neoproterozoic events and the rise of metazoans. *Astrobiology*, 2: 457.

Bowring S. A., & Erwin, D. H. (1998). A new look at evolutionary rates in deep time; uniting paleontology and high-precision geochronology. *Geological Society of America Today*, 8: 1-8.

Bradley, P. J., Lahti, C. J., Plumper, E., & Johnson, P. J. (1997). Targeting and translocation of proteins into the hydrogenosome of the protist trichomonas - similarities with mitochondrial protein import. *EMBO Journal*, 16: 3484-3493.

Braiser, M. D., Green, O. R., Jephcoat, A. P., Kleepe, A. K., Van Kranendonk, M. J., Lindsay, J. F., Steele, A., & Grassubeay, N. V. (2002). Questioning the evidence of Earth's oldest fossils. *Nature*, 416: 76-81.

Brasier, M. D., and Lindsay, J. F. (1998). A billion years of environmental stability and the emergence of eukaryotes: new data from northern Australia: *Geology*, 26: 555-558.

Brown, J. R., & Doolittle, W. F. (1997). Archaea and the prokaryote to eukaryote transition. *Microbiology and Molecular Biology Reviews*, 61: 465-487.

Brown, W. L., Augustyniak, W. M., Simmons, E., Marcantonio, K. J., Lnazerotti, L. J., Johnson, R. E., Reimann, C. T., Foti, G., & Porronello, V. (1982). Erosion and molecular formation in condensed gas films by electronic energy loss of fast ions. *Nuclear Instrumentation Methods*, 198: 1-8.

Budd, G. E. (2002). A palaeontological solution to the arthropod head problem. *Nature*, 417: 271-

275.

Byerly, G. R., Lowe, D. R., & Walsh, M. M. (1986). Stromatolites from the 3,300-3,500 Myr Swaziland Supergroup, Barberton Mountain Land, South Africa. *Nature*, 319: 489-491.

Caffee, M. W., Hudson, G. U., Velsko, C., Huss, G. R., Alexander, E. C., & Chivas, A. R. (1999). Primordial noble cases from Earth's mantle: Identification of a primitive volatile component. *Science*, 285: 2115-22118.

Carlson, R. W., Anderson, M. S., Johnson, R. E., Smythe, W. D., Hendrix, A. R., Barth, C. A., Soderblom, L. A., Hansen, G. B., McCord, T. B., Dalton, J. B., Clark, R. N., Shirley, J. H., Ocampo, A. C., & Matson, D. L. (1999). Hydrogen peroxide on the surface of Europa. *Science*, 283: 2062-2064.

Catling, D. C., Zahnle, K. J., & McKay, C. (2001). Biogenic methane, hydrogen escape, and the irreversible oxidation of early Earth. *Science*, 293: 839-843.

Cavalier-Smith, T. (2002). The phagotropic origin of eukaryotes and phylogenetic classification of Protozoa. *International Journal of Systematic and Evolutionary Microbiology*, 52: 297-354.

Chambers, J. E., & Lissauer, J. J. (2002). A new dynamical model for the Lunar late heavy bombardment. *33rd Annual Lunar and Planetary Science Conference March 11-15, 2002.*, Houston, Texas, abstract 109.

Chapman, C. R., Merline, W. J., Bierhaus, B., Keller, J., & Brooks, S. (1997). Impactor populations on the Galilean Satelites, American Astronomical Society, DPS meting 29, no. 12.10. *Bulletin of the American Astronomical Society*, 20: 984.

Charlou, J. L., & Donval, J. P. (1993). Hydrothermal methane venting between 12ºN and 26ºN along the Mid-Atlantic Ridge. *Journal of Geophysical Research*, 98: 9625-9642.

Chen, C.H., & Jura, M. (2001). A possible massive asteroid belt around zeta Leporis. *Astrophysical Journal*, 560: L171-L174.

Christensen, U. R., & Yuen, D. A. (1985). Layered convection induced by phase transitions. *Journal of Geophysical Research*, 90: 10,291-10,300.

Chupin, S. V., Chupin, V. P., Barton, J. M., & Barton, E. S. (1998). Archean melt inclusions in zircon from quartzite and granitic orthogneiss from South Africa - magma compositions and probable sources of protoliths. *European Journal of Mineralogy*, 10: 124-1251.

Chyba, C. F. (1990). Impact delivery and erosion of planetary oceans in the early inner solar system. *Nature*, 343: 129-133.

Chyba, C. F. (2000). Energy of microbial life on Europa. *Nature*, 403: 381-382.

Chyba, C. F., & Hand, K. P. (2001). Life without photosynthesis. *Science*, 292: 2026-2027.

Chyba, C. F., & McDonald, G. D. (1995). The origin of life in the solar system - current issues. *Annual Review of Earth, & Planetary Sciences*, 23: 215-249.

Chyba, C. F., & Phillips, C. B. (2001). Possible ecosystems and the search for life on Europa. *Proceedings of the National Academy of Sciences of the United States of America*, 98: 801-804.

Clayton, R. N. (2002). Self-shielding in the solar nebula. *Nature*, 415: 860-861.

Clayton, R. N., Grossman, L., & Mayeda, T. K. (1973). A component of primitive nuclear composition in carbonaceous meteorites. *Science*, 182: 485-488.

Clayton, R. N., & Mayeda, T. K. (1984). The oxygen isotope record in Murchison and other carbonaceous chrondrites. *Earth and Planetary Science Letters*, 67: 151-161.

Cloud, P. (1965). Significance of the Gunflint (Precambrian) microflora. *Science*, 148: 27-45.

Compston, W., & Pidgeon, R. T. (1986). Jack Kills, evidence of more very old detrital zircons in Western Australia. *Nature*, 321: 766-769.

Conrad, C. P. (1999). The thermal evolution of an Earth with strong subduction zones. *Geophysical Research Letters*, 26: 3041-3044.

Conway Morris, S., & J. S. Peel. 1995. Articulated halkieriids from the Lower Cambrian of north Greenland and their role in early protostome evolution. *Philosophical Transactions of the Royal Society of London B,* 347: 305-358.

Cooper, J. F., Johnson, R. E., Mauk, B. H., H.B., G., & Gehrels, N. (2001). Energetic ion and electron irradiation of the icy Galilean satellites. *Icarus*, 149: 133-159.

Costard, F. F., forget, N., Mangold, N., & Peulvast, J.P. (2002). formation of recent Martian debris flows by melting of near surface ground ice at high obliquity. *Science*, 295: 110-115.

Coveney, R. M., Goebel, E. D., Zeller, E. J., Dreschoff, G. A. M., & Angino, E. E. (1987). Serpentinization and the origin of hydrogen gas in Kansas. *American Assosciation of Petroleum Geologists Bulletin*, 71: 39-48.

Davaille, A. (1999). Simultaneous generation of hotspots and superswells by convection in a heterogeneous planetary mantle. *Nature*, 402: 756-760.

Davies, G. F. (1992). On the emergence of plate-tectonics. *Geology*, 20: 963-966.

Davies, G. F. (1995). Punctuated tectonic evolution of the Earth. *Earth and Planetary Science Letters*, 136: 363-379.

Dehler, C. M., Elrick, M. E., Karlstrom, K. E., Smith, G. A., Crossey, L. J., and Timmons, M. J. (2001). Neoproterozoic Chuar Group (~800-742 Ma), Grand Canyon: a record of cyclic marine deposition during global climatic and tectonic transitions. In: Eriksson, P. G., Catuneanu, O., Aspler, L. B., Chiarenzelli, J. R., and Martins-Neto, M. A., (Eds.), *The influences of magmatism, tectonics, sea-level change and paleoclimate on Precambrian basin evolution: change over time*: Sedimentary Geology, p. 465-499.

Dehler, C. M., Elrick, M. E., Karlstrom, K. E., Smith, G. A., Crossey, L. J., and Timmons, J. M. (2002). Chuar Group (~800 Ma-742 Ma), Grand Canyon: a record of cyclic marine deposition during global cooling and supercontinent rifting. *Sedimentary Geology*,141-142: 465-499.

Delaney, J. S., Dyar, M. D., Sutton, S. R., & Bajt, S. (1998). Redox ratios with relevant resolution - solving an old problem by using the synchrotron microxanes probe, *Geology*, 26: 139-142.

Delano, J. W. (2001). Redox history of the Earth's interior since ~3900 Ma: Implications for prebiotic molecules. *Origins of Life and Evolution of the Biosphere*, 31: 311-341.

Delitsky, M. L., & Lane, A. L. (1998). Ice chemistry on the Galilean satellites. *Journal of Geophysical Research*, 103: 31391-31403.

Delsemme, A. H. (2001). An argument for the cometary origin of the biosphere. *American Scientist*, 89: 432-442.

Dole, M. (1935). The relative atomic weight of oxygen in water and air. *Journal of the American Chemical Society*, 57: 2731.

Dyall, S. D., & Johnson, P. J. (2000). Origins of hydrogenosomes and mitochondrial: Evolution and organelle biogenesis. *Current Opinion in Microbiology*, 3: 404-411.

Edwards, S. F., & Wilkinson, D. R. (1982). The surface statistics of a granular aggregate. *Proceedings of the Royal Society of London A*, 381: 17-31.

Eiler, J.M., Kitchen, N., & Rahn, T.A. (2000). Experimental constraints on the stable isotope systematics of CO2 ice/vapor systems and relevance to the study of Mars. *Geochimica et Cosmochimica Acta*, 64: 733-746.

Fagents, S. A., Greeley, R., Sullivan, R. J., Pappalardo, R. T., Prockter, L. M., & Team, T. G. S. (2000). Cryomagmatic mechanisms for the formation of Rhadamanthys Linea, Triple Band Margins, and Other low-albedo features on Europa. *Icarus*, 144: 54-88.

Farley, K. A., Montanari, A., Shoemaker, E. M., & Shoemaker, C. S. (1998). Geochemical evidence for a comet shower in the Late Eocene. *Science*, 280: 1250-1253.

Farquhar, J. F., Wing, B. A., McKeegan, K. D., Harris, J. W., Cartigny, P., & Thiemens, M. H. (2002). Mass-independent sulfur of inclusions in diamond and sulfur recycling on early Earth. *Science*, 298: 2369-2372.

Farquhar, J., Bao, H. M., & Thiemens, M. (2000). Atmospheric influence of Earth's earliest sulfur cycle. *Science*, 289: 756-758.

Farquhar, J., Savarino, J., Airieau, S., & Thiemens, M. H. (2001). Observation of wavelength-sensitive mass-independent sulfur isotope effects during SO2 photolysis: Implications for the early atmosphere. *Journal of Geophysical Research-Planets*, 106: 32829-32839.

Farquhar, J., Thiemens, M.H., & Jackson, T. (1998). Atmosphere-surface interactions on Mars: D17O measurements of carbonate from ALH 84001. *Science*, 280: 1580-1582.

Feng, D. F., Cho, D., & Doolittle, R. F. (1997). Determining divergence times with a protein clock: update and reevaluation. *Proceedings of the National Academy of Sciences of the United States of America*, 61: 456-461.

Fitzgerald, R. (2003). Isotope ratio measurements firm up knowledge of Earth's formation. *Physics Today*, 56: 16-18.

Fitz-Gibbon, S. T., Ladner, H., Kim, U.-J., Stetter, K. O., Simon, M. I., & Miller, J. H. (2002). Genome sequence of the hyperthermophilic crenarchaeon Pyrobaculum aerophilum. *Proceedings of the National Academy of Sciences*, 99: 984-989.

Friedrich, M. W. (2002). Phylogenetic analysis reveals multiple lateral transfers of adenosine-5'-phosphosulfate reductase genes among sulfate-reducing microorganisms. *J Bacteriol*, 184: 278-89.

Gaidos, E. J., Nealson, K. H., & Kirschvink, J. L. (1999). Life in ice-covered oceans. *Science*, 284: 1631-1633.

Gao, Y. Q., & Marcus, R. (2001). Strange and unconventional isotope effects in ozone formations. *Science*, 293: 259-263.

Garity, G.M., & Holt, J.G. (2001) The road map to the manual. In *Bergey's manaual of systematic bacteriology*, 2: 119-141.

Gehling, J. G., Narbonne, G. M., & Anderson, M. M. (2000). The first named Ediacaran body fossil, *Aspidella terranovica*. *Palaeontology*, 43: 427-456.

Geissler, P. E., Greenberg, R., Hoppa, G., Helfenstein, P., McEwen, A., Pappalardo, R., Tufts, R., Ockert-Bell, M., Sullivan, R., Greeley, R., Belton, M. J. S., Denk, T., Clark, B., Burns, J., & Veverka, J. (1998). Evidence of non-synchronous rotation of Europa. *Nature*, 391: 368-370.

Gersonde, R., Kyte, F. T., Bleil, U., Diekmann, B., Flores, J. A., Gohl, K., Grahl, G., Hagen, R., Kuhn, G., Sierro, F. J., Völker, D., Abelmann, A., & Bostwick, J. A. (1997). Geological record and reconstruction of the late Pliocene impact of the Eltanin asteroid in the Southern Ocean. *Nature*, 390: 357-363.

Gilmour, J. D., Lyon, I. C., Johnston, W. A., & Turner, G. (1994). Relax - an ultrasensitive, resonance ionization mass spectrometer for xenon. *Review of Scientific Instruments*, 65: 617-625.

Goldsby, D. L., & Kohlstedt, D. L. (2001). Superplastic deformation of ice: Experimental observations. *Journal of Geophysical Research*, 106: 11017-11030.

Gould, S. J., (1989). *Wonderful Life: The Burgess Shale and the Nature of History*. W. W. Norton, New York.

Gray, M.W., Burger, G., & Lang, B.F. (1999). Mitochondrial evolution. *Science*, 283: 1476-1481.

Grazier, K., Newman, W. I., Kaula, W. M., Varadi, F., & Hyman, J. M. (1999). Dynamical evolution of Planetesimals in the outer solar system: II The Saturn/Uranus and Uranus/Neptune zones. *Icarus*, 140: 353-368.

Greenberg, R., Geissler, P., Tufts, B. R., & Hoppa, G. V. (2000). Habitability of Europa's crust: The role of tidal-tectonic processes. *Journal of Geophysical Research*, 105: 17551-17562.

Greenwood, J. P., Mojzsis, S. J., & Coath, C. (2000). Sulfur isotopic compositions of individual sulfides in Martian meteorites ALH84001 and Nakhla: Implications for crust-regolith exchange on Mars. *Earth and Planetary Science Letters*, 184: 23-35.

Grotzinger, J. P., & Rothman, D. H. (1996). An abiotic model for stromatolite morphogenesis. *Nature*, 383: 423-425.

Gubbins, D. (2001). The Rayleigh number for convection in the Earth's core. *Physics of the Earth, & Planetary Interiors*, 128: 3-12.

Gupta, R.S., Golding, G.B., & Singh, B. (1994). HSP40 phylogeny and the relationship between Archaebacteria, Eubacteria, and eukaryotes. *Journal of Molecular Evolution*, 39: 537-540.

Haberle, R. M., Tyler, D., McKay, C. P., & Davis, W. L. (1994). A model for the evolution of CO2 on Mars. *Icarus*, 109: 102-120.

Haghighipour, N., Couetdic, J., Varadi, F., & Moore, W. (Submitted, 2003). Stable 1:2 resonant periodic orbits in elliptic three-body systems. *Astrophysical Journal*,

Halliday, A. N., & Porcelli, D. (2001). In search of lost planets - the paleocosmochemistry of the inner solar system. *Earth and Planetary Science Letters*, 192: 545-559.

Hanyk, L., Yuen, D. A., & Matyska, C. (1996). Initial-value and modal approaches for transient viscoelastic responses with complex viscosity profiles. *Geophysical Journal - International*, 127: 348-362.

Harper, C. L., & Jacobsen, S. B. (1992). Evidence from coupled SM-147 ND-143 and SM-146 ND-142 systematics for very early (4.5 Gyr) differentiation of the Earths mantle. *Nature*, 360: 728-732.

Hartman, H., & Federov, A. (2002). The origin of the eukaryotic cell: a genomic investigation. *Proceedings of the National Academy of Sciences in the United States of America*, 99: 1420-1425.

Hass, W. 1981. Evolution of calcareous hardparts in primitive molluscs. *Malacologia,* 21:403-418.

Hayes, J. M., Kaplan, I. R., & Wedeking, K. W. (1983). Precambrian organic geochemistry, preservation of the record. In: Schopf, J.W. (Eds.), *Earth's Earliest Biosphere, Its Origin and Evolution* (pp. 93-134). Princetion, New Jersey Princeton University Press

Herrera, T. A., Manning, C. E., & House, C. H. (2003). Growth of Methanopyrus handleri during serpentinization of olivine. *NASA NAI General Meeting abstr.* 12665.

Hirth, G. , & Kohlstedt, D. L. (1996). Water in the oceanic upper mantle: implications for rheology, melt extraction and the evolution of the lithosphere. *Earth and Planetary Science Letters*, 144: 93-108.

Hofmann, H. J., Grey, K., Hickman, A. H., & Thorpe, R. I. (1999). Origin of 3.45 Ga coniform stromatolites in Warrawoona Group, Western Australia. *Geological Society of America Bulletin*, 111: 1256-1262.

Holland, H. D. (2002). Volcanic gases, black smokers, and the Great Oxidation Event. *Geochimica et Cosmochimica Acta*, 66: 3811-3826.

Holland, W.S., Greaves J.S., Dent W.R.F., Wyatt, W.C., & Zuckerman B., et al. (2003). Submillimeter observations of an asymmetric dust disk around Fomalhaut. *Astrophysical Journal*, 582: 1141-1146.

Holmer, L. E., C. B. Skovsted, & Williams, A. (2002). A stem group brachiopod from the Lower Cambrian: support for a *Micrina* (halkieriid) ancestry. *Palaeontology*, 45:875-882.

Honda, M., McDougall, I., Patterson, D. B., Doulgeris, A., & Clague, D. A. (1991). Possible solar noble-gas component in Hawaiian Basalts. *Nature*, 349: 149-151.

Hoppa, G. V., Tufts, B. R., Greenberg, R., & Geissler, P. E. (1999). Formation of cycloidal features on Europa. *Science*, 285: 1899-1902.

Horneck, G., Krasavin, E., & Kozubek, S. (1994). Matagenic effects of heavy ions in bacteria. *Advanced Space Research*, 14: 315-329.

Horner, D. S., Heil, B., Happe, T., & Embley, T. M. (2002). Iron hydrogenases - ancient enzymes in modern eukaryotes. *Trends in Biochemical Sciences*, 27: 148-153.

House, C. H., & Fitz-Gibbon, S. T. (2002). Using homolog groups to create a whole-genomic tree of free-living organisms: An update. *Journal of Molecular Evolution*, 54: 539-547.

House, C. H., Runnegar, B., & Fitz-Gibbon, S. T. (Submitted 2002). Geobiological analysis using whole genome-based tree building applied to the Bacteria, Archaea, and Eukarya. *Geobiology*.

House, C. H., Schopf, J. W., McKeegan, K. D., Coath, C. D., Harrison, T. M., & Stetter, K. O. (2000). Carbon isotopic composition of individual Precambrian microfossils. *Geology*, 28: 707-710.

Hugenholtz, P. (2002). Exploring prokaryotic diversity in the genomic era. *Genome Biol* 3, Reviews 0003.

Hure, J. M. (2000). On the transition to self-gravity in low mass AGN and YSO accretion disks. *Astronomy, & Astrophysics*, 358: 378-394.

Itoh, T., Suzuki, K., Sanchez, P. C., & Nakase, T. (1999). Caldivirga maquilingensis gen. nov., sp. nov., a new genus of rod-shaped crenarchaeote isolated from a hot spring in the Philippines. *Int J Syst Bacteriol,* 49 Pt 3: 1157-63.

Itoh, T., Suzuki, K., & Nakase, T. (1998). Thermocladium modestius gen. nov., sp. nov., a new genus of rod-shaped, extremely thermophilic crenarchaeote. *Int J Syst Bacteriol,* 48 Pt 3: 879-87.

Jacobs. D. K. (2002). Biases and biology produce spurious early molecular divergence dates for the metazoan radiaition: A test by outgroup comparison. *Geological Society of America Annual Meeting Abstracts with Programs*, 34: 266.

Jacobs, D.K., & Gates, R.D. (2001). Evolution of POU/homeodomains in basal metazoa: Implications for the evolution of sensory systems and the pituitary. *Developmental Biology*, 235: 323

Jacobs, D. K., Wray, C. G., Wedeen, C. J., Kostriken, R., DeSalle, R., Staton, J. L., Gates, R. D., & Lindberg, D. R. (2000). Molluscan engrailed expression, serial organization, and shell evolution. *Evolution, & Development*, 2: 340-347.

Jain, R., Rivera, M. C., & Lake, J. A. (1999). Horizontal gene transfer among genomes: The complexity hypothesis. *Proceedings of the National Academy of Sciences of the United States of America*, 96: 3801-3806.

Jakosky, B.M. (1993). Mars volatile evolution - implications of the recent measurement of O-17 in water from the SNC meteorites. *Geophysical Research Letters*, 20: 1591-1594.

Janecky, D. R., & Seyfried, W. E., Jr. (1986). Hydrothermal serpentinization of peridotite within the oceanic crust: Experimental investigations of mineralogy and major element chemistry. *Geochimica et Cosmochimica Acta*, 50: 1357-1378.

Javaux, E. J., Knoll, A. H., and Walter, M. R. (2001). Morphological and ecological complexity in early eukaryotic ecosystems. *Nature*, 412: 66-69.

Jayawardhana, R., & Greene, T. (2001). Young stars near earth: Progress and prospects. *Astronomical Society of the Pacific*. 244: San Francisco, California.

Jell, P. A. (1981). *Thambetolepis delicata* gen. et sp. nov., an enigmatic fossil from the Early Cambrian of South Australia. *Alcheringa*, 5: 85-93.

Jögi, P. M., & Runnegar, B. N. (2002). Theoretical support for biological activity in ancient stromatolites. *Astrobiology*, 2: 616.

Kardar, M., Parisi, G., & Zhang, Y-C. (1986). Dynamic scaling of growing interfaces. *Physical Review Letters*, 56: 889-892.

Karlstrom, K. E., Bowring, S. A., Dehler, C. M., Knoll, A. H., Porter, S. M., Marais, D. J. D., Weil, A. B., Sharp, Z. D., Geissman, J. W., Elrick, M. B., Timmons, J. M., Crossey, L. J., and Davidek, K. L. (2000). Chuar Group of the Grand Canyon: record of breakup of Rodinia, associated change in the global carbon cycle, and ecosystem expansion by 740 Ma. *Geology*, 28: 619-622.

Kasting, J. F., Eggler, D. H., & Raeburn, S. P. (1993a). Mantle redox evolution and the oxidation-state of the Archean atmosphere. *Journal of Geology*, 101: 245-257.

Kasting, J. F., Whitmire, D. P., & Reynolds, R. T. (1993b). Habitable zones around main sequence stars. *Icarus*, 101: 108-128.

Kasting, J. F., Zahnle, K., J., Pinto, J. P., & Young, A. T. (1989). Sulfur, ultaviolet-radiation, and the early evolution of life. *Origins of Life and Evolution of the Biosphere*, 19: 95-108.

Kelley, D. S. (1996). Methane-rich fluids in the oceanic crust. *Journal of Geophysical Research*, 101: 2943-2962.

Kelley, D. S., Baross, J. A., & Delaney, J. R. (2002). Volcanoes, fluids, and life at mid-ocean ridge spreading centers. *Annual Review of Earth, & Planetary Sciences*, 30: 385-491.

Kempe, A., Schopf, J. W., Altermann, W., Kudrysvtsev, A. B., & Heckl, W. M. (2002). Atomic force microscopy of Precabrian fossils. *Proceedings of the National Academy of Sciences of the United States of America*, 99: 9117-9120.

Kilinc, A., Carmichael, I. S. E., Rivers, M. L., & Sack, R. O. (1983). The ferric-ferrous ratio of natural silicate liquids equilbrated in air. *Contributions to Mineralogy, & Petrology*, 83: 136-140.

Knoll, A. H., & Barghoon, E. S. (1977). Archean microfossils showing cell division from the Swaziland System of South Africa. *Science*, 198: 396-398.

Koonin, E. V., Mushegian, A. R., Galperin, M. Y., & Walker, D. R. (1997). Comparison of archaeal and bacterial genomes: computer analysis of protein sequences predicts novel functions and suggests a chimeric origin for the archaea. *Molecular Microbiology*, 25: 619-637.

Kudryavtsev, A. B., Schopf, J. W., Agresti, D. G., & Wdowiak, T. J. (2001). *In situ* laser-Raman imagery of Precambrian microscopic fossils. *Proceedings of the National Academy of Sciences of the United States of America*, 98: 823-826.

Kump, L. R., Kasting, J. F., & Barley, M. E. (2001). Rise of atmospheric oxygen and the "upside-down" Archean mantle. *Geochemistry Geophysics Geosystems*, 2: NIL-1-NIL-10.

Kunz, J., Staudacher, T., & Allegre, C. J. (1998). Plutonium-fission xenon found in Earths mantle. *Science*, 280: 877-880.

Kutzner, C., & Christensen, U. R. (2002). From stable dipolar towards reversing numerical dynamos. *Physics of the Earth, & Planetary Interiors*, 131: 29-45.

Kyte, F. T. (1998). A meterorite from the Cretaceous-tertiary boundary. *Nature*, 396: 237-239.

Kyte, F. T. (2002a). Composition of impact melt debris from the Eltanin impact strewn field, Bellingshausen Sea. *Deep-Sea Research II*, 49: 1029-1047.

Kyte, F. T. (2002b). Iridium concentrations and abundances of meteoritic ejecta from the Eltanin impact in sediment cores from *Polarstern* expedition ANT XII/4. *Deep-Sea Research II*, 49: 1049-1061.

Kyte, F. T. (2002c). Unmelted meteoritic debris collected from Eltanin ejecta in *Polarstern* cores from expedition ANT XII/4. *Deep-Sea Research II*, 49: 1063-1071.

Kyte, F. T., Gersonde, R., & Kuhn, G. (2003). Were ocean impacts an improtant mechanism to deliver meteoritic organic matter to the early Earth? Some inferences from Eltanin. *NASA NAI General Meeting*, abstr. no. 12622.

Kyte, F. T., Shukolyukov, A., Lugmair, G., Lowe, D. R., & Byerly, G. R. (2003). Early Archean spherule beds: Chromium isotopes confirm origin through multiple impacts of carbonaceous chondrite type projectiles. *Geology*, in press.

Labrosse, S., Poirier, J. P., & LeMouel, J. L. (1997). On cooling of the Earth's core. *Physics of the Earth, & Planetary Interiors*, 99: 1-17.

Lake, J. A., Jain, R., & Rivera, M. C. (1999). Mix and match in the tree of life. *Science*, 283: 2027-2028.

Lake, J. A., & Moore, J. E. (1998). Phylogenetic analysis and comparative genomics. *Trends Guide To Bioinformatics*, Supplement S: 22-23.

Larsen, T. B., & Yuen, D. A. (1997). Fast plumeheads-Temperature-dependent versus non-Newtonian rheology. *Geophysical Research Letters*, 24: 1995-1998.

Laskar, J., Levrard, B., & Mustard, J. F. (2002). Orbital forcing of the Martian polar layered deposits. *Nature*, 419: 375-377.

Lecar, M., Franklin, F. A., Holman, M. J., & Murray, N. J. (2001). Chaos in the Solar System. *Annual Review of Astronomy, & Astrophysics*, 39: 581-631.

Lécuyer, C., & Ricard, Y. (1999). Long-term fluxes and budget of ferric iron: Implication for the redox states of the Earth's mantle and atmosphere. *Earth and Planetary Science Letters*, 165: 197-211.

Levison, H. F., Dones, L., Chapman, C. R., Stern, S. A., Duncan, M. J., & Zahnle, K. (2001). Could the Lunar late heavy bombardment have been triggered by the formation of Uranus and Neptune? *Icarus*, 151: 286-306.

Lowe, D. R., & Byerly, G. R. (1986). Early archaen silicate spherules of probable impact origin, South Africa and Western Australia. *Geology*, 14: 83-86.

Lowe, D. R., Byerly, G. R., Kyte, F. T., Shukolyukov, A., Asaro, F., & Krull, A. (2003). Spherule beds 3.47-3.24 billion years old in the Barberton greenstone belt, South Africa: A record of large meteorite impacts and their influence on early crustal and biologival evolution. *Astrobiology*, in press.

Luz, B., Angert, A., Barkan, E., and Bender, M.L. (2002). How large is the mass independent O-17 anomaly in the atmosphere? *Transations of the American Geophysical Union EOS*, 83: B61D-05.

Luz, B., Barkan, E., Bender, M.L., Thiemens, M.H., and Boering, K.A. (1999). Triple-isotope composition of atmospheric oxygen as a tracer of biosphere productivity. *Nature*, 400: 547-550.

Lyons, J. R. (2001). Transfer of mass-independent fractionation in ozone to other oxygen-containing radicals in the atmosphere. *Geophysical Research Letters*, 28: 3231-3234.

Lyons, P. D., Rioux, M., & Patterson, R.T. (2000). Application of a three-dimensional color laser scanner to paleontology: an interactive model of a juvenile Tylosaurus sp.

basisphenoid-basioccipital. *Palaeontologica Electronica* 3(2).

Maas, R., Kinny, P. D., Williams, I. S., Froude, D. O., & Compston, W. (1992). The Earth's oldest known crust - a geochronological and geochemical study of 3900-4200 MA old detrital zircons from Mt. Narryer and Jack Hills, Western Australia. *Geochimica et Cosmochimica Acta*, 56: 1281-1300.

Macintosh, B., Max, C., Zuckerman, B., Becklin, E. E., Kaisler, D., Lowrance, P., Weinberger, A., Christou, J., Schneider, G., & Acton, S. (2001). Keck Adaptive Optics observations of TW Hydrae Association Members. *Astronomical Society of the Pacific*. 244: 309. San Francisco, California.

Malin, M. C., & Edgett, K. S. (2000). Sedimentary rocks of early Mars. *Science*, 2990: 1927-1937.

Manga, M., & Nimmo, F. (2002). Causes, characteristics and consequences of convective diapirism on Europa. *Geophysical Research Letters*, 29:

Marcotte, E. M., Xenarios, I., van de Bliek, A. M., & Eisenberg, D. (2000). Localizing proteins in the cell from their phylogenetic profiles. *Proceedings of the National Academy of Sciences of the United States of America*, 97: 12115-12120.

Marcy, G.W., Cochran, W.D., & Mayor, M. (2002). Extrasolar planets around main-sequence stars. In: Mannings et al. (Eds.), *Protostars and Planets IV* , (pp. 1285-1312). Tucson, University of Arizona Press.

Marin, F., Smith, M., Isa, Y., Muyzer, G., &. Westbroek., P. (1996). Skeletal matrices, muci, and the origin of invertebrate calcification. *Proceedings of the National Academy of Sciences of the United States of America*, 93: 1554-1556.

Martin, W., & Muller, M. (1998). The hydrogen hypothesis for the first eukaryote. *Nature*, 392: 37-41.

Martin, W., Rujan, T., Richly, E., Hansen, A., Cornelsen, S., Lins, T., Leister, D., Stoebe, B., Hasegawa, M., & Penny, D. (2002). Evolutionary analysis of Arabidopsis, cyanobacterial, and chloroplast genomes reveals plastid phylogeny and thousands of cyanobacterial genes in the nucleus. *Proceedings of the National Academy of Sciences of the United States of America*, 99: 12246-12251.

Mauersberger, K., Erbacher, B., Krankowsky, D., Gunther, J., & Nickel, R. (1999). Ozone isotope enrichment: Isotopomer-specific rate coefficients. *Science*, 283: 370-372.

McCabe, C., Duchene, and Ghez, A.M. (2003). The first detection of spatially resolved mid-infrared scattered light from a proto-planetary disk. *Astrophysical Journal,* submitted.

McKay, C. P. (1997). The search for Life on Mars. *Origins of Life and Evolution of the Biosphere*, 27: 263-289.

Mendelson, C. V., & Schopf, J. W. (1992). Proterozoic and selected Early Cambrian microfossils and microfossil-like objects. In J.W. Schopf' and C. Klein (Eds.). *The Proterozoic Biosphere, A Multidisciplinary Study*. (pp. 865-951). New York Cambridge University Press

Mischna, M. A., & Newman, W. I. (In preparation). Atmospheric accretion of airless planets: The role of oblique impact events.

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

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

Moore, M. H., & Hudson, R. L. (2000). IR detection of H202 at 80 K in ion-irradiated laboratory ices relevent to Europa. *Icarus*, 145: 282-288.

Morbidelli, A., Petit, J. M., Gladman, B., & Chambers, J. (2001). A plausible cause of the late heavy bombardment. *Meteoritics, & Planetary Science*, 36: 371-380.

Muir, M. D., & Grant, P. R. (1976). Micropaleontological evidence from the Onverwacht Group, South Africa. In: B.F. Windley (Eds.). *The Early History of the Earth* (pp. 595-604). Wiley, London.

Murray, N., Hansen, B., Holman, M., & Tremaine, S. (1998). Migrating planets. *Science*, 279: 69-72.

Mumma, M. J., Dello Russo, N., DiSanti, M. A., Magee-Sauer, K., Novak, R. E., Brittain, S., Rettig, T., McLean, I. S., Reuter, D. C., & Xu, L. H. (2001). Organic composition of C/1999 S4 (Linear): A comet formed near Jupiter? *Science*, 292: 1334-1339.

Narbonne, G. M., & Gehling, J. G. (2003). Life after snowball: The oldest complex Ediacaran fossils. *Geology*, 31: 27-30.

Navon, O., & Wasserburg, G. J. (1985). Self-shielding in O2-a possible explanation for oxygen isotopic anomalies in meterorites? *Earth and Planetary Science Letters*, 73: 1-16.

Newman, W. I., Symbalisty, E. M. D., Ahrens, T. J., & Jones, E. M. (1999). Impact erosion of planetary atmospheres: Some surprising results. *Icarus*, 138: 224-240.

Nimmo, F., & Gaidos, E. (2001). Thermal consequences of strike-slip motion on Europa. *Journal of Geophysical Research*, 107: 10.1029

Nimmo, F., & Stevenson, D. J. (2000). Influence of early plate tectonics on the thermal evolution and magnetic field of Mars. *Journal of Geophysical Research*, 105: 11969-11980.

Nimmo, F., & Stevenson, D. J. (In Press, 2002). Why does Venus lack a magnetic field? *Geology*,

Nimmo, F., Pappalardo, R. T., & Giese, B. (2002). Effective elastic thickness and heat flux estimates on Ganymede. *Geophysical Research Letters*, 107:

Nutman, A. P., Mojzsis, S. J., & Friend, C. R. L. (1997). Recognition of greater-than-or-equal-to 3850 MA water-lain sediments in West Greenland and their significance for the early archaean Earth. *Geochimica et Cosmochimica Acta*, 61: 2475-2484.

O'Keefe, J. D., & Ahrens, T. J. (1977). Impact-induced energy partitioning, melting, and vaporization on terrestrial planets. *Proceedings of the Lunar Science Conference, VIII.* 3: 3357-3374. Houston, Texas.

Olsen, P. E., Kent, D. V., Sues, H. D., Koeberl, C., Huber, H., Montanari, A., Rainforth, E. C., Fowell, S. J., Szajna, M. J., & Hartline, B. W. (2002). Ascent of dinosaurs linked to an iridium anomaly at the Triassic-Jurassic boundary. *Science*, 296: 1305-1307.

Olson, P., & Christensen, U. R. (In Press, 2002). Effects of heterogeneous heat flux on numerical dynamo models. *Geophsical Journal - International*,

Orphan, V. J., House, C. H., Hinrichs, K., McKeegan, K. D., & DeLong, E. F. (2001). Methane-consuming archaea revealed by directly coupled isotopic and phylogenetic analysis. *Science*, 293: 484-487.

Pappalardo, R. T., Belton, M. J. S., Breneman, H. H., Carr, M. H., Chapman, C. R., Collins, G. C., Denk, T., Fagents, S., Geissler, P. E., Giese, B., Greeley, R., Greenburg, R., Head, J. W., Helfenstein, P., & Hoppa, G. (1999). Does Europa have a subsurface ocean? Evaluation of the goelogical evidence. *Journal of Geophysical Research*, 104: 24015-24056.

Pappalardo, R. T., Head, J. W., Greeley, R., Sullivan, R. J., Pilcher, C., Schubert, G., Moore, W. B., Carr, M. H., Moore, J. M., & Belton, M. J. S. (1998). Geological evidence for solid-state convection in Europa's ice shell. *Nature*, 391: 365-368.

Paranicas, C., Mauk, B. H., Ratliff, J. M., Cohen, C., & Johnson, R. E. (2002). The ion environment near Europa and its role in surface energetics. *Geophysical Research Letters*, 29: 1-4.

Pavlov, A. A., & Kasting, J. F. (2002). Mass-independent fractionation of sulfur isotopes in Archean sediments: Strong evidence for an ananoxic Archean atmosphere. *Astrobiology*, 2: 27-41.

Peck, W. H., Valley, J. W., Wilde, S. A., & Graham, C. M. (2001). Oxygen isotope ratios and rare earth elements in 3.3 to 4.4 Ga zircons: Ion microprobe evidence for high delta 0-18 continental crust and oceans in the Early Archean. *Geochimica et Cosmochimica Acta*, 65: 4215-4229.

Peterson, K. J., & Eernisse, D. J. (2001). Animal phylogeny and the ancestry of bilaterians: inferences from morphology and 18S rDNA gene sequences. *Evolution and Development*, 3: 170-204.

Peterson, K. J., & Takacs, C. M. (2002). Molecular clocks, snowball earth, and the Cambrian explosion. *Annual Meeting of the Society for Integrative and Comparative Biology*. 41: 1554. Anaheim, California.

Pierazzo, E., & Chyba, C. F. (1999). Amino acid survival in large cometary impacts. *Meteoritics, & Planetary Science*, 34: 909-918.

Pierazzo, E., & Melosh, H. J. (2000). Understanding oblique impacts from experiments, observations, and modeling. *Annual Review of Earth and Planetary Science*, 28: 141-167.

Podosek, F. A. (1972). Gas retention chronology of Petersburg and other meteorites. *Geochimica et Cosmochimica Acta*, 36: 755-772.

Pollack, J. B., Hollenbach, D., Beckwith, S., Simonelli, D. P., Roush, T., & Fong, W. (1994). Composition and radiative properties of grains in molecular clouds and accretion disks. *Astrophysical Journal*, 421: 615-639.

Porter, S. M. (in press). Halkieriids in Middle Cambrian phosphatic limestones from Australia. *Journal of Paleontology*.

Porter, S. M. (2002). Windows on Early Eukaryotic and Early Animal Life. Ph.D. Thesis, Harvard University, 217 pp.

Porter, S. M., Meisterfeld, R., and Knoll, A. H. (2003). Vase-shaped microfossils from the Neoproterozoic Chuar Group, Grand Canyon: a classification guided by modern testate amoebae. *Journal of Paleontology*, in press.

Porter, S. M., and Knoll, A. H. (2000). Testate amoebae in the Neoproterozoic Era: evidence from vase-shapes microfossils in the Chuar Group, Grand Canyon. *Paleobiology*, 26: 360-385.

Rasmussen, B. (2000). Filamentous microfissils in a 3,235-million-year-old volcanogenic massive sulphide deposit. *Nature*, 405: 676-679.

Rivera, M. C., Jain, R., Moore, J. E., & Lake, J. A. (1998). Genomic evidence for two functionally distinct gene classes. *Proceedings of the National Academy of Sciences of the United States of America*, 95: 6239-6244.

Rivera, M.C., & Lake, J.A. (1992). Evidence that eukaryotes and eocyte prokaryotes are immediate relatives. *Science*, 257: 74-76.

Rocha, E. P., Sekowska, A., & Danchin, A. (2000). Sulphur islands in the Escherichia coli genome: markers of the cell's architecture? *FEBS Lett* 476, 8-11.

Roger, A. J. (1999). Reconstructiong early events in eukaryotic evolution. *American Naturalist*, 154: S146-S163.

Roger, A.J., & Silberman, J.D. (2002). Mitochondria in hiding. *Nature*, 418: 827-828.

Rona, P. A., Bougault, H., Charlou, J. L., Appriou, P., Nelsen, T. A., Trefry, J. H., Eberhart, G. L., Barone, A., & Needham, H. D. (1992). Hydrothermal circulation, serpentinization, and degassing at a rift-valley fracture-zone intersection - mid-Atlantic ridge near 15°N, 45°W. *Geology*, 20: 783-786.

Rost, M., Smilauer, P., & Krug, J. (1996). Unstable epitaxy on vicinal surfaces. *Surface Science*, 369: 393-402.

Ruiz, J. M. G., Carnerup, A., Crristy, A. G., Welham, N. J., & Hyde, S. T. (2002). Morphology: An ambiguous indicator of biogencity. *Astrobiology*, 2: 353-369.

Runnegar, B., Coath, C. D., Lyons, J. R., Manning, C. E., & McKeegan, K. D. (2002). Mass-independent fractionations of four sulfur isotopes as tracers of Archean base metal and gold ore-forming fluids. *Geological Society of America Abstracts with Programs*, 34(6): 516.

Runnegar, B. (2000). Body building in *Halkeria* and comparisons with chitons and other molluscs. *Geological Society of America Abstracts with Programs*, 32: A72.

Runnegar, B., Coath, C. D., Mojzsis, S. J., Farquhar, J., Lyons, J. R., McKeegan, K. D., & Harrison, T. M. (2001a). Sulfur isotope evidence for atmospheric but not bacterial processes in formation of early Archean sedimentary sulfides and sulfates. *Geological Society of America Abstracts with Programs*, 33(6): A-95

Runnegar, B., Dollase, W. A., Ketcham, R. A., Colbert, M., & Carlson, W. D. (2001b). Early Archean sulfates from Western Australia first formed as hydrothermal barites not gypsum evaporites. *Geological Society of America Abstracts with Programs*, 33(6): A-404.

Ryder, G. (1990). Lunar samples, lunar accretion and the early bombardment of the moon. *EOS*, 71: 322-333.

Seaver, E. C., & Martindale, M. Q. (2002). Engrailed expression in three polychaete annelids: A possible role in chaetogenesis. *Developmental Biology*, 247: 519.

Schenk, P. M. (2002). Thickness constraints on the icy shells of the Galilean satellites from a comparison of crater shapes. *Nature*, 417: 419-421.

Scherbenski, J.M., & Paige, D.A. (2002). Mars polar thermal inertia and albedo properties using TES data. *Transations of the American Geophysical Union EOS*, 83: P27C-04.

Schopf, J. W. (1992a). Paleobiology of the Archean. In Schopf, J.W., Klein, C. (Eds). *The Proterozoic Biosphere, A Multidisciplinary Study* (pp. 25-39). New York Cambridge Univesity Press.

Schopf, J. W. (1992b). Proterozoic prokaryotes: Affinities, geologic distribution, and evolutionary trends. In: J.W. Schopf and C. Klein (Eds). *The Proterozoic Biosphere, A multidisiplinary Study* (pp. 195-218). New York.

Schopf, J. W. (1993). Microfossils of the Early Archean Apex chert: New evidence of the antiquity of life. *Science*, 260: 640-646.

Schopf, J. W., Kudryavtsev, A. B., Agresti, D. G., Czaja, A. D., & Wdowiak, T. J. (In Press). Laser-Raman chemistry and organic metamorphism of Precambrian microscopic fossils. *Precambrian Research*.

Schopf, J. W., Kudryavtsev, A. B., Agresti, D. G., Wdowiak, T. J., & Czaja, A. D. (2002a). Images of Earth's earliest fossils? - reply. *Nature*, 420: 477.

Schopf, J. W., Kudryavtsev, A. B., Agresti, D. G., Wdowiak, T. J., & Czaja, A. D. (2002b). Laser-Raman imagery of Earth's earliest fossils. *Nature*, 416: 73-76.

Schopf, J. W., & Packer, B. M. (1987). Early Archean (3.3-billion to 3.5-billiion years old) microfossils from Warrawoona Group, Australia. *Science*, 237: 70-73.

Schopf, J. W., & Walter, M. R. (1983). Archean microfossils: New evidence of ancient microbes. In J.W. Schopf (Eds.). *Earth's Earliest biosphere, Its Origin and Evolution* (pp. 214-239). Princeton, New Jersey Princetion University Press

Seaver, E. C., & Martindale, M. Q. (2002). Engrailed expression in three polychaete annelids: A possible role in chaetogenesis. Sixty-first annual meeting of the Society for Developmental Biology. Madison, Wisconsin. *Developmental Biology*, 247: 519.

Sheffer, Y., Lambert D.L., & Federman, S.R. (2002). Ultraviolet detection of interstellar 12C17O and the CO isotopomeric ratios twoard X Persei. *Astrophysical Journal*, 574: L171-L174.

Shen, Y., Buick, R., & Canfield, D. E. (2001). Isotopic evidence for microbial sulfate reduction in the early Archean era. *Nature*, 410: 77-81.

Shizgal, B. D., & Arkos, G. G. (1996). Nonthermal escape of the atmospheres of Venus, Earth, and Mars. *Reviews of Geophysics*, 34: 483-505.

Shu, F. H., Shang, H., Glassgold, A. E., & Lee, T. (1997). X-rays and fluctuating X-winds from protostars. *Science*, 277: 1475-1479.

Shuping, R.Y., Chiar, J.E., Snow T.P., & Kerr, T. (2001). Direct measurement of the CO depletion in the Elias 18 circumstellar disk. *Astrophysical Journal*, 547: L161-L164.

Sleep, N. H., & Zahnle, K. (1998). Refugia from asteroid impacts on early Mars and the early Earth. *Journal of Geophysical Research*, 103: 28529-28544.

Sleep, N. H., & Zahnle, K. (2001). Carbon dioxide cycling and implications for climate on ancient Earth. *Journal of Geophysical Research*, 106: 1373-1399.

Slesarev, A. I., Mezhevaya, K. V., Makarova, K. S., Polushin, N. N., Shcherbinina, O. V., Shakhova, V. V., Belova, G. I., Aravind, L., Natale, D. A., Rogozin, I. B., Tatusov, R. L., Wolf, Y. I., Stetter, K. O., Malykh, A. G., Koonin, E. V., & Kozyavkin, S. A. (2002). The complete genome of hyperthermophile Methanopyrus kandleri AV19 and monophyly of archaeal methanogens. *Proceedings of the National Academy of Sciences of the United States of America*, 99: 4644-4649.

Smilauer, P., Rost, M., & Krug, J. (1999). Fast coarsening in unstable epitaxy with desorbtion. *Physical Review E*, 59: R6263-R6266.

Song, I., Zuckerman, B., & Bessell, M. S. (Submitted, 2003). New members of the TW Hydrae, Beta Pictoris moving group, and Tucana/Horoloquim Association. *Astrophysical Journal,*

Staudacher, T. H., & Allegre, C. J. (1982). Terrestrial xenology. *Earth and Planetary Letters*, 60: 389-406.

Stern, S. A., & Levison, H. F. (1999). A warm early Mars and CO2 influx from the late heavy bombardment. 30th Annual Lunar and Planetary Science Conference, March 15-29. Houston, Texas. Abstract #1141

Strauss, H., Des Marais, D. J., Hayes, J. M., & Summons, R. E. (1992). Concentrations of organic carbon and maturities, and elemental compositions of kerogens. In: J.W. Schopf and C. Klein (Eds). *The Proterozoic Biosphere, A Multidisciplinary Study.* (pp. 95-99). New York Cambridge University Press

Strauss, H., & Moore, T. B. (1992). Abundances and isotopic compositions of carbon and sulfur species in whle rock and kerogen samples: In J.W. Schopf and C Klein (Eds.). *The Proterozoic Biosphere, A Multidisciplinary Study.* (pp. 709-798). New York Cambridge University Press

Strom, R. G., Woronow, A., & Gurnis, M. (1981a). Crater populations and Ganymede and Callisto. *Journal of Geophysical Research*, 86: 8659-8674.

Szathmary, E., & Maynard Smith, J. (1995). The major evolutionary transitions. *Nature*, 374: 2270232.

Tackley, P. J. (1995a). Influence of the transition zone. *US National Report to the IUGG, 1991-1994.*, 275-282.

Tackley, P. J. (1995b). Mantle dynamic-influence of the transition zone, *US National Report to the IGUU, 1991-1994. Reviews of Geophysics*, 33: 275-282.

Tackley, P. J. (2000a). Mantle convection and plate tectonics: Toward an integrated physical and chemical theory *Science*, 288: 2002-2007.

Tackley, P. J. (2000b). Self-consistent generation of tectonic plates in time-dependent, three-dimensional mantle convection simulations, Part1: Pseudo-plastic yielding. Paper number 2000GC000036. *Geochemistry Geophysics Geosystems*, 1:

Tackley, P. J., & Xie, S. (In Press 2002). The thermal-chemical structure and evolution of Eath's mantle: Constraints and numerical models. *Philosophical Transactions of the Royal Society of London Series A.*

Taylor, H. P., & Sheppard, S. M. F. (1986). Reviews in Mineralogy. *Mineralogical Society of America*, 16: 227-271.

Thiemens, M. H., & Heidenreich, H. E. (1983). The mass-independent fractionation of oxygen: A novel effect and its possible cosmochemical implications. *Science*, 219: 1073-1075.

Thommes, E.W., Duncan, M.J., & Levison, H.F. (2002). the formation of Uranus and Neptune among Jupiter and Saturn. *Astronomical Journal*, 123: 2862-2883.

Timmons, J. M., Karlstrom, K. E., Dehler, C. M., Geissman, J. W., and Heizler, M. T. (2001). Proterozoic multistage (~1.1 and ~0.8 Ga) extension in the Grand Canyon Supergroup and establishment of northwest and north-south tectonic grains in the southwestern United States. *Geological Society of America Bulletin*, 113: 163-180.

Ueno, Y., Isozaki, Y., Yurimoto, H., & Maruyama, S. (2001). Carbon isotopic signatures of individual Archean microfossils (?) from Western Australia. *International Geology Review*, 40: 196-212.

van Dishoeck, E. F., & Black, J. H. (1988). The photodissociation and chemistry of interstellar CO. *Astrophysical Journal*, 334: 771-802.

Van Kranendonk, M. J. (In Press). Volcanic degassing, hydrothermal circulation and the flourishing of early life on Earth: New evidence from the c. 3.46 Ga Warrawoona Group, Plilbara Craton, Western Australia. *Precambrian Research*.

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

Varadi, F. (1999). Periodic orbits in the 3:2 orbital resonance and their stability. *Astronomical Journal*, 118: 2526-2531.

Varadi, F., Ghil, M., & Kaula, W. M. (1999). Jupiter, Saturn and the edge of chaos. *Icarus*, 139: 286-294.

Varadi, F., Ghil, M., & Runnegar, B. (2002). Chaotic migration of asteroids over very long time scales. DDA meeting 33, no. 02.03. *American Astronomical Society*,

Varadi, F., Runnegar, B., & Ghil, M. (Submitted, 2002). Successive refinement in long-term integrations of planetary orbits

Vickery, A. M., & Melosh, H. J. (1990). Atmospheric erosion and impactor retention in large impacts: Application to mass extinctions. Special Paper *Geological Society of America Bulletin*, 247: 289-300.

Waller, R. F., Keeling, P. J., Donald, R. G. K., Striepen, B., Handman, E., Langunnasch, N., Cowman, A. F., Besra, G. S., Roos, D. S., & Mcfadden, G. I. (1998). Nuclear-encoded proteins target to the plastid in toxoplasma gondii and plasmodium falciparum. *Proceedings of the National Academy of Sciences of the United States of America*, 95: 12352-12357.

Wagner, M., Roger, A. J., Flax, J. L., Brusseau, G. A., & Stahl, D. A. (1998). Phylogeny of dissimilatory sulfite reductases supports an early origin of sulfate respiration. *J Bacteriol*, 180: 2975-82.

Walsh, M. M., & Lowe, D. R. (1985). Filamentous microfossils lfrom the 3,500-Myr-old Onverwacht Group, Barverton Mountain Land, South Africia. *Nature*, 314: 530-532.

Walsh, M. M., & Lowe, D. R. (1999). Modes of accumulation of carbonaceous matter in the Early Archean: A petrographic and geochemical study of the carbonaceous cherts of the Swaziland Supergroup: in Lowe, D.R., and Byerly, G.R., (Eds.). Geologic evolution of the Barberton Greenstone Belt, South Africa. *Geological Society of America Special Paper*, 329: 115-132.

Walter, M. R., Buick, R., & Dunlop, J. S. R. (1980). Stromotlites 3,400 to 3,500 Myr old from the North Plole area, Western Australia *Nature*, 284: 443-445.

Ward, P. D., Haggart, J. W., Carter, E. S., Wilbur, D., Tipper, H. W., & Evans, T. (2001). Sudden productivity collapse associated with the Triassic-Jurassic boundary mass extinction. *Science*, 292: 1148-1151.

Watson, E. B., & Cherniak, D. J. (1997). Oxygen diffusion in zircon. *Earth and Planetary Science Letters*, 148: 527-544.

Webster, M. (2003). Ontogeny and phylogeny of Early Cambrian olenelloid trilobites, with emphasis on the Late Dyeran Biceratopsidae. Unpublished Ph.D. Thesis, University of California, Riverside, 538 pp.

Webster, M., Sheets, H. D., & Hughes, N. C. (2001). Allometric patterning in trilobite ontogeny: Testing for heterochrony in *Nephrolenellus*. *Beyond Heterochrony: The evolution of Development.* (pp. 105-144). New York Wiley-Liss.

Weil, A. B., Voo, R. V. d., Geissman, J., and Karlstrom, K. (1999). Preliminary paleomagnetic results from the Neoproterozoic Chuar Group, Grand Canyon Supergroup, Arizona. *Geological Society of America Abstracts with Programs,* 3: A-317.

Weinberger, A., Becklin, E., & Zuckerman, B. (2003). The first spatially resolved mid-infrared spectroscopy of beta Pictoris. *Astrophysical Journal*, 584: L33-L37.

Weinberger, J., Becklin, E., Schneider, G., et al. (1999). the circumstellar disk of HD 141569 imaged with NICMOS. *Astrophysical Journal*, 525: L53-L56.

Werner, S. C., Harris, A. W., Neukum, G., & Ivanov, B. A. (2002). NOTE: The Near-Earth asteroid size-frequency distribution: A snapshot of the Lunar impactor size-frequency distribution. *Icarus*, 156: 287-290.

Westall, F., de Wit, M. J., Dann, J., van der Gaast, S., de Ronde, C. E. J., & Gerneke, D. (2001). Early Archean fossil bacteria and biofilms in hydrothermally-influenced sediments from the Barberton greenstone belt, South Africa. *Precambrian Research*, 106: 93-116.

Wicht, J. (2002). Inner-core conductivity in numerical dynamo simulations. *Physics of the Earth, & Planetary Interiors*, 132: 281-302.

Wilde, S. A., Valley, J. W., Peck, W. H., & Graham, C. M. (2001). Evidence from detrital zircons for the existence of continental crust and oceans on the Earth 4.4 Gyr ago. *Nature*, 409: 175-178.

Williams, J. G., & Hierath, J. E. (1987). Palomar-Leiden minor planets: Proper elements, frequency distributions, belt boundaries, and family membership. *Icarus*, 72: 276-303.

Williams, P. L., & Fitch, W. M. (1989). Finding the minimal change in a given tree. *In The hierarchy of life. Proceedings of Nobel Symposium*, 70: 453-470.

Young, E.D., & Lyons, J.R. (2003). CO self shielding in the outer solar nebula: an astrochemical explanation for the oxygen isotope slope-1 line. *Lunar and Planetary Science Conference abstr*., in press.

Young, E.D., Galy A., & Nagahara H. (2002). Kinetic and equilibrium mass-dependent isotope fractionation laws in nature and their geochemical and cosmochemical significance. *Geochimical et Cosmochimica Acta*, 66: 1095-1104.

Young, E. D., Ash, R. D., England, P., & Rumble, D., III (1999). Fluid flow in chondrite parent bodies: Deciphering the compositions of planetesimals. *Science*, 286: 1331-1335.

Young, E. D., & Russell, S. S. (1998). Oxygen reservoirs in the early solar nebula inferred from an Allende CAI. *Science*, 282: 452-455.

Yung, Y.L., & DeMore, W.B. (1999). *Photochemistry of Planetary Atmospheres*, Oxford, Oxford University Press.

Yurimoto, H., & Kuramoto, K. (2002). A possible scenario introducing heterogeneous oxygen isotopic distribution in protoplanetary disks. *65th Meteoritical Society Meeting abstr*. 5149.

Zen, E. (1988). Phase relations of peraluminous granitic rocks and their petrogenetic implications. *Annual Review Earth Planetary Science*, 16: 21-51.

Zuckerman, B., Song, I., Bessell, M. S., & Webb, R. A. (2001). The Beta Pictoris moving group. *Astrophysical Journal*, 562: L87-L90.

Plan for Strengthening the Astrobiology Community

1 INTRODUCTION

The UCLA Center for Astrobiology is engaged in developing the field of astrobiology through a number of initiatives that play to the strengths of an institution of higher learning such as ours. These include formal courses, public lectures, sponsorship of the UCLA Astrobiology Society, participation in the Minority Astrobiology Collaborative, and convening of international meetings concerned with astrobiology-related research. Numerous activities are planned for the next five years, as outlined below.

In the past several years members of the UCLA lead team have taught a number of courses related to astrobiology. These courses were inspired in part by the existence of the Center for Astrobiology. In addition, the Department of Earth and Space Sciences has hired Edwin Schauble as a new Assistant Professor in Astrobiology. A new course in Astrobiology is planned as part of the CAB five-year plan.

Our series of free public lectures entitled “Astrobiology Superstars” has proven popular and will continue in the next two years. However, the historically-significant venue, the Midnight Special Bookstore in Santa Monica, California, is closing and so we will continue the series in a new location (see below). After the first two years the “Superstars” series is to be replaced by a series of public lectures at the Griffith Observatory, also described below.

The activities of the UCLA Astrobiology Society continue to grow and will be encouraged under CAB sponsorship. New initiatives include a research apprenticeship involving CAB team members and mentoring programs to facilitate the proliferation of similar societies at other institutions of higher learning.

Current CAB Administrative Assistant, Barbara A. Laval, will continue in her roles as University Liaison for the Minority Astrobiology Collaborative (MIAC) and NAI Minority Institution Collaboration lead. As she is taking on more duties, her position will be upgraded from Administrative Assistant to Administrator (UCLA Senior Analyst). Through this contact and future participation in the MIAC faculty sabbatical program, CAB remains committed to the goal of increasing the number of minority students in the sciences by providing opportunities for participation in, and learning about, cutting-edge research.

2 EDUCATION AND PUBLIC OUTREACH (EPO)

2.1 Astrobiology curriculum

Several courses related to astrobiology have been taught over the past several years at UCLA. These include: Origin and Evolution of the Solar System (Earth and Space Sciences 9); Astrobiology (Molecular Biology 298); Life in the Universe (Astronomy 4); and Origin of the Cosmos and Life (Cluster General Education course no. 70). This last course, taught by Morris, McKeegan, and UCLA faculty in the life sciences ran for 3 quarters each of the past several years. The cluster courses in general were designed to provide students with the option of a common intellectual experience during their freshman year (i.e., “freshman studies”).

The Department of Earth and Space Sciences is in the midst of designing a new General Education course in Astrobiology that will be taught by our faculty. The first draft of a course description can be found in §2.4 below.

2.2 Public lectures

The “Astrobiology Superstars” lecture series will continue but at a new venue due to closure of the Midnight Special Bookstore in Santa Monica, California. This lecture series has been free to the public and this policy will continue in the future. Lecturers for 2001 included team members Zuckerman, Moore, Manning, and Rivera as well as JPL lead team member Kenneth Nealson. Lecturers for 2002 included UCLA lead team members Song, Schubert, Lyons, and Venkatesan, among others.

The new venue for 2003 and 2004 will be the UCLA Faculty Center. A suitably sized hall within the Faculty Center costs approximately $130.00 per three hour session. The Lectures are scheduled to be bimonthly and the total cost of $780.00 will be paid from our budget.

Twelve of the Superstars lectures are on videotape. The UCLA Office of Instructional Media has been contacted about processing the tapes and encoding them for on-demand viewing on the UCLA webcast web site (webcast.ucla.edu). Encoding and steaming each video on the site will cost $203.00 per tape. This includes a title, credits, editing, and 13 weeks of web hosting on webcast.ucla.edu. Additional time on the web site is provided at a rate of $50.00 per academic quarter. We are also considering the possibility of providing the digitized lecture tapes to the NASA Astrobiology web host if the server is capable of handling the band width and disk space. Experiments with the first 12 tapes will begin immediately. The outcome will be used to inform future taping of lectures and to decide how long to run each of the lectures.

In late 2005 we intend to discontinue the Superstars lecture series in favor of a more visible series to be held at Griffith Observatory in Los Angeles. These Griffith Observatory lectures are in the planning stages at present because the Observatory is currently undergoing an $83 million renovation and is due for reopening in late 2005. Until then, the Observatory staff functions out of the Satellite facility near the Los Angeles Zoo. The PI (Young) has contacted Dr. Ed Krupp, Director of the Observatory about prospects for using both the Satellite facility (including the nearby Autry Museum of Western Heritage) and ultimately the newly-renovated Observatory for the new lecture series. Krupp has in turn put us in contact with the Friends of the Observatory group for further planning.

The new lecture series at Griffith is envisioned to be one in which the highest caliber speakers are brought in from around the world to educate the community about astrobiology-related science (the concept is based on the Carnegie Institution of Washington’s Capital Science lecture series). Lectures will be held approximately four times per year and will be sponsored jointly by both the UCLA lead team and the JPL-II lead team headed by Victoria Meadows. It is our intention to take advantage of our proximity to a prominent local public radio station in Pasadena (KPCC) to obtain air time for some of the guest speakers on their morning talk show “Air Talk.” This show often devotes up to an hour to scientific issues. Firm plans for media coverage will have to wait until closer to the time of the lectures.

2.3 Additional team members related to EPO

The UCLA Center for Astrobiology has facilitated the training of numerous students and postdoctoral researchers. Some of them are listed below. Other team members not listed as collaborators, co-investigators, students, or postdoctoral researchers are staff or collaborators engaged in EPO activities. They are also listed here.

2.3.1 Administration

Todd Gary (team member) is a molecular biologist and Associate Professor in the Department of Geological Science at Tennessee State University (which currently has 850 undergraduate Biology majors that are African-American) and the director of the Institute for Understanding Biological Systems. Gary was one of the first NAI Minority Astrobiology Faculty Fellows. He spent the summer of 2002 in the laboratory of James Lake at UCLA investigating evolutionary genomics and horizontal gene transfer. He is also the co-Director of the Minority Institution Astrobiology Collaboratory (MIAC), which was formed to create a “virtual collaboration” of faculty and students at minority institutions focused on achieving common educational and research goals in astrobiology.

Barbara A. Laval (Manager, Education & Public Outreach Coordinator) manages the Center for Astrobiology and its Education and Public Outreach programs. She acts as liaison to NAI Central, the UCLA Astrobiology Society, and the NAI Minority Institution program (**blaval@ucla.edu**).

2.3.2 Past and present students and postdoctoral researchers (field, advisor, date completed)

Jocelyn Couetdic, undergraduate intern, celestial dynamics, Ference Varadi (advisor), 2003

Andrew Czaja, graduate student, paleobiology, J. William Schopf (advisor), present

Tracy Herrera, graduate student, geochemistry, Craig E. Manning (advisor), present

Andrew Hock, graduate student, planetary science, David A. Paige advisor), present

Cristopher H. House, graduate student, paleobiology, J. William Schopf (advisor), 1999

Ravi Jain, graduate student, molecular biology, James A. Lake (advisor), 2002

Dana N. Kovaric, graduate student, planetary science, David A. Paige (advisor), 2002

Crispin T.C. Little, postdoctoral researcher, geobiology, Bruce Runnegar (advisor), 2001

James R. Lyons, postdoctoral researcher, geochemistry, T. Mark Harrison (advisor), 2001

Caer-Eve McCabe, graduate student, astronomy, Andrea M. Ghez (advisor), 2003

Sabrina S. Mayerberger, graduate student, astrobiology, Bruce Runnegar (advisor), present

Michael A. Mischna, graduate student, planetary science, David A. Paige (advisor), present

Stephen J. Mojzsis, postdoctoral researcher, isotope geochemistry, T. Mark Harrison,(advisor) 2000

Johnathan E. Moore, graduate student, molecular biology, James A. Lake (advisor), 2003

Jeffrey D. Silberman, postdoctoral researcher, microbiology, Patricia J. Johnson (advisor), 2003

AnneSimonson, graduate student, molecular biology, James A. Lake (advisor), present

Richard A. Webb, graduate student, astronomy, Benjamin Zuckerman (advisor), 2000

Alycia J. Weinberger, postdoctoral researcher, astronomy, Ian S. McLean (advisor), 2000

2.4 Description of Astrobiology General Education Course (by William I. Newman, March 2002)

2.4.1 Nature of the Course

The mission of astrobiology is to study the origin, evolution, distribution, and future of life on Earth and in the Universe. NASA statement as well as objective of this course.

> UCLA Catalog Description: 3. **Astrobiology. (5)**
>
> Lecture, three hours; discussion one hour; field trips. Origin, evolution, distribution, and future of life on Earth and in the Universe paralleling NASA’s mission. Course material primarily from planetary and earth science, paleontology and biology, as well as some elements from astronomy, chemistry, and physics. Contains relatively little mathematics Letter grading.

Astrobiology shares with other space related science programs a broad range of research interests. Astrobiology encompasses the understanding of biology as a planetary phenomenon. This includes how planetary processes give rise to life, how they sustain or inhibit life, and how life can emerge as an important planetary process; how astrophysical processes give rise to planets elsewhere, what the actual distribution of planets is, and whether there are habitable planets outside of our solar system; a determination of whether life exists elsewhere and how to search for and identify it; what the ultimate environmental limits of life are, whether Earth's biota represent only a subset of the full diversity of life, and the future of Earth's biota in space.

This will be a three hour per week lecture course, as well as have two full-day field trips. (Field trips will include visits to spacecraft assembly facilities at JPL, as well as various UCLA laboratories. In addition we will visit sites of geological/biological interest, since they illustrate processes pertinent to the evolution of diversity in varied terrestrial environments.) Presentations will be based largely on lecture notes, as well as Jakosky, B. 1998. *The Search for Life on Other Planets*, Cambridge: Cambridge University Press and Goldsmith, D. and Owen, T. 1992. *The Search for Life in the Universe* (second edition), Reading, Massachusetts: Addison-Wesley Publishing Company and other existing texts. (The professor proposing this course has had direct discussion with Cambridge University Press regarding developing a textbook for this course.)

The *sine qua non* of astrobiology is its multidisciplinary nature and, as a result, a substantial number of lecture will be given by experts from other disciplines. The course will be given for letter grade, and grades will be assessed on the basis of an extensive research paper, on a topic to be selected by individual students in consultation with their TA/professor, a paragraph/essay-based mid-term examination, and final examination. A preliminary syllabus for the course appears below.

2.4.2 Week 1. Prologue: From philosophical speculation to scientific exploration

Astrobiology, as defined by NASA, is the study of the origins, evolution, distribution, and future of life in the universe. It requires fundamental concepts of life and habitable environments that will help us to recognize biospheres that might be quite different from our own. Interdisciplinary research is needed that combines molecular biology, ecology, planetary science, astronomy, information science, space exploration technologies, and related disciplines.

2.4.3 Week 2. The meaning of "life"—could we recognize life elsewhere?

How do we go about characterizing life? We can design machines that regulate their environment, undergo self-organization, and reproduce themselves, but when do we call a complex system a living organism? E.g., D.E. Koshland, Jr., 2002. "The Seven Pillars of Life," *Science*, **295**, 2215-16. The 1976 Viking I and II Mars spacecraft life-science experiments; the Galileo spacecraft's search for life on Earth; future experiments to be conducted on Mars.

2.4.4 Week 3. Case Study: Earth

Archaeobacteria's unfulfilled destiny. The sedentary life of prokaryotes, and the Cambrian invention of eukaryotic life and the explosion of diversity. Catastrophism, impacts, and extinctions: the case for coevolution of planets and life. Extremophiles and exotic environments: life on sea-floor vents and Antarctica, and implications to extraterrestrial life. Evolutionary divergence and convergence: is intelligence desirable and therefore inevitable? Is there any evidence supporting the evolution of intelligence?

2.4.5 Week 4. Goldilocks and the three terrestrial planets

Goldilocks would have found that Venus was too hot, Mars was too cold, and that Earth was just right. Or would she? The early dim sun paradox and habitable zones. Europa's oceans, Titan's environs, and Jovian chromophores. From terrestrial extremophiles to possible habitats on Mars. NASA's exploration strategy. Expanding perspectives on our solar system.

2.4.6 Week 5. NASA's Voyages of Discovery and the Future of Space Exploration

The five phases of planetary exploration. History of the space program, and possibilities for its future. Free samples from space: the SNC meteorites, Martian meteorite ALH84001, Pathfinder and Sojourner, and the case for past life on Mars. Search strategies and the problem of forward and backward contamination.

2.4.7 Week 6. Good planets are hard to find: other solar systems and extraterrestrial life.

What can we say about the formation of stable habitats where life could emerge? From where do suitable stars and planets come? How do we look for them, and have we found any, or are likely to observe any? Where does life fit in, and how long can life persist on different worlds? From geoastrobiopoetry to astrobiology—the role of multidisciplinarity in the quest for life. Hallmarks of intelligence—are any observable?

2.4.8 Week 7. Space Travel

Two post-Columbian perspectives: 1492 and European colonization vs. 2003 and the Columbia shuttle disaster. What lessons have we learned? Will we colonize the solar system, solely pursue its exploration by humans and their robotic agents, or enter a state of eternal senescence. Are there lessons learned that we can apply to other extant civilizations?

2.4.9 Week 8. Life Beyond: From physical constraints to design principles.

By blending together elements of physics and chemistry with those of biology and physical anthropology, especially ingredients learned from recent advances ranging from genetics and planetary science, what can we say about life elsewhere? Can scaling principles observed on Earth, e.g., allometric relationships governing animal metabolisms and scaling laws describing the size and mass of mammalian and other brains, tell us anything about life elsewhere?

2.4.10 Week 9. Are we alone?

The Fermi "paradox," Drake equation, and the Heraclitusian dilemma. The media and the popular view of the subject: from UFO sightings and alien abductions to mass hallucinations. How can we communicate with alien life? Emergent technologies: the medium is the message.

2.4.11 Week 10. Societal implications for our "Pale Blue Dot"—planetary stewardship and the future of this planet.

From anthropocentrism to a cosmic perspective. What if we are alone? What if we are not? What have we learned from studying other planets and solar systems? What implications does this have to life on Earth? What lies ahead for humanity in the distant future?

3 THE ASTROBIOLOGY SOCIETY

The UCLA Astrobiology Society is a student-run organization sponsored by the IGPP Center for Astrobiology and the IGPP Center for the Study of Evolution and Origin of Life (CSEOL) at UCLA. The organization was founded in 1999 by two undergraduate students (Jason Finley and Laurel Methot) inspired by what they had learned in the General Education Cluster course (Cluster General Education course no. 70).

The Society is the first student-run organization devoted to fostering the discipline of astrobiology at the university level. Its mission is to "present the studies and goals of astrobiology to science and non-science majors in an integrated fashion that is both interesting and applicable to all fields." The Society has been lauded by NASA officials, including the former and current directors of the NAI, for its activities directed towards engaging undergraduate and graduate students in the burgeoning field of astrobiology. Their value to the field is evidenced by the fact that they were awarded recently their own funding from NAI central (administered through UCLA IGPP).

Astrobiology Society activities include regular meetings, a monthly newsletter, a joint project with the Space Frontier Foundation aimed at high school students, participation in the NAI's Pathfinder program, and running a student research program that pairs students seeking research opportunities with faculty and researchers in the Center for Astrobiology. The Society also hosts lectures on a regular basis. Past lecturers include Dr. Juan Perez Mercader from del Centro de Astrobiologia, Madrid, Spain and Dr. Bruce Jakosky of the University of Colorado, Boulder.

Most recently, the Society is hosting a public symposium with an astrobiology theme. The event, to take place 1 June 2003 on the UCLA campus (Ackerman Union Grand Ballroom), will begin with a lecture by Dr. Jill Tarter, Director of the Search for Extraterrestrial Intelligence (SETI) Institute, who will discuss SETI activities. This lecture will be followed by questions and an opportunity to peruse displays with information about astrobiology and hands-on items such as meteorites and fossils. The symposium will end with a lecture by Bill Nye (the "Science Guy") who will provide an overview of the field of astrobiology. The purpose of the event is to enhance public awareness of astrobiology and science in general.

A new long-term goal of the Society and the NAI is proliferation of the concept of the UCLA Astrobiology to other colleges and universities. They have begun this process through presentations at the NASA NAI General Meeting in 2003.

The UCLA lead team regularly supports the Astrobiological Society through financial support of their speakers program and underwriting travel expenses. The high value placed on the Society is manifest by the fact that the two current Co-Presidents, Geoff Robertson and Dan Fingal, are members of the UCLA lead team.

4 MINORITY PROGRAMS

The UCLA lead team is committed to fostering minority participation in the new field of astrobiology. Their commitment manifests in two ways: 1) participation in the NAI Minority Institution Involvement Program's Faculty Sabbatical Program; and 2) participating in the Minority Institution Astrobiology Collaboratory (MIAC).

UCLA lead team member Lake was one of the first hosts in the new Faculty Sabbatical program. Dr. Todd Gary (§2.3.1) spent the summer of 2002 in Lake's laboratory at UCLA working in the area of evolutionary genomics and horizontal gene transfer. In addition to Lake, several other UCLA team members have offered to participate in the Minority Institution Sabbatical program in the future, including Ghez, Jacobs, Jura, and Zuckerman. Team member Barbara Laval (§2.3.1) is the first point of contact for faculty at minority institutions seeking to collaborate with NAI investigators. Laval has established credibility with participants in the program and can take credit for providing the follow through that is necessary to ensure that the program succeeds.

MIAC was formed in 2002 and includes representatives from several minority institutions, including Hampton University inHampton VA and Tennessee State University in Nashville TN. MIAC's goals include increasing minority participation in astrobiology, building research capabilities at the participating minority institutions, and affording minority students with greater opportunities in the sciences. The ultimate goal is that members of MIAC should one day become an NAI lead team. UCLA lead team member Laval is the University Liaison to MIAC. Founding MIAC member Dr. Todd Gary of Tennesee State is to be named a UCLA lead team member in CAN-3.

As MIAC University Liaison, Laval's role is to advise on establishment of student societies analogous to the UCLA Astrobiology Society at other minority institutions of higher education, to coordinate minority institution faculty and student research internships in the Evolutionary Genomics Astrobiology Focus

Group, and to advise MIAC members in establishing virtual meetings and seminars related to the NAI. Inclusion of Gary in the UCLA lead team facilitates his ability to carry out MIAC activities. It provides him a base of operations from within the NAI from which he can seek out research opportunities for faculty from minority institutions and educational opportunities for students from those institutions.

5 RUBEY COLLOQUIA

Rubey Colloquia are held by the Department of Earth and Space Sciences at UCLA in honor of W. W. Rubey (1898-1974). Rubey was a career geologist with the U.S. Geological Survey and Professor of Geology and Geophysics at UCLA. The colloquia, funded by the Division of Physical Sciences, are flexible in their format, but typically consist of a week of lectures addressing a “hot topic” delivered by preeminent scientists from around the world. Students enroll in the colloquia and receive academic credit for their participation.

The last Rubey Colloquium was held in February of 2002 and was organized by UCLA lead team member

Frank Kyte and Peter Ward from the University of Washington (a NAI lead team PI). The Colloquium was entitled “Impacts and the Origin, Evolution and Extinction of Life.” About 30 experts (see below) in the field of impacts were brought together to present their latest research and ideas. Topics included planet

formation and early bombardment of Earth, the impact history of Earth and catastrophic causes of mass extinctions, the environmental effects of impacts, and impacts as mechanisms for dispersal of life with the Solar System and beyond.

Team members McKeegan, Morris, and Young propose to hold another Rubey Colloquium in January of 2005. The theme will be the origins of Solar-like planetary systems. The total budget for this event is estimated to be $9,000.

Rubey Colloquium, February 9-10, 2002, UCLA