Astrobiology: Exobiology and Evolutionary Biology
Abstracts of selected proposals.
(NNH08ZDA001N-EXOB)

Below are the abstracts of proposals selected for funding for the Astrobiology: Exobiology and Evolutionary Biology program. Principal Investigator (PI) name, institution, and proposal title are also included. 111 proposals were received in response to this opportunity, and 28 were selected for funding.

Jason Barnes/University of Idaho
Orbital Stability of Habitable Moons and Moons of Habitable Planets

We propose to constrain the distribution of worlds capable of bearing life by exploring the orbital stability of both habitable moons and of moons of habitable planets. Moons of gas giant, ice giant, or super-Earth planets in their stars' habitable zones are more likely to be amenable to life than are their parent planets. The presence or absence of a moon of a habitable planet may affect life's evolution there via tidal effects and the moon's torques that control changes in the planet's obliquity. A first step toward understanding the formation and evolution of these systems is a calculation of whether or not moons that formed with such planets could possibly survive to the present-day. Tidal evolution of the moons' orbits limits the long-term orbital instability in both of these types of systems. We will first use numerical orbital integrations to calculate the outer edge of the zone of continuously stable orbits around a planet in the restricted three-body problem. This value for the outermost stable orbit (a fraction of the planet's Hill Sphere) is the least well-known parameter limiting the lifetime of large moons. We will then generalize the early work of Barnes & O'Brien (2002) to the case where the masses of the planet and moon are comparable, investigating both the mutual-tidal-lock end state similar to that of Pluto-Charon and the more middling state like that of the Earth and Moon. This work will employ both analytical and computational analysis of planet-moon evolution. We will use the results to show where, when, and how moons of extrasolar planets in their stars' habitable zones can survive. With recent discoveries of hot-Neptunes and super-Earths near the habitable zones of red-dwarf stars, and future discoveries to be made by the _Kepler_ mission, this proposed work is both scientifically and technically timely. It is relevant to NASA regarding its interests in determining "the potential for life elsewhere" and to "search for Earth-like planets" in the sense that some Earth-like planets may in fact be moons of other planets. It is relevant to the Exobiology program with respect to its charge to "delineate the galactic and planetary conditions conducive to the origin of life" and its interests in the "stability of habitable planets".

William Berelson/University of Southern California
A Community Education and Outreach Activity: International GeoBiology Summer Course

With support from the Agouron Institute and the National Science Foundation (NSF) and in close collaboration with experts in the field, we at the University of Southern
California (USC) and the Colorado School of Mines (CSM) have developed a summer course which provides graduate students from around the US and world a blended education into the disparate fields that come together to form Astro-Geobiology. This course has been in existence since 2002, and here we propose to merge continued support from Agouron, a match from USC with funding we are requesting from NASA and NSF, to continue this course for another four years. This will allow a full generation of bio- and geoscientists to benefit from this unique educational experience. Our course has come to play an important role in structuring the interdisciplinary community of astro-geobiologists, composed of scientists from varied disciplines.

In the proposal that follows, we describe the format of the course, emphasize its success, and discuss how we can continue to improve this unique educational experience. The relevance to NASA is clear: we are training the next generation of geobiologists, many of whom will interact with NASA in the future. Our goal is to give an intense, hands-on, geobiological research experience to students from different academic disciplines, backgrounds, and cultures and build a strong collegial community in the process. All of our efforts, field, lab and lecture, are directed through a research-based curriculum. By merging scientists and students on real research topics, the students get a deep understanding of the different disciplines and long-lasting professional relationships are developed.

We have built a solid base of matching support such that we are requesting four years of support at a level of 1/7 the actual course cost- thus representing a significant "bang for the buck" for NASA. We feel that our track record and the value to the community warrants continuation of this effort. We hope to convince the reviewer that this course is unique in its approach and execution in a field that already has a number of summer courses in tangentially related fields. We intend to demonstrate the scientific value of this course by describing the novel research projects that were undertaken during GeoBio2008 and describe how these projects were woven into an educational experience. As this proposal is written, 5 groups of GeoBio2008 students have submitted abstracts to AGU to deliver posters on topics they researched during the course.

We consider this phenomenal follow-through as clear evidence of our impact. Our success at placing students in excellent post-doc and faculty positions is further evidence. We also feel strongly that this course must be "of our academic community and for our academic community" and not become stagnant, but that it serves the broad objectives of NASA as outlined in the Astrobiology Roadmap.

We can sum up the uniqueness of our astro-geobiology course in several key areas: 1) Synergistic approach, 2) Field and lab research-based approach, 3) Built-in response to the evolution of the field, and 4) Commitment to promotion of underrepresented groups.

We have in place a leadership group of committed scientists. Our administrative staff have 6 years experience with this class and commit time and effort well beyond compensation level. We have lined up substantial matching support that will provide their foundation of support for this class. Insofar as our curriculum is designed to train
the next generation of Astrobiologists in interdisciplinary research through geobiology, we feel this is of tremendous value for NASA, both to demonstrate NASA's commitment to education and outreach in this area but also to link itself with a research-oriented course that is building a cohort of future astro- and geobiologists.

Geoffrey Blake/California Institute of Technology
Observational and Laboratory Constraints on the Creation of Nebular Organics

Nearly all comparisons of nebular organic chemistry, as traced by the composition of comets and carbonaceous chondrites, with possible interstellar precursors have concentrated on the "hot core" environments created by O and B stars or the infalling envelopes of nearby Sun-like protostars. Studies of the gas and ice in the planetesimal-forming regions of the circumstellar disks around T Tauri stars would offer a much more direct link to nebular processes, but to date only a few species have been studied in the very outermost regions of disks using mm-wave spectroscopy. The inner regions of disks may exhibit a chemistry quite distinct from that in hot cores due to the radial migration of solids that can dramatically alter the O/C ratio inside of the so-called "snow line." In our recent work with the Spitzer IRS and ground-based instruments (at Keck) we have robustly detected water and organics in the inner few AU of dozens of protoplanetary disks, and seen evidence of this chemical variation. Here we propose to take the next step in chemical complexity via the unique properties of the softest vibration-torsion modes of organics and the deployment of new THz facilities by NASA (Herschel+SOFIA) and the NSF (ALMA). Specifically, we propose to combine measurements of the vibration-torsion modes of organics in both icy matrices and the gas phase using state-of-the-art THz time domain spectrometers in order to guide astronomical observations of protoplanetary disks culled from the Spitzer/Keck sample. Of the many potential targets to be studied over the next three years, this program will concentrate on amino acids and sugars along with their likely grain-mantle and gas phase precursors.

Frank Corsetti/Earth Sciences
Magnetic Susceptibility as a Biosignature

Microbialites - macroscopic sedimentary structures built or influenced by microorganisms - constitute an exobiologist's dream and nightmare at the same time. As visible structures built by microscopic organisms that are themselves too small to be imaged remotely, microbialites provide an excellent target in the search for life on other planets and in the ancient rock record on Earth. However, it is well known that abiotic processes can mimic microbialite morphology - so which ones are actually biogenic? Microscopic investigation can provide some relief, but many, if not most, putative microbialites in the rock record have been subjected to post-depositional alteration that obscures the original microfabric. Isotope ratios (e.g., d13C) can be difficult to interpret, and organic matter is rarely preserved in such structures. Here, we propose a new biosignature based on the detrital magnetic mineral component present in nearly all sedimentary rocks.
We hypothesize that the distribution of detrital magnetic grains within a putative microbialite will depend on the presence or absence of "sticky" microbial mats/biofilms. Simply stated, magnetic grains in an abiotic structure should obey the laws of gravity/angle of repose (swept off peaks, concentrated in lows), while magnetic grains adhered to a biofilm will seem to "defy" the laws of gravity and appear in positions inconsistent with simple physical sorting. The microbial communities that built microbialites are inherently sticky compared to the surrounding sediment, possess the ability to trap and bind sediment via their activity, or both. Detrital minerals will adhere to the microbial mats that built the microbialite, and a component of the minerals will be magnetic (magnetite, hematite, etc.). Recent advances in our ability to measure miniscule magnetic moments open up the possibility to map the magnetic susceptibility of a putative microbialite sample, even when the grains are too small to be seen with a standard petrographic microscope. Furthermore, such magnetic grains reside in the insoluble fraction of carbonate rocks - a common host rock for many microbialites - and would be less affected by certain post-depositional alteration processes than the carbonate itself.

In order to test this hypothesis, we will take a dual approach: 1) experimental (biotic and abiotic experimental systems), and 2) field-based (known biotic and unknown samples). We will perform laboratory experiments in which we grow microbial biofilms at a variety of inclinations in still and gently agitated water while introducing magnetic particles. A parallel abiotic experiment will take place. In this way, we will be able to map the differences between the magnetic susceptibility patterns of both biotic and abiotic structures. For the field-based studies, we will map the magnetic susceptibility of modern and ancient microbialites, from modern biotic stromatolites in Yellowstone hot springs to some of the oldest putative microbialites in the world.

The stated goal of exobiology research into the early evolution of life is to determine the nature of the most primitive organisms, the environment in which they evolved, and the way in which they influenced that environment. Our study encompasses all three key areas, as microbialites are the most ancient putative fossils in the rock record, they record evidence of the environments in which they formed, and, most fundamentally, it is critical to determine if something was, or was not, influenced by biotic processes. As stated, morphology is not conclusive - we view magnetic susceptibility as a biosignature as a highly novel technique that can be added to the astrobiologist's toolkit.

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**Glen Cushing/U.S. Geological Survey**  
**Characterization of pit-crater/cave interactions for comparison of Earth/Mars analogs**

Primary NASA and Exobiology objectives include gaining access to the subsurface of Mars, continuing the search for microclimates and habitability zones, and continuing the search for evidence of past or present microbial life. These objectives will be significantly advanced by detecting and exploring Mars’ subsurface cave networks, opening vast possibilities to astrobiology, geology, technology development and mission planning.
A small number of anomalous Martian pit craters have strikingly unusual thermal signatures that may reveal the presence of cave entrances existing beneath and beyond the crater rims. These atypical Martian pits appear to be morphologically analogous to many pit craters in Kilauea Volcano’s Southwest Rift Zone (SWRZ) on Earth, which frequently contain entrances to extensive cave systems. If the formation mechanisms are indeed analogous, then at least some of the anomalous Martian pits must contain cave entrances as well. Thus, by determining how cave systems on Earth can influence overall thermal trends when connected to host pit craters, we can then determine when similar interactions occur on Mars (thereby indirectly detecting substantial cave systems on Mars). If funded, this will be the first Mars cave-detection study to involve targeting real Earth/Mars analogs.

The anomalous Martian pit craters were first noticed in THEMIS visible-wavelength images as dark spots or cylindrical “holes” with vertical or sub-vertical walls - deep enough that late-afternoon sunlight does not reach their floors. THEMIS thermal-infrared images show that diurnal temperature variations in these pits are completely different from those in adjacent “typical” pit craters (and from any other known feature on Mars). Subsequent images obtained by HiRISE show the anomalous Martian pits in detail, revealing several with overhanging rims and interiors that extend out-of-sight beneath the surface. The sheer >200 m cliff walls in some of these anomalous Martian pits must hold a wealth of exposed stratigraphy revealing millions of years of Mars depositional and atmospheric histories.

Compared with surface temperature values, we know that thermal variations in caves are severely damped and are phase-delayed in time. This behavior encourages us to learn how pit craters are thermally affected when they contain a boundary between 2 distinctly different climates. The primary goal of this proposal is to characterize and quantify the time-dependent thermal behavior of various pit craters in order to identify thermal influences from internal cave systems.

We propose record temperature variations inside and around various terrestrial pit craters over diurnal and annual timescales. A thermal camera will also record diurnal temperature variations at a high spatial resolution. Kilauea Volcano’s southwestern rift zone (SWRZ) has probably the largest and most diverse collection of pit craters on Earth, as well as the best examples of Mars analogs for us to study. Quality terrestrial counterparts to Martian features are often either difficult to find or non-existent, making the SWRZ an extremely valuable resource.

Analysis will involve comparing the in-situ and thermal-imaging data, and applying Fourier-transformation techniques to determine how differences of phase and amplitude between pit-crater and surface temperature curves can reveal either the presence, or lack of, of cave entrances. Higher-order Fourier terms may indicate general cave characteristics such as internal shape, volume and/or total surface area. We will calibrate thermal images of each pit crater to the respective in-situ temperature data, and then convert the temperatures into band-specific radiance values (via Planck’s function) similar to those returned by spaceborne remote sensing instruments. Such will enable us to directly compare thermal behaviors between Martian and terrestrial pit craters, and to infer the presence and locations of Martian caves.
Banded iron formation (BIF), a chemical precipitate from seawater, represents the oldest sedimentary rock on Earth, and so is a potential repository for hosting relicts of the nascent biosphere. Because it forms in the ocean, the composition of BIF is critical for assessing the evolution of seawater chemistry and provides a critical context for conditions associated with the establishment of life on Earth. However, once subjected to younger geologic events, such as metamorphism, there may be problems recognizing the signatures characteristic of both depositional environment and life. This proposal seeks funding to examine the major- and trace-element geochemistry and iron isotopic composition of BIF from three different times, specifically, ~3.8 Ga, ~3.0 Ga, and ~1.9 Ga. Using these three time periods, several interconnected hypotheses will be addressed: (1) Contact and regional prograde metamorphism of BIF, whose ages range from 3.8 Ga to 1.9 Ga, does not substantially affect its REE, trace-element, and iron isotope composition, which are all thought to carry a specific sedimentary fingerprint; (2) Apatite present in BIF formed originally on the sea floor in association with organic matter and thus may serve as a repository for biological relicts; and (3) rocks superficially resembling depositional BIF but that formed entirely by replacement processes have geochemical and isotopic compositions that are distinct from their sedimentary counterparts. The research will focus on collecting samples from well characterized field settings, followed by detailed petrographic examination of mineral compositions and textures. Geochemistry of bulk rocks and individual bands of BIF will be characterized using high quality ICP-MS data. Iron isotopes will be collected utilizing the high spatial resolution of secondary ion mass spectrometry, which will permit documentation of microscale variations, as well as bulk signatures with MC-ICP-MS. This research fits directly into the Early Evolution of Life and the Biosphere objective of the program by elucidating environmental conditions at the time of the earliest biosphere and its evolution through the Precambrian. One particular issue in dealing with the geological record of this time is developing a better understanding of how geologic and geobiologic materials are modified by subsequent events. This proposal is aimed at generating a better understanding of these processes so that original compositions can be evaluated in a meaningful way. Research proposed herein will focus on two seminal astrobiologic units, namely the BIF in the Isua Greenstone Belt, Greenland, which may host the first fossils on Earth, and the Gunflint Iron Formation, found in the Great Lakes region of the USA and Canada, long known for its microbiota. A third largely unexamined BIF from the Buhwa Greenstone Belt in Zimbabwe, which is very well preserved, will also be examined.
Multiple sulfur isotope ratios have become one of the most useful geobiological tools for probing Archean and Paleoproterozoic sedimentary rocks with regard to the evolution of the sulfur cycle and the first appearance and subsequent rise of atmospheric oxygen. Bulk rock analyses of sedimentary sulfide minerals of Late Archean age demonstrate sulfur isotope ratios that carry a strong non-mass-dependent isotope fractionation, thought to arise from photolysis of sulfur-bearing species in an atmosphere containing less than 1ppm O2. Interpretation of these data is hindered by the persistent observation that the sulfide-bearing minerals present commonly have complex origins that combine detrital, pelagic, diagenetic, and metamorphic components. Deciphering the multiple origins of sulfide minerals in a sample is critical to extract meaningful information about the depositional and diagenetic environment.

We propose to study a suite of rock samples from drill core through the Transvaal Supergroup in the Northern Cape Province, South Africa. These samples were deposited in distal slope and basinal environments adjacent to a major Late Archean-age (ca. 2.6-2.52 Ga) carbonate platform. Petrographic textures reveal that, much like other deposits of the same age, this rock succession has witnessed several episodes of sulfide mineralization. Rock magnetic data indicate that later ca. 2.0 Gyr sulfide mineralization is carried by the magnetic sulfide-bearing mineral pyrrhotite. Using scanning high-resolution low-temperature superconductivity SQUID (superconducting quantum interference device) microscopy, we will image at a 50 um scale, the late magnetization in black shale samples containing diverse sulfide components. When combined with petrography, these magnetic images allow both the identification of pristine unaltered sulfides and later stages of mineralization. At the same scale, precise measurements of $^{32}$S, $^{33}$S, and $^{34}$S will be made by secondary ion mass spectrometry (SIMS) using a Cameca 7F/Geo and Cameca NanoSIMS 50L. In addition to resolving non-mass dependent isotopic fractionation, systematic micron-scale variations in sulfur isotopes in early diagenetic pyrite nodules can provide quantitative constraints on biological processes operating in Late Archean sedimentary environments. The novel combination of scanning SQUID microscopy and SIMS, allows us to investigate, at a scale previously unobtainable, the origin and preservation of geobiological signals recording the evolution of oxygen in early Earth's atmosphere.

Preliminary sulfur isotope data (d$^{34}$S, d$^{33}$S, D$^{33}$S) have been collected on a Cameca 7F Geo. We are able to obtain high precision measurements on a range of (mass-dependent) pyrite standards sufficient to resolve relevant isotope variability due to both atmospheric and biological processes in these Archean samples. In this proposal, we demonstrate the ability to identify attractive sample targets using SQUID microscopy, and resolve geobiologically meaningful isotopic relationships in these targets.
Complimentary analyses of carbonate-associated sulfate (CAS) in Late Archean carbonates will also be conducted. Preliminary results indicate that reproducible d34SCAS can be obtained in standards of known isotopic composition with a d34SCAS precision of ~1 permil. The extremely low concentration of CAS in Archean samples (1e3 fewer counts than Phanerozoic samples) make these measurements extremely challenging and the best d34SCAS precision obtained is ca. 2 permil. Nonetheless, by measuring Archean d34SCAS from distinct carbonate phases (thereby separating primary and/or early diagenetic precipitates from the products of late stage recrystallization, we have the potential to directly constrain the isotopic composition of seawater sulfate at this time, an important measurement that has eluded conventional techniques.

**Daniel Glavin/NASA Goddard Space Flight Center**

**Investigating the Distribution and Nitrogen Isotopic Composition of Nucleobases in Carbonaceous Meteorites**

In modern terrestrial biochemistry, nucleobases are the informational components in RNA and DNA and are vital to metabolism in numerous co-enzymes. The availability of nucleobases as feedstock for prebiotic chemistry leading to the first self-replicating systems of the early Earth depends on their endogenous synthesis and their exogenous delivery. Nucleobases have been detected in the Murchison meteorite and other carbonaceous chondrites. However, their extraterrestrial origins have not been conclusively determined, due in part to their low abundances, lack of isotopic data, and the presence of other organic compounds in the meteorites such as dicarboxylic acids that interfere with carbon isotope measurements and the identification of nucleobases.

In this study, we propose to investigate the distribution and nitrogen isotopic composition of nucleobases in Murchison and five other carbonaceous chondrites using improved extraction and analytical methods recently developed in our laboratory. Our first objective is to determine whether nitrogen isotope values of the pyrimidine uracil and the purine xanthine in the Murchison meteorite show enrichment in 15N indicating extraterrestrial origins for these nucleobases. Our second objective is to examine the structural diversity of N-heterocycles in the Murchison meteorite in order to constrain the availability of alternative nucleobases for pre-RNA chemistry. Our third objective is to investigate the structural diversity and nitrogen isotopic composition of nucleobases in other carbonaceous meteorites, particularly the newly discovered amino acid-rich Antarctic CM and CR meteorites, to better understand how nucleobase abundances and distributions compare with other organics in meteorites, and thus their inventories on the ancient Earth and other Solar System bodies.

**Nader Haghighipour/University of Hawaii**

**From Planetesimals to Terrestrial Planets: Habitable Planet Formation in Binary Star Systems**

We propose to study the formation of habitable planets in binary star systems that host Jovian-type planets. With approximately 25% of extrasolar planet-hosting stars in binary systems, questions such as: how have planets formed in such dynamically complex
environments, under what conditions do such systems form and harbor habitable bodies, and how do volatiles necessary for life appear on their habitable planets, have now found realistic grounds. We have recently completed and published a study of the late stage of habitable planet formation in binary systems that host Jovian-type planets (Haghighipour & Raymond 2007). The purpose of this proposal is to extend previous study to an earlier stage, when the protoplanets are formed through the collisional growth of planetesimals, and use the final results as the initial conditions for a disk of protoplanets to continue our simulations of the late stage of habitable planet formation in binary-planetary systems.

We propose to carry such simulations for different orbital characteristics of the binary and its giant planets, for different number of Jovian-type bodies, and within the region of the parameter-space that has been mapped by our recent study. Our goal is to identify the orbital characteristics of the stellar components and Jovian-type planets of binary-planetary systems that are capable of harboring habitable bodies. We plan to numerically simulate the collisional growth of planetesimals to planetary embryos, and study the formation of Earth-like objects in the habitable zones of their primary stars. We will carry out simulations for different values of the mass-ratio and orbital parameters of the binary as well as those of its giant planets. In brief, (1) We will study the long-term stability of terrestrial planets in a binary-planetary system for different values of the mass-ratio and orbital parameters of the binary, as well as the number, masses and orbits of giant planets. In Haghighipour & Raymond (2007), we considered a binary star system with only one giant planet. We plan to extend our study to systems with more than one giant body. (2) We will simulate the formation of planetary embryos in a disk of planetesimals for different disk models and for different orbital and physical characteristics of the binary and its Jovian planets. (3) We will use the final results of the simulations of the formation of protoplanets as initial conditions for the simulations of the late stage of terrestrial planet formation to examine the effect of the orbital dynamics of giant planets and the binary companion on the growth of planetary embryos and formation of habitable planets. As shown by Levison & Agnor (2003), secular resonances caused by a system of multiple giant planets can have significant effects on terrestrial planet accretion. We plan to study this effect in binary-planetary systems. (4) We will use estimates of the distribution of water-bearing bodies in the solar nebula to predict the distribution of such bodies in binary stars, and determine which combination of the mass-ratio and orbital parameters of the binary and giant planets makes the delivery of water to the habitable zone of each star more efficient. (5) We will also study the effect of giant planet migration on the formation of terrestrial bodies in the habitable zones of binary-planetary systems.

This project will further our knowledge of the formation of planetary systems and supports NASA strategic sub-goal 3D: "Discover the origin, structure, evolution, and the density of the universe, and search for Earth-like planets," and NASA science outcome 3D.4, "progress in creating a census of extrasolar planets and measuring their properties."
Yongsong Huang/Brown University

New insight to the prebiotic chemical evolution from advanced molecular and compound-specific isotopic analyses of carbonaceous chondrites

Organic compounds in carbonaceous chondrites provide unique insights to the prebiotic organic chemistry. Despite substantial progress in the past fifty years, fundamental questions remain, notably, 1) Compound-specific isotopic data for volatile organic compounds (VOC), especially branched hydrocarbons are virtually absent, which severely hinders our ability to assess the interstellar versus nebular sources for meteoritic hydrocarbons. 2) Enantiomeric excess (ee) is only found for amino acids, but not in any other presumed interstellar organic compounds, making the much popularized UVCPL hypothesis for the origin of chirality equivocal. 3) Our knowledge on the structures of the most dominant form of organic substances in carbonaceous chondrites, the insoluble organic matter (IOM), is extremely limited. For example, we know little about the functionality of sulfur in IOM. Sulfur is a key element in the formation of terrestrial S-rich kerogen and may have played important role in incorporating interstellar molecules into the macromolecular framework of meteorites.

We propose to apply a novel series of analytical approaches to carbonaceous chondrites of different classifications. We will: 1) Perform integrated compound specific C/H isotopic analyses on the meteorite VOCs. 2) Determine the ee in key classes of non amino acid chiral compounds, including branched hydrocarbons, monocarboxylic acids and hydroxyl acids. The data are essential for testing the prevailing theories for the origin of chirality in life. 3) Introduce novel analytical methods to study meteoritic IOMs. In particular, we will explore the role of sulfur in the formation of meteorite macromolecules.

The proposed work will permit continued development of the advanced organic and isotopic analytical capabilities at Brown University for studying samples from the Antarctic meteorite collection and from NASA’s future sample return missions. The research is highly relevant to the fundamental objectives of the NASA Astrobiology/Exobiology program and the NRA.

Hiroshi Imanaka/University of Arizona

Organic aerosols in the early Earth atmosphere: Reaction network and its isotope signature

Abiotic formation of complex organic macromolecule aerosols is important not only for the potential for prebiotic chemical evolution, but also in the global elemental cycle and long-term climate stability. The direct clues of the habitable environment and biosphere on the early Earth are mostly obtained from geological records, such as isotope signatures and biomarkers in the ancient organic sediments. The recent Cassini-Huygens mission revealed the generation of complex organic aerosols in Titan's upper atmosphere, and similar processes could have lead to the formation of organic aerosols in the early Earth atmosphere. Understanding the formation reaction network and accompanying isotope
fractionation processes of the organic aerosols is necessary to constrain the active organic environment on the early Earth from the available geological evidence. We propose a systematic laboratory investigation of the abiotic formation of organic aerosols in simulated early Earth atmospheres, with particular focus on carbon and nitrogen isotope fractionation. The primary goal is to constrain the plausible range of $^{13}$C and $^{15}$N isotope abundances in the various organic aerosols. Development of a new ICP/helicon plasma system and our state-of-the-art VUV-EUV photolysis system will advance the capabilities to simulate the natural atmospheric environments. Complex reaction networks such as those involved in aerosol generation would be expected to have reactions demonstrating a broad range of isotope fractionation. The systematic measurements of the mass balance and compound-class specific isotopic ratios in the chemical products would help elucidate the key isotope fractionation processes and the corresponding chemical functional groups containing significant imbalances. We might be able to use both the isotope signatures recorded in the early Earth and the lessons from Titan's atmospheric chemistry to understand the abiotic process in the early Earth.

David Jablonski/University of Chicago

The Impact of the Impact: Evolutionary and Biogeographic Effects of the K-T Impact

The most recent of the major mass extinctions, the end-Cretaceous (KT) event, has been linked to an extraterrestrial impact. Most research has focused on the physical/chemical signature of this impact, models of its immediate environmental effects, and, to a lesser degree, the intensity and selectivity of the associated extinction. However, research on the "long-term effects of extraterrestrial phenomena such as... infalling comets and asteroids on life" (2008 Astrobiology Roadmap, Objective 4.3) is essential for understanding the role of impacts and other extraterrestrial drivers on the evolution of life on earth and other planets. We propose to make a novel assessment of the long-term impact of the KT Impact by examining how that event shaped the present-day marine biota, not just in terms of losses 65 Myr ago, but in the subsequent dynamics of survivors and newly evolved taxa. We will build on our prior NASA-supported research on global diversity gradients to track evolutionary and biogeographic dynamics in 3 key ~15 Myr-long intervals between the KT and today, using marine bivalves as a model system. (Bivalves have the richest, best-sampled and taxonomically standardized fossil record of all post-Paleozoic metazoans, and show spatial and temporal diversity patterns closely correlated with most other marine groups.) Preliminary analyses show (a) a surprisingly strong KT signal in the ages of extant genera globally and regionally, suggesting a permanent increase in origination rates; (b) a loss of high-turnover groups at the KT that was never re-filled; and (c) hints that preferential post-KT tropical origination and poleward expansion set up a latitudinal gradient in genus ages. We will use the resources and methods developed under prior NASA support to construct a spatially explicit, taxonomically standardized database of marine bivalve occurrences for the Paleocene-Eocene interval, leveraging our existing databases for the latest Cretaceous and the late Neogene-Recent intervals, and our global database for the first and last occurrences of bivalve genera through the Phanerozoic, to make comparative analyses of faunal dynamics among our target intervals: the recovery interval (65-ca. 50 Ma), the post-
recovery Eocene (ca. 50-34 Ma), and the Mid Miocene-Recent (16-0 Ma). Our Paleocene-Eocene database will be global, but we will focus on 5 regions with more complete faunal successions as anchors of our spatial analyses (the West Coast and Gulf & Atlantic Coasts of North America, northern Europe, North Africa, and India-Pakistan). We will analyze the extent to which three key components of evolutionary dynamics were influenced by the KT in each of, and among, our time bins: (a) global origination and extinction rates, (b) variations in these rates among clades (i.e., sets of closely related species, herein genera and families) and modes of life, and (c) spatial patterns of origination, extinction, and range shifts. Because the two post-recovery intervals differ strongly in environmental context (the Eocene is predominantly greenhouse, the late Neogene predominantly icehouse), comparisons between them, and to the dynamics of the recovery interval, will test the relative roles of the KT versus post-KT climatic conditions in driving the evolutionary and spatial patterns of the global bivalve fauna. Our new database in conjunction with our existing ones will allow us to test patterns rigorously, including accounting for sampling biases (e.g. using occurrence-based sampling standardization techniques). Our proposed comparative analyses of temporal and spatial dynamics of marine bivalves will provide a richer understanding of the long-term consequences of the KT impact, and its imprint on the evolutionary history and biogeography of the living biota.

Ludmilla Kolokolova/University of Maryland
Circular Polarization: A Key Tool in Remote Sensing of Homochirality in Cosmic Organics

A unique characteristic of life is the homochirality of biological molecules, i.e. predominance of one of the mirror forms of the molecules. This characteristic may be manifested on a macroscopic scale through the optical activity of the chiral molecules and, hence, the presence of circular polarization in the light they scatter. If such a signal can be detected remotely then large-scale exploration for biology-related processes may become feasible. Due to recent work by the proposers, a unique set of data on circular polarization in comets has been accumulated. We have also explored remote sensing capabilities of circular polarization in the laboratory, studying light scattering from astrobiologically relevant microorganisms and setting these in the context of abiotic minerals. In this project we will establish whether the presence of chiral organics can produce the observed characteristics of comet circular polarization and explain the results of our laboratory measurements. For this, as the primary goal of this proposal, a new development in one of the most popular light-scattering codes, the multi-sphere T-matrix code, will be made to allow it to work with aggregates made of optically active materials. Such a model is the best description for comet dust as well as provides a plausible model for a variety of biological particles. The results of this project can be applied to search for materials containing molecules of prebiological and biological origin in astronomical objects including comets, planets, extrasolar planets, and protoplanetary nebulae.
**Eric Korpela/University of California**  
**Arecibo Multibeam Sky Survey for Direct Detection of Inhabited Planets**

Using the 7-beam Arecibo L-band Feed Array (ALFA), a SETI spectrometer (SERENDIP V, previously funded by NASA), and a real-time multibeam RF data recorder (the SETI@home II data recorder) we propose to conduct a high sensitivity survey of the entire sky visible to Arecibo observatory. This survey will search for artificial narrow-band signals in a 300 MHz band surrounding 1420 MHz. The observations will be 10 times more sensitive and hundreds of times more comprehensive than the most sensitive existing SETI large-area surveys (SERENDIP IV and SETI@home). This sky survey will also search for dispersed microsecond timescale radio pulses at unprecedented sensitivity.

SERENDIP V is designed to operate in conjunction with the multi-beam receiver systems such as ALFA. The SERENDIP V system will analyze signals from all beams simultaneously in dual polarization, effectively observing seven points on the sky simultaneously. The multibeam observing mode allows development of techniques to which can be used to notify our commensal observing partners of radio frequency interference which we detect. We will investigate the possibility of removing radio frequency interference (RFI) in real-time. The development of these techniques for multibeam observation is a required step in the development of proposed large radio arrays, such as the Allen Telescope Array, the Low Frequency Array (LOFAR), the Square Kilometer Array (SKA) and NASA's next generation Deep Space Network.

The data recorded by the SETI@home II data recorder will be analyzed using the techniques we developed for SETI@home and our BOINC distributed computing infrastructure. This data will transferred via the internet to the computers of millions of volunteers. These computers will perform a numerically intensive analysis faster than the fastest available supercomputers.

**Ramanarayanan Krishnamurthy/The Scripps Research Institute**  
**Exploring the Chemistry of Glyoxylate and Dihydroxyfumarate in the Context of the Origin of Life Problem**

The goal of our research over the last decade was to extend the chemical basis for an etiology of nucleic acid structure. One of the aims of the project is to map, by chemical synthesis, the structural landscape of potentially primordial informational oligomer systems, using in essence two criteria in selecting oligomer structures: (a) the capability of informational Watson Crick pairing (functional criterion), and (b) the potential of an oligomer system to be generated under primordial geochemical conditions (generational criterion), to be assessed by chemical reasoning. Recent work along these lines, extended to oligomer structures that have backbones and recognition elements different from the natural nucleic acids, has made it clear that application of the generational criterion demands the commitment to, and experimental exploration of, a specific scenario for the chemistry of the origin of life - if the work is to result in a contribution to the problem of life’s origin and not only constitute an exploration of new chemistry.
We seek funding for a systematic experimental exploration of such a scenario on the chemical level, believing that such work will be complementary to the landscape mapping project mentioned above which is already being funded by NASA.

The scenario we propose to investigate is in essence one of a low temperature autotrophic origin of life, in as far it postulates biogenic sugars, pyrimidines, amino acids and constituent of the citric acid cycle to derive from one chemical as single carbon source, glyoxylate, a material hypothesized to be potentially derivable from a multitude of geochemical sources (HCN, CO, CO2 , (CN)2 etc. The intrinsically non-robust chemistry of the scenario is postulated to harbor a variety of (hypothetical) autocatalytic cycles which to document experimentally will be one of the major goals of the research project.

Ronald Oremland/US Geological Survey

Arsenic metabolism is a process that developed on the primordial Earth as a means to both detoxify and exploit this element for energy gain. Previous research conducted on this grant has revealed a widespread occurrence of arsenate-respiration amongst diverse anaerobic prokaryotes, suggesting that it too is an ancient process. Yet a paradox exists, because if the ancient Earth was anoxic, the primary form of arsenic would have been arsenite [As(III)] rather than arsenate [As(V)]. Although a number of chemoautotrophs can grow by coupling oxidation of As(III) to As(V), they require a strong oxidant to achieve this, like O2 or in the case of Alkalilimnicola ehrlichii, nitrate. However, anoxygenic photosynthesis characteristic of photosynthetic bacteria and cyanobacteria has been present for > 2.7 Ga, a process where sulfide, Fe(III) and nitrite serve as its driving electron donor. We have recently expanded this list to include As(III) (Kulp et al., 2008). Experiments with cyanobacterial and photosynthetic bacterial mats located in hot springs in Mono Lake demonstrated a light driven anaerobic oxidation of As(III) to As(V). An Ectothiorhodospirum, strain PHS-1, was isolated that grew using As(III) as it electron donor. Strain PHS-1 lacks an As(III) oxidase (AoxB) but runs its dissimilatory arsenate reductase in reverse, as does Alkalilimnicola ehrlichii. In this proposal we will further study the process of As(III)-fueled anoxygenic photosynthesis, carrying out additional field and laboratory experiments to determine its occurrence among novel (and stock cultures) of photosynthetic bacteria and cyanobacteria, the physiological ecology of these microbes, and the biochemical mechanisms whereby they oxidize As(III). The work is relevant not only to the early evolution of life on Earth, but to the possibility of life occurring on planets like Mars that were once volcanically-active and wet.

Alexander Pavlov/University of Arizona
Snowball Glaciations and Climate Stability on the Early Earth.

Snowball glaciations caused the most severe stress to the biosphere in the entire Earth history. Therefore it is important to understand how Earth could recover from Snowball
glaciations and how long the snowball conditions could have persisted. The standard recovery mechanism suggests that the volcanic CO₂ accumulated in the atmosphere during Snowball and the increased atmospheric greenhouse deglaciated the planet eventually. Recently, several fundamental problems with the CO₂ recovery mechanism were discovered. Using 3-D general circulation models, it has been shown that it takes more than 0.2 bars of CO₂ to bring the equatorial temperature above freezing. Secondly, CO₂ was likely to condense in the polar regions during snowball episodes and that would preclude CO₂ buildup in the atmosphere. However, any modeling results of the Snowball Earth climate would remain incomplete because the current atmospheric general circulation models do not calculate properly the greenhouse warming under the extremely high (bars) levels of CO₂. Furthermore, current 3-D models do not include various physical processes which would be important in Snowball conditions - latent heat release due to CO₂ condensation, formation of the CO₂ clouds, temporal changes of the snow albedo etc.

As a part of this proposal we will develop the absorption coefficients (k-coefficients) for calculations of shortwave and thermal radiative fluxes in atmospheres with large amounts of CH₄, CO₂, SO₂ and H₂O, over a large range of possible planetary temperatures and pressures. We will then introduce these new coefficients into the NCAR’s Community Atmospheric Model (CAM3.1). We will adapt CAM3.1 for calculations of the extreme cold climate by including effects of CO₂ condensation. We will use the adapted CAM3.1 model to identify the amounts of different greenhouse gases needed to recover Earth from the Snowball state. We will explore various scenarios of Snowball recovery - abrupt release of methane clathrates, slow accumulation of CO₂, gradual changes in surface albedo in the equatorial regions, abrupt release of SO₂ etc.

Although our primary goal is to explain how Earth recovered from snowball glaciations, our calculations will have much broader implications. Any Earth-like water-rich planet is susceptible to snowball conditions but a truly habitable planet should have mechanisms to overcome them. Therefore, our calculations will place important constraints on the potential targets for the future search of the habitable planets.

Jonathan Payne/Stanford University

Testing End-Permian Mass Extinction Scenarios Using Calcium Isotopes

Planetary habitability and the evolution of advanced life depend not only on the bulk average physical and chemical compositions of the planet and its fluid envelope. They also depend critically upon secular changes in surface environments and in particular on the frequency and severity of short-term events that induce extreme conditions which may approach or exceed the tolerance limits of many types of organisms. Mass extinction events provide our only direct record of extreme environmental change and its effect on advanced life; they are therefore valuable natural experiments on the limits of planetary habitability and biological adaptability, so long as the causes of these events are potentially identifiable. Of the major mass extinction events, the end-Permian mass extinction (252 million years ago) stands out as the most severe extinction event and the only event in which animal life was nearly eliminated from the planet. Unlike the better-
studied end-Cretaceous mass extinction, however, the precise circumstances of this extinction event remain incompletely understood. Therefore, it has been impossible to make any detailed assessment of which end-Permian environmental conditions approached the tolerance limits of terrestrial life and whether or not similar events should be expected in Earth’s future or on other potentially inhabited planets with differing surface conditions and/or interior dynamics.

Many aspects of Permian-Triassic global change are well characterized. The isotope composition ($\delta^{13}C$) of organic carbon and carbonate rocks shifted abruptly toward lighter values, and marine animals likely to be most sensitive to CO2 increase were also those that experienced the greatest extinction rates, extinction affected terrestrial and marine ecosystems. The cause of these changes remains poorly understood, however. Two suggested source of the CO2 are a stratified ocean with anoxic, alkaline deep waters or the release of carbon from sedimentary carbon reservoirs such as methane clathrates, coal, or carbonate rocks, possibly related to the emplacement of the Siberian Traps large igneous province. The predictions of these scenarios for carbon isotope records, extinction patterns, and climate change are largely concordant, making it difficult to determine the extent to which the mass extinction may have resulted from changes in ocean dynamics or from crustal volcanism or deep Earth processes. These scenarios differ substantially in their predicted effects on the calcium isotopic composition of seawater. Therefore, we propose to analyze the calcium isotope composition ($\delta^{44/40}Ca$) of carbonate rocks and phosphatic microfossils across the Permian-Triassic boundary to differentiate between geological and oceanic sources of CO2 release during the end-Permian extinction.

If the greatest hazard to advanced life comes from ocean dynamics, then understanding deep planetary processes may not be necessary for assessing planetary habitability. However, knowledge of the interior dynamics of planetary bodies may be essential to evaluating habitability if processes such as mantle plume formation can have a severe negative impact on advanced life. A Permian-Triassic calcium isotope record will help us to identify whether the greatest threats to advanced life involve surface processes only or whether they also involve factors hidden deep beneath the crust.

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**Elisabetta Pierazzo/Planetary Science Institute**

**Impacts and environmental catastrophes: Investigating the effects of impact events on the climate system**

An environmental catastrophe occurs when abrupt changes in the environment lead to an increased mortality of living organisms that may culminate in a mass extinction. This may have happened as a result of the Cretaceous/Paleogene boundary impact event. Environmental catastrophes that do not culminate in mass extinction events are much more difficult to identify in the geologic record. Therefore, we cannot identify potentially important environmental effects associated with other impact events recorded on Earth. Today’s world is strongly affected by the rise of human civilization. Natural resources can barely support the world population, and we depend on the development of new technologies (genetically enhanced crops and livestock, alternative energy sources) to support our civilization. What would happen if an asteroid or comet struck the Earth’s surface in the near future? While the Spaceguard Survey is close to identifying the
majority of large Near Earth Asteroids, little specific work has been dedicated to the investigation of the potential environmental consequences of non-mass-extinction size impacts.

We want to use state-of-the-art three-dimensional climate models to investigate quantitatively the environmental and climatic perturbation associated with the impact hazard. The main goals of the proposed work are to:

1) Model the impact of potentially dangerous asteroids and/or comets between about 300m and 2km in diameter. The simulations will provide estimates of the amount and distribution of material ejected and deposited in the atmosphere.

2) Model the perturbation of atmosphere’s radiative, dynamic and chemical state following the injection of impact-related material and energy, and investigate the relative perturbation of the climate system, and in particular the hydrologic cycle, over time.

3) Assess the atmospheric and climatic perturbations associated with the large K/P impact event. In particular, we wish to re-address the short-term perturbation of the atmosphere’s dynamics and chemistry from energy, dust, water and CO2 loads.

Richard Quinn/SETI Institute
Astrobiological Investigations of Martian Perchlorate and Carbonate Containing Soils

Several remarkable discoveries made by the Mars Phoenix Mission Science Team have recently been described in the press including, an alkaline soil pH as well as the presence of both perchlorates and carbonates. These results have shown that either the polar-region soils are quite unique, or else that the global soil unit on Mars has unexpected properties. In light of these ground-breaking new results, and their potentially major impact upon habitability and the design of future experiments to search for life forms on Mars, it is appropriate to assess the implications on astrobiology in a timely and thorough manner.

The primary objective of this work is to experimentally and theoretically model processes that perchlorate and carbonate chemistry may play in the alteration of organic biosignatures on Mars. On Mars, as on Earth, both reaction kinetics and thermodynamic energetics play roles in determining which chemical mechanisms dominate and correspondingly what final products are formed. The parameters that will be investigated in this work that dictate which mechanisms will dominate include: perchlorate and carbonate chemistry, the possible catalytic nature of natural components in the soil (especially Fe minerals, and certain other transition elements), water activity, temperature, the details of the soil-organic interface, the oxygen activity in the system, and the presence of other types of oxidizing species such as odd-oxygen and odd-hydrogen species. We will also reexamine the Viking chemistry results (GCMS and life detection experiments) in the context of these Phoenix discoveries to establish whether the Viking data sets are consistent with the presence of perchlorate (and related compounds) and carbonates at those two landing sites.
The need for investigation results from the desire to characterize the distribution, lifetime, and chemical state of organic content of soil and soil/ice surface materials on Mars. The likelihood of the successful detection of organic compounds on Mars and the successful interpretation of the significance of the chemical distribution of detected organic compounds will be greatly enhanced by an understanding of the rate and nature of any chemical weathering that may be altering compounds of interest. This project directly addresses the NASA Astrobiology Program goal to understand "Planetary Conditions for Life" and NASA Strategic Subgoal 3C "Advance scientific knowledge of the origin and history of the solar system, the potential for life elsewhere, and the hazards and resources present as humans explore space". This project will address these goals by constraining and extending the understanding of the organic chemical systems and processes that are relevant to the origin, preservation and distribution of organic biomarkers on Mars.

Kevin Sowers/University of Maryland Biotechnology Institute
Desiccation and Radiation Tolerance by the Anaerobic Methane Producing Archaeon Methanosarcina Barkeri: A Model for Extraterrestrial Adaptation

The discovery of microbial life in extremes ranging from deep submarine vents and subsurface rock to frozen Antarctic lakes have extended parameters of environments now considered hospitable to life. Compared with most extremophiles that have evolved specific adaptations for survival within a narrow range of environments, the methanogenic archaeon M. barkeri has the ability to survive in a broader range of adverse environments. This obligately anaerobic, single cell microorganism requires only water and minerals as nutrients can obtain cellular nitrogen from nitrogen gas and uses simple substrates such as hydrogen as an energy source for growth. Our preliminary data indicate that M. barkeri has developed mechanisms that enable this species to survive extreme conditions similar to those observed for spore formers, but with unique mechanisms that do not involve spore formation, nor does this species depend on robust DNA repair mechanisms associated with hyperthermophiles and halophiles for long term survival in a desiccated state. The formation of unicellular structures by synthesis of a unique extracellular polymeric substance (EPS), which is chemically similar to mammalian chondroitin, has a key role in the long term survival of this species in a desiccated state without significant loss of viability. Unknown processes associated with the desiccation process also appear to increase resistance of desiccated cells to high temperatures and oxidation. We propose to study the mechanisms of adaptation by M. barkeri to extreme conditions using biochemical, genomic and genetic approaches. DNA microarrays will be used to identify genes expressed in response to desiccation and compared with morphological changes observed by 3D tomography. By defining the adaptive strategies of M. barkeri this research will seek to redefine the range of physiological parameters for survival and identify on a molecular level the unique mechanisms that enable this species to maintain viability after extended periods of desiccation.
Roger Summons/Massachusetts Institute of Technology
Molecular and Isotopic Studies of Two Contrasting Mass Extinction Events

Processes which lead to biological mass extinctions in the Phanerozoic are topics of debate within the astrobiological and paleontological communities. Of the “big five”, mass extinctions at the end of the Cretaceous (K-P) and the end of the Permian (P-T) continue to command most interest and research activity. The K-P Event is widely accepted to have been accompanied by a large bolide impact but the actual extinction mechanism remains unclear. In contrast, the inception, duration and causes of the P-T Event are all controversial.

Research conducted during the current period of NASA Exobiology support shows that, of eight well-documented sections of P-T Event distributed across the Tethys, Panthalassic and Boreal oceans, all show molecular evidence for euxinic conditions in the upper water column. Biogeochemical data suggests there was a long-term disruption to the N-cycle and that planktonic communities were dominated by bacteria, not algae, for significant periods of time presaging and following the extinction. Tectonic processes likely underlie this event.

Here we propose a high resolution study of biogeochemical signals through the K-P Extinction at an expanded section of the Fish Clay and bounding chalks at Stevns Klint, Denmark. We will compare these signals with those present at the Permian-Triassic Boundary where we will continue to examine events that presaged the extinction. We will focus on processes that can be discerned by biomarker and isotopic analyses of Middle and Late Permian marine and lacustrine sections to determine the succession of plankton communities. We will investigate the Lopingian and Changshingian stages to better understand paleoenvironmental conditions at different localities prior to the main extinction event.

Studies of the environmental conditions associated with the evolution of advanced life, including the planetary and extra-terrestrial processes leading to mass extinctions, are of particular interest to the NASA Exobiology Program.

Christopher Switzer/University of California
Search for a pre-RNA

This proposal seeks to identify molecular evolutionary predecessors to RNA, or pre-RNAs. The proposed work explores the capacity of simplified nucleic acids with alternative backbones or base-pairs for template-directed replication. The capacity of a pre-RNA candidate for replication will be assessed through template-directed polymerization reactions and biophysical studies. Template-directed polymerization reactions will be conducted enzymatically. Biophysical studies will screen for the formation of stable secondary structures, such as a double helix. The proposed studies will take advantage of late developing information in published work from the PI's laboratory -- the recent demonstration of two distinct cases where accurate copying by a polymerase enzyme of one informational polymer into another occurred, despite the
inability of the two polymers to interact to form a stable double-stranded secondary structure free in solution. In modern terms, this outcome implies that the formation of a free-standing DNA/RNA chimeric double helix is not required for transcription. These recent results will be used to cast a wider net for pre-RNAs than previously considered, and to develop better and more exacting criteria for evaluation of the candidates. In particular, greater emphasis will be placed on enzymatic over non-enzymatic template-directed synthesis during evaluation, including the use of a novel polymerization catalyst. The proposed work is part of the longer-term goal of creating a pre-RNA polymerase composed of pre-RNA and re-creation of the pre-RNA World.

Brian Thomas/Washburn University
Astrophysical Ionizing Photon Events and Primary Productivity of Earth's Oceans

Previous work has shown that ionizing photons from astrophysical events such as gamma-ray bursts (GRBs) and supernovae (SNe) may have a significant impact on the Earth's atmosphere and biosphere through ozone depletion and subsequent enhancement of surface level solar ultraviolet (UV) radiation. Primary producers in the oceans are expected to be especially hard-hit by such events, potentially affecting the entire marine ecosystem and beyond.

The goal of this study is to substantially improve predictions of the impact of such ionizing photon sources on primary producers in Earth's oceans. We will:
1. Conduct a census of the various probable sources of ionizing photons in the Galaxy, utilizing the best rate, spectral, and intensity data available from galactic and extragalactic observations, to assess likely impact on terrestrial planets.
2. Model atmospheric effects, especially ozone depletion, due to sufficiently energetic events and determine enhancement of biologically active irradiance for ozone-depleted atmospheres.
3. Experimentally measure biological weighting functions for the most important primary producers in the oceans, and apply these weighting functions to computed irradiance to quantify the biological impact.

Our methodology will include:
* analysis of data existing in the literature and newly available from NASA missions such as Swift and the Fermi Gamma-ray Space Telescope
* computational modeling of atmospheric effects of ionizing photons
* computational and analytical modeling of transmission of UV through the atmosphere and into ocean water
* laboratory experimental evaluation of UV effects on primary producer organisms

This study is directly relevant to the Evolution of Advanced Life research area specified in the Exobiology and Evolutionary Biology call, which specifically mentions gamma-ray bursts. It also suggests that mass extinctions are of special interest, and ionizing events are a major causal candidate. We will address several areas of interest described in the Astrobiology Roadmap (also mentioned in the Exo/Evo call): 1) Ionizing photon events are not distributed uniformly in the Galaxy; this will help in understanding the
distribution of habitable planets (Goal 1). 2) Events to be considered will put constraints on the emergence of life on planetary surfaces or atmospheres, and may impact the possible survival of life being transferred from one planet to another (Goal 3). 3) Astrophysical ionizing photon events are a direct example of the interaction of the biosphere with its extraterrestrial environment (Goal 4). The Roadmap specifically mentions nearby supernovae, one of the sources in our census. 5) Experimental measurement of biological weighting functions directly contributes to understanding "effects of environmental changes on microbial ecosystems" (Goal 6).

This study also is relevant to a wide variety of NASA missions, past and present, too numerous to list. We consider astrophysical ionizing radiation. Since this radiation interacts so strongly with matter, little of it reaches the surface of the Earth, and nearly all data comes from NASA spaceborne observatories. We use both archival data and data from missions such as Swift and the Fermi Gamma-ray Space Telescope.

Alexandre Tsapin/Jet Propulsion Laboratory
Martian Oxidant

Since the discovery by Viking missions in late 1970s of the presence of strong oxidant(s) in Martian soil, the nature and origin of this oxidant is still a puzzle. Resolving this question about the nature, origin and distribution of strong Martian oxidants is extremely important for Astrobiology and Planetary science. Life as we know it cannot exist in the presence of such oxidants, as it has a destructive effect on organics.

Recent data from the Phoenix lander indicated the presence of perchlorate on the Martian surface. Preliminary measurements of soil pH by the MECA instrument on Phoenix showed that soil in this location is alkaline. Combining these direct measurements on Martian soil made by Phoenix with results obtained 30 years earlier by Viking missions in 2 equatorial locations we elucidate the nature of Martian oxidants. Our hypothesis is supported by laboratory experiments we carried out and published in 2000 - 2003.

We propose a testable hypothesis about the nature of the Martian oxidant. We will show that grinding perchlorate with soil particles containing Fe(III) results in the tribochemical synthesis of a strong oxidant - ferrate Fe(VI).

Just the evidence of perchlorate in the top layer of Martian soil cannot solve the conundrum of Martian oxidants found by the Viking missions. If one adds water to perchlorate, mimicking the Viking experiment, nothing really happens - there will be no water decomposition, and no oxygen evolution. And the reason is very simple - perchlorate in a water solution does not manifest the properties of a strong oxidant. Perchlorate solutions are very stable. However, it is possible to make much more reactive compounds, namely ferrates Fe(VI) that can and will oxidize water with oxygen evolution. It can be achieved by tribochemical processes that involved mechanical mixing of perchlorate with sandy particles containing Fe(III), that are ubiquitous on Martian surface. It is important that synthesis of Fe(VI) from perchlorates through tribochemical pathways can be achieved only in water-free conditions. As soon as there is water present it will dissolve perchlorate, diminishing its reactivity almost completely.
We propose continued investigation of two kinds of hot spring microbial mats that are considered modern analogs of the Earth’s most abundant Precambrian fossils (stromatolites). One type is constructed by cyanobacteria, whose oxygenic photosynthesis is thought to have played a role in oxygenation of Earth’s atmosphere. The other type is constructed by anoxygenic phototrophic microorganisms that do not produce oxygen and may have been more primordial. Our project has five main objectives:

(1) We will compare newly available metagenomes from oxygenic and anoxygenic mats, and genomes from genetically relevant anoxygenic phototrophic isolates (some of which we will obtain in this study), to identify the genes in the community associated with populations of these kinds of mat inhabitants and thereby gain insight into their metabolisms.

(2) We will study the diversity and distributions of four types of anoxygenic phototrophs (including two that were just discovered) relative to different hot spring environments in order to gain insight into how environmental features have affected their evolution. To do so we will conduct cultivation-independent surveys of diversity based on sequences of a common housekeeping gene and key metabolic genes involved with photosynthesis. These sequences will enable us to design ways to study the distribution of these phototrophs quantitatively.

(3) We will use insights gained from genomic, metagenomic analyses and distribution relative to physiochemical conditions in the effluent water and mat microenvironments to cultivate genetically relevant isolates of Chloroflexus and green sulfur bacteria, and to obtain additional strains of a newly discovered phototrophic acidobacterium.

(4) We will study the lipids and 13C fractionations of these isolates in order to learn whether they contain distinctive “chemical fossils” that might persist in the geologic record and thus provide information about the kinds of microorganisms and metabolic processes that once occurred in fossilized mat communities.

(5) We will study how the metabolisms of these four types of anoxygenic phototrophs shift through the daily light cycle in order to better understand how light and other environmental resources have been partitioned through evolutionary processes to provide niches for so many diverse types of phototrophs. To do so we will measure when these organisms turn on and off genes associated with different metabolic pathways.

This research is significant in many ways to the interests of NASA because it focuses on understanding (i) the predominant types of microbial communities that left a record of their presence during the Precambrian Era, (ii) a type of metabolism that was one of biology’s greatest inventions and that changed the face of the planet in terms of its
atmosphere and the possibility for evolution of more advanced life forms, (iii) the interactions within microbial communities that control biogeochemical cycles and (iv) the environmental extremes tolerated by life.

Rachel Whitaker/University of Illinois
Geochemical Change in Isolated Extreme Environments Defines the Evolutionary Trajectory of the Thermoacidophilic Crenarchaeon Sulfolobus islandicus and its Pan-genome.

Life on Earth likely evolved in extreme environments. On Earth today, extreme environments are fragmented, discontinuous, and often unstable over time. This proposal addresses population dynamics of thermoacidophilic Archaea to determine the evolutionary consequences of living in structured and highly variable environments, analogous to conditions on early Earth. We propose to examine how the interplay between three fundamental evolutionary processes important to early life on Earth (horizontal genetic exchange, gene loss, and interactions with viruses and plasmids) and environmental change shape evolutionary dynamics. By identifying relationships between environmental heterogeneity and genome dynamics, this proposal will link the two natural repositories of evolutionary history: the molecular record in living organisms and the geological record. Calibrating molecular and geologic evolution will provide accurate rates of molecular evolution, tools for determining the time scale on which microbial life on other planets may have diverged from microorganisms on Earth, and predictions about the rates at which new organisms introduced by humans to other planets will adapt to their new environments. Understanding genome dynamics in extant microorganisms from extreme environments will define parameters for modeling the evolutionary processes of primitive organisms and the environment in which they evolved.

We propose the following primary objectives to explore the ways that spatial and temporal heterogeneity shape the evolutionary trajectory of extremophilic organisms.

1. Identify the generation and spatial distribution of genetic and genomic variation within thermoacidophilic Sulfolobus species.

2. Determine how temporal environmental changes shape genomic variation in Sulfolobus.

Both objectives overlay high-resolution genomics, metagenomics, and quantitative measures of microbial population dynamics with geochemical environmental parameters through time and space. Both assess diversity and its dynamics in the core (maintained in all members of a species) and variable (varying among individuals) components of the microbial pan-genome.
Shuhai Xiao/Virginia Polytechnic Institute and State University
Integrated Morphological, Taphonomic, Ecological, and Geochemical Investigation
of a Weakly Biomineralized Biota of Late Ediacaran Age: Prelude to the Evolution
of Advanced Life

The radiation of biomineralizing animals during the Cambrian explosion is an important
evolutionary innovation that signifies both the advent of advanced life forms and
complex Earth systems, because it markedly modified the dynamics of marine
ecosystems and global biogeochemical cycles. This radiation, however, was preceded by
the evolution of a few weakly biomineralizing animals in the late Ediacaran Period
(~550-541 Ma), which can be regarded as a prelude to the evolution of more advanced
life forms during the Cambrian explosion. But the morphology, phylogenetic affinities,
and ecology of these Ediacaran biomineralizing organisms are poorly understood,
hindering our attempt to gauge their significance to the widespread emergence of
biomineralization and evolution of complex life. To contribute to this knowledge gap, we
propose to carry out an integrated investigation of a weakly biomineralized biota
preserved in the Gaojiashan Member of the late Ediacaran Dengying Formation (~551-
541 Ma) in South China. The proposed research directly addresses NASA's Strategic
Subgoal 3D: Discover the origin, structure, evolution, and destiny of the universe. More
specifically, it supports the research emphasis of NASA's Exobiology and Evolutionary
Biology Program (EEB) research directive on the evolution of advanced life.

The research team identifies the Gaojiashan biota (551-541 million years old) of the
Dengying Formation in southern Shaanxi Province, South China, as their research focus.
The Gaojiashan biota represents one of the earliest biomineralizing faunas on Earth.
Previously published reports and preliminary research show that the Gaojiashan biota is
not only one of the most diverse early biomineralizing eukaryote communities, but it also
provides exceptionally and uniquely preserved fossils that allow for extraction, three
dimensional (3-D) morphological characterization, and geochemical analyses. This biota
contains calcareous, phosphatized, and pyritized fossils, allowing for taphonomic
comparisons among different preservational styles. Such morphological and taphonomic
analyses, coupled with sedimentological and geochemical data, form a solid basis for
ecological and phylogenetic interpretation. The Gaojiashan biota will be analyzed using a
variety of advanced technologies, including scanning and transmission electron
microscopy (SEM and TEM), laser ablation inductively coupled plasma mass
spectrometry (LA-ICP-MS), X-ray computed tomography (X-ray CT), focused ion beam
electron microscopy (FIB or FIB-EM), and secondary ion mass spectrometry (SIMS).
The objectives of this study in the Gaojiashan biota are to (1) collect stratigraphically
oriented samples and describe sedimentological features; (2) characterize the 3-D
morphologies and ultrastructures of fossils; (3) determine the elemental (Sr, Fe, Mn, P,
Ca, Mg) and isotopic compositions (d13C and d34S) of fossils and their hosting rocks;
(4) infer phylogenetic affinities, taphonomy, and paleoecology of the Gaojiashan biota
from these sedimentological, morphological, and geochemical data. Results from this
study will contribute to the understanding of how the early evolution of biologically
controlled mineralization was linked with the dynamic change of the surface Earth
system, and how it transformed the biosphere in general. Thus, the proposed program of
study directly addresses NASA's research emphasis on the evolution of advanced life on Earth and the search for possible biosignatures of advanced life on other planets.