PRELIMINARY PLANNING DOCUMENT 1
ASTROBIOLOGY AS AN INTERDISCIPLINARY AND INTEGRATING THEME IN SPACE SCIENCES AND EXPLORATION

This part of the planning process is aimed at linking the questions and goals of astrobiology to the new NASA vision. Contact: Bruce Jakosky, jakosky@lasp.colorado.edu

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Astrobiology as an Interdisciplinary and Integrating Theme in Space Science and Exploration: A White Paper in Response to the Nov. 5, 2004, Call for Input

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The NASA Vision for Science and Exploration is, at heart, an *astrobiology* vision. Central issues involve understanding the potential and actual distribution of life elsewhere in the solar system and beyond. These goals respond directly to the intense public interest in determining whether we are alone in the universe, perhaps combined with having achieved for the first time the ability to answer these questions within our lifetimes. Below, we describe briefly an integrated scientific approach to implementing the Exploration Vision in a way that takes advantage of scientific advances in both earth and space sciences.

Astrobiology has many components, including exploration of the Earth, which contains the only known example of life. It seeks to understand Earth's habitability over time, the earliest geological history that provided opportunities for life, the actual origin of life, and the nature of the first organisms. Astrobiologists study ways in which early life interacted with its planetary environment, the co-evolution of organisms and their environment, and the physical and chemical drivers of evolution. Addressing these issues requires a unique combination of interdisciplinary approaches. These include understanding the nature of living organisms and how they function, reading the history of life as recorded in both the biological record (for example, in genomic comparisons that tell us the genetic relationships between organisms) and the geological and fossil record (tying the evolution of organisms to geological processes). Major advances during the last decade involve integrated studies in geology, geochemistry, geophysics, atmospheric science, microbial ecology, evolutionary biology, biochemistry, and molecular biology. From these studies, we can learn about the range of environments that are able to support life, and we try to infer the requirements that an environment must meet in order to sustain either the origin or the continued existence of life.

Beyond Earth, astrobiologists try to determine the range of environments within the solar system that might be capable of sustaining life. They seek to understand the *processes* that were responsible for creating these environments. Only by doing this can they know why our solar system is the way it is and thus be able to extrapolate to the potential for habitable planets or environments in other planetary systems. Understanding planetary habitability involves looking at each planet and satellite in turn, but understanding what controls planetary habitability requires an examination of the interactions between objects and looking at the solar system as an integrated system. For example, important roles in determining Earth's habitability were played by Jupiter, the Kuiper belt, the Oort cloud of comets, and so forth. Only by studying the multiple interactions between all of the different classes of objects can we truly understand how the architecture of our solar system came about and what the broader implications are for habitability. The approaches to this problem come from, for example, planetary science, geology, geochemistry, geophysics, atmospheric science, and celestial mechanics, and they require in situ analysis by spacecraft, sample return to the Earth, telescopic observations, laboratory analyses, and theoretical approaches.

We now know of more than one hundred extrasolar planetary systems. By studying these systems, it will be possible to obtain robust statistics as to the numbers and structures of planetary systems and what the implications might be for habitable planets or satellites there. We then can learn how the processes responsible for producing the architecture of our own solar system may have played out differently elsewhere. In addition, observations of protoplanetary disks provide important constraints on the processes of planet formation and on the chemical and physical properties of the resulting planetary systems. Studying other planetary systems requires a combination of planetary science, cosmochemistry, and astrophysics, and it includes theoretical, telescopic, laboratory, and spacecraft-based approaches.

These three approaches play complementary roles in understanding the nature and potential distribution of life beyond Earth. Earth studies give us a detailed example of the history of a single planet and of the nature of life that is infinitely richer than anything we will learn about other planets for the foreseeable future. By studying the other planets, satellites, and small objects in our solar system, we learn how the system-wide processes affected our own planet and how these same processes gave rise to the tremendous diversity in planetary environments that we see today. And in the exoplanetary systems we can examine a much larger number of systems and see the tremendous range in possible outcomes of planet-forming that are possible even at the grossest scale.

This broadbased approach to understanding planetary habitability and the potential for life, as well as searching for life elsewhere, is a necessary component of an intellectually viable exploration program. For example, a search for life on Mars cannot be fulfilled just by going to Mars and searching for life. There also is a requirement to understand the broader geological and geochemical context in order to be able to determine whether the observable characteristics of martian materials are indicative of biological activity or of abiological processes. The science communities' experiences with both the Viking mission in the 1970s and the martian meteorite ALH84001 in the 1990s demonstrates the difficulties in addressing questions about life detection without understanding the broader context. In each case, initial results were presumptive indicators of biological activity. Each required detailed follow-on analyses involving the characterization of non-biological processes that might be capable of producing the same features before it was possible to reach any firm conclusions about whether or not life might be present in the samples.

A determination of the presence or absence of life on Mars (or elsewhere) requires this broader context from the astrobiological perspective in order to be believable. Knowing, for example, that there is not and never was life on Mars does not, by itself, inform us about the possibility of life elsewhere in the solar system. Similarly, without understanding the processes responsible for the architecture and evolution of our own solar system, it is difficult to say anything meaningful about the occurrence of habitable planets elsewhere. If we wish to be able to predict the occurrence of life elsewhere in the universe, rather than just cataloging on a case-by-case basis where life does or does not exist, it is necessary to investigate and ultimately understand these much broader issues.

Astrobiology represents an effective integrating theme in NASA Science and Exploration programs. It brings together major results from a broad range of disciplines, and focuses their efforts onto a single problem of great scientific and public interest. Only through an integrated approach to understanding the Earth, the solar system, and beyond, can we address the scientific and intellectual questions in front of us in a viable, compelling, and intellectually honest manner.

PRELIMINARY PLANNING DOCUMENT 2
ASTRONOMY AND COSMOCHEMISTRY OF PROTOPLANETARY DISKS

This is an outcome of the Jackson Hole NAI retreat. It focuses on the chemistry of protoplanetrary disks using the tools and theories of both disciplines. Contact: Ed Young young@ess.ucla.edu

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Probing the Chemistry of Protoplanetary Disks

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Introduction: Among the tasks laid out as part of the NASA Vision for Space Exploration is to "conduct advanced telescopic searches for Earth-like planets and habitable environments around other stars." Fundamental to this mission is the need to understand the environment in which Earth, the other planets, and the sun formed. Did our solar system form in an energetic region of high mass stars – such as Orion – or in a more quiescent region of low mass stars – such as Taurus? The chemical compositions of planets, and thus their habitability, are intimately linked with the chemistry of the protoplanetary disk from which they grew. Is the solar system, the only system we know of with terrestrial planets, anomalous with respect to its complement of water? What processes determined the chemical composition of the planets and how do those processes depend on location, temperature, and environs of star formation? In order to answer these questions we need to understand the chemistry and physics of protoplanetary disks.

Another goal of the Vision for Space Exploration is "investigation of the Earth, Moon, Mars and beyond with emphasis on understanding the history of the solar system" (italics added). A full understanding of the record of solar system evolution contained within the rocky and icy bodies can only come if this record is read in the context of the chemical and physical evolution of the solar protoplanetary disk.

The study of astrochemistry in young, extrasolar protoplanetary disks is a rapidly advancing growth area in astrophysics. The recent launch of the Spitzer Space Telescope and the anticipated commissioning of the SOFIA and Herschel observatories promise to revolutionize the field, and the Hubble Space Telescope (HST) has provided astounding images of disks. Nonetheless, further advancements are required. We submit that a priority should be placed on disk astrochemistry in the coming years and that major advances can come only with a commitment by NASA. This endeavor will be truly interdisciplinary as it involves integrating high-resolution astronomical observations of disks, astrophysical models of disks, and new chemical and isotopic data from meteorites and from samples returned from other bodies of the solar system.

Organosynthesis in disks: From where did the building blocks for life in our solar system originate? Speculations abound. Most emphasize the delivery of organics to Earth during the chaotic period when the solar system was cleared of the rocky and icy flotsam and jetsam from which planets were made. Comets are the most pristine harbingers of these primitive sources of organic molecules. It is possible that the organics within comets were synthesized prior to formation of the protoplanetary disk. However, it appears that disks themselves are rife with opportunities for organosynthesis. Models suggest that ion-molecule reactions at disk surfaces involving organic compounds released from ices are veritable factories for organic chemistry and the high ultraviolet (UV) fluxes attending young star formation provides for photochemistry involving gases and ices. Chemical and isotopic studies of meteorites show that the planets were made not from aggregates of pristine molecular cloud solids but rather from highly-processed materials transformed within the confines of the solar protoplanetary disk. For example, the $^{15}N/^{14}N$ variability in asteroids (meteorites) is less than the variability in comets which is in turn less than the variability seen among presolar grains. Solar system organics and terrestrial reservoirs have high $^{15}N/^{14}N$ compared with estimates of bulk solar system values and the variations in solar system $^{15}N/^{14}N$ exceed what is accessible by ion-molecule reactions alone. Analogous arguments obtain for the isotopes of carbon. Signals such as these imply extensive processing within the disk. Evidently, chemistry within the solar protoplanetary disk played a crucial role in determining the nature of organic compounds that were ultimately delivered to Earth. Direct observation of organic chemistry deep within disks will be required to understand the origin of the building blocks of life.

Delivering water to rocky planets: The origin of Earth's oceans is another question closely tied to protoplanetary disk chemistry. Here again, comparisons between isotope ratios in rocky and icy bodies of the solar system and expectations from variations within disks prove crucial. It has been argued that since D/H in comets is about twice the ratio for terrestrial water, that comets can't be the source of Earth's oceans. Results from chemical and isotopic models for protoplanetary disk evolution show that this conclusion is too simplistic. The expected D/H of gas-phase molecules within the interiors of a single disk vary by orders of magnitude. The lesson is that before we can interpret intelligently measurements of isotope ratios from meteorites, comets, and samples returned from primitive bodies we must understand the chemical variability of, and transport within, protoplanetary disks. This understanding will come from verification of detailed chemical and physical disk models by new observations.

The goal is to understand disk evolution with the same level of detail that obtains for stellar evolution. Only NASA can provide the resources necessary to develop the new observational tools required. As planned, the James Webb Space Telescope (JWST) will have the capability to measure D/H in solar system comets, a key data set for verifying chemical models for disk evolution. The Spitzer Space Telescope is already providing direct evidence for water ice in the interiors of disks, but further understanding will require imaging deeper.

Developing tools to probe deeper into disks: Probing the chemistry and physical state of disk interiors requires high sensitivity, high angular resolution, and high spectral resolution at wavelengths that penetrate to the midplane of the disks. The mid-infrared wavelengths from 2.5 to 300 micrometers (μm) are most suitable given the luminosity of young disks in this spectral region. The terrestrial atmosphere is opaque and bright at these wavelengths, meaning that *spacebased platforms will be needed.*

In order to resolve features in disks at a scale commensurate with the distribution of planets in the solar system (1 to 10 AU), at distances comparable to Orion for example, these new tools will need angular resolutions of ~ 2 to 20 milli-arcseconds. Apertures or interferometer baselines of roughly 10^8 wavelengths will be necessary. This scale (e.g., 100 m to 1 km at μm or 1 to 10 km at 100 μm) implies large interferometers in space, although ground-based projects like the Atacama Large Millimeter Array (ALMA) for mm and sub-mm observations represent a significant first step. "Astromineralogy" of ices and silicate/oxide grains (the ultimate building blocks of rocky planets) requires spectral resolution ($\lambda/\Delta\lambda$) on the order of 10^3 to 10^4. Measurement of thermal and turbulent line widths, isotope shifts in ro-vibrational transitions in molecules, and disk kinematics requires resolutions on the order of 10^5. Both incoherent and coherent/heterodyne methods should be developed to make these measurements in the short wavelength, medium spectral resolution and the long-wavelength high spectral imaging regimes, respectively. In the longer term, the Terrestrial Planet Finder (TPF/Darwin) mission will meet some of these needs, if high spectral resolution options are included, and will bring important new capabilities to studying disks in addition to finding terrestrial exo-planets.

In the near term, the JWST will provide images with 10 to 100 AU angular resolution. However, there are at present no approved space-based missions to provide spectroscopic resolution greater than 3000. NASA should seek to ensure that the JWST has the near-infrared and mid-infrared capabilities to permit detection of ices and other molecules within disks. Proposals to construct space-based infra-red observatories optimized for organic compound detection (e.g., high spectral resolution) represent opportunities for taking the first steps towards a better understanding of disk chemistry as it relates to the origins of life.

Lastly, these new pursuits should include ample support for theory, laboratory astrophysics, and laboratory chemical and isotopic analysis of samples (sample return and meteorites) as these areas of research provide important driving forces and ground truth for the observation programs.

PRELIMINARY PLANNING DOCUMENT 3
COLLISIONAL PROCESSES IN THE EVOLUTION OF PLANETS AND LIFE

This was a "grass roots" white paper which is added here because it incorporates and extends the scientific activities of the NAI's Impacts and Evolution Focus Group.
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COLLISIONAL PROCESSES AND ASTROBIOLOGY
A White Paper in Response to the Nov. 5, 2004, Call for Input

David Morrison (NASA Astrobiology Institute), Peter Ward (University of Washington),
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Note: This white paper addresses the astrobiology aspects of one example topic from the HQ request: "How have collisional processes played a role at differing time and spatial scales within our solar system in creating such a diverse and yet related set of terrestrial planets, with unique atmospheres? What shaped the biological systems on Earth during the last few billion years of planetary history?"

One of the fundamental science developments of the past quarter century has been the recognition of the role in Earth history of impacts by asteroids and comets. At the same time, space exploration has revealed impact cratering as a ubiquitous process for sculpting landforms and exchange of materials on the planets, moons, and smaller bodies of the solar system.

A parallel revolution has occurred in the life sciences. Up through the late 1970s, mass extinctions were thought to have been gradual events of multi-million-year duration that caused a slow change in the flora and fauna of the Earth. However, the identification of the end-Cretaceous (KT) extinction as resulting from collision with an asteroid or comet has introduced a new paradigm to paleontology and evolutionary biology. We now recognize that the history of life on Earth has been punctuated by catastrophic events, apparently both endogenic and exogenic in origin. Further, we are beginning to realize that these sudden events have been critical for the course of biological evolution. Understanding such catastrophic processes is necessary not only to interpret the history of the Earth, but also to evaluate the prospects for life on other worlds.

The frequency and intensity of mass extinctions may significantly influence both the emergence of complex life (metazoans) and their duration. Mass extinctions are probably of greatest consequence to metazoans, while microbes are less susceptible. Short of planetary sterilization by a supernova or very large collision, the deep microbial biosphere of any planet serves as an effective reserve of life, because the regions several kilometers beneath the surface are effectively insulated from even prodigious disasters affecting the surface regions. Surface life, on the other hand, even bacterial surface life, is susceptible to major planetary catastrophes. It may be that life on the surface of Earth was repeatedly sterilized during the period of heavy bombardment about 4 billion years ago, only to be re-seeded by the deep-Earth microbes, or by rocks ejected by the collision and then returned to Earth. But for animal life, quite the opposite is true; if they are wiped out by catastrophe they cannot be restocked from some underground reserve. They have to be re-evolved, a process potentially lasting hundreds of millions or even billions of years. On Earth, mass extinction events were followed by rapid periods of diversification leading to a higher global biodiversity. The frequency and severity of mass extinction are factors influencing the evolutionary history of any planet with life, and are thus appropriate areas of astrobiological study.

At the present time two major questions dominate study of mass extinctions. First, we ask: Is there a critical number and severity of mass extinctions necessary for the development, and/or subsequent diversification of metazoans? The second major question deals with causation. Of the so-called “Big Five” extinctions (the Ordovician, Devonian, Permian, Triassic, and Cretaceous events), only the end Cretaceous (KT) event has consensus as to cause: asteroid impact. Yet, impact as a cause for the other major Phanerozoic extinctions cannot yet be ruled out, nor have convincing alternative scenarios emerged.

Impacts by asteroids and comets are not of purely historical interest. The Earth is continuously bombarded by small space debris, and occasional it is struck by larger objects. The risk to human life and property from such impacts is substantial, at a level comparable to that of other natural hazards (earthquakes, volcanoes, floods) that are taken very seriously by society. NASA's mission arguably includes understanding and ultimately controlling our impact environment.

There is great potential for improving our understanding of the current impact environment of the Earth and the effect of such impacts on the viability of the planet. NASA-supported surveys are discovering thousands of new Near Earth Objects, determining their orbits, and providing insight into their dynamics. NASA space missions are visiting asteroids and comets and providing us detailed information on their composition, structure, and history. First efforts are even being made to explore ways to defend against impacts by carrying out direct experiments through the Deep Impact mission and the proposed Prometheus space tug mission.

Research on impacts will be important for the improved understanding of the Moon that will both precede and accompany new missions, including human visits. The Moon records the joint bombardment history of both Moon and Earth, including the period during which life originated on Earth. One important aspect of lunar exploration (robotic and manned) will be getting a better handle on its early impact history as an input to the terrestrial history in the Archean. To interpret the lunar data, we need new age dates on returned samples, seismic studies of lunar impact basins, and better models of the effects of large impacts on both airless bodies like the Moon and those with atmospheres and oceans like the Earth. It will also be important to refine our understanding of the consequences for the biosphere of large impacts on Earth.

There is tremendous potential in these multifaceted investigations for cross-disciplinary studies of potential impactors and of the consequences of their collisions with the Earth. One of the prime motivations in such studies is to understand the cosmic context for the evolution of life on our planet and, perhaps, on others. Another product of such studies will be strategies to protect our planet from catastrophic collisions in the future. A third long-range motivation is to understand the potential space resources represented by near-Earth comets and asteroids.

In summary: We encourage an integrated approach to research on collisions and cratering, including: improved modeling of the collisional process and its environmental consequences on Earth (both ancient and contemporary); examination of the range of physical properties of potential impactors (near-Earth asteroids and comets); linking lunar and terrestrial cratering histories through in-situ investigations and lunar sample return; modeling of the response of life to environmental crises associated with mass extinctions; and detailed examination of the geological mass extinction record in order to understand these evolutionary drivers for life on Earth.

PRELIMINARY PLANNING DOCUMENT 4
EARLY EARTH AS A GUIDE TO THE SEARCH FOR HABITABLE WORLDS

This topic has evolved from the "Earth in Transition" initiative of the Jackson Hole NAI retreat.
It also continues the work of the NAI's former Mission to Early Earth focus group.
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Exploring Earth's Past as a Guide in the Search for Habitable Worlds

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The Earth is the only planet known to harbor life and so it is inevitable that the prospects for life beyond Earth will be measured against our knowledge of Earth's biosphere. However, during most of the past 4 billion years, life and environment on Earth were profoundly different than the modern state. For example, for the first half of Earth's history, the atmosphere was anoxic and transparent to ultraviolet radiation. Its radiative characteristics as observed from space would have been fundamentally different from those seen today. Thus, studying Earth's past ensures that the astronomical exploration of exoplanets is not refracted through the prism of the modern Earth. Early Earth research also reveals general principles that allow astrobiologists to assess the habitability of planets in solar systems fundamentally different from our own, and it stimulates the development of tools and paradigms useful for life detection within the Solar System. Exploration of Earth's past is therefore an essential complement in the search for habitable worlds.

Long-lived steady states in the evolution of Earth's ocean-atmosphere system are particularly important targets for exploration. Our knowledge of these periods strongly influences our understanding of how terrestrial planetary atmospheres evolve and how diverse metabolisms can influence atmospheric composition on a planetary scale. Examination of these periods therefore guides the design of observations and instruments that might, for example, be used in exploration for signs of extant life in the atmospheres of Mars or planets circling other stars. These long-lived steady-state periods also act as extensive and diverse geological testbeds for life detection methods that may be applied in future to search for evidence of past life on Mars, whether it be by means of in situ experiments or examination of returned samples.

Knowledge of these steady states in Earth's atmospheric evolution and the transitions between these periods of stasis comes from research that integrates many kinds of observational data. For example, pioneering work published in 2000 by James Farquhar and his colleagues demonstrated that the gas-phase chemistry of atmospheric sulfur compounds is prohibited by a trace amount of oxygen in the atmosphere and that this chemistry may be recorded in sedimentary rocks. Rocks older than about 2.3 billion years show a profound change in sulfur chemistry that reflects the rise of atmospheric oxygen. At that time, the modern oxygen-rich atmosphere began to develop, possibly very rapidly, leading ultimately to the modern conditions. This time of atmospheric transition is also reflected in the geological record of the global carbon cycle and in sedimentary rocks that preserve evidence of worldwide glaciation. Models suggest that this glaciation may have coincided with a transition from methane-dominated to carbon dioxide-dominated greenhouse warming. Geological and geochemical data point to an approximately concomitant change in the chemistry of the bulk ocean from one containing dissolved iron to one in which iron was scarce, possibly because of an increase in biologically-produced sulfide. Research into molecular organic biomarkers is in progress to elucidate the changes in microbial ecology during this time. Thus, integration of diverse lines of evidence reveals how the connections between atmospheric, oceanic, living, and non-living processes operated before, during and after one of the most profound transitions in the state of the whole Earth system.

The NASA Astrobiology Institute advocates an integrated research and analysis focus on these long-lived steady states in Earth's atmosphere-ocean history and on the transitions between them. Three principal periods have been identified for future work:

(1) The almost unknown Hadean (4.6 to 3.9 billion years ago), prior to the oldest known record of sedimentary rocks. Two difficult approaches to sampling this time period are advocated: Searching for Hadean-age minerals and possibly rock fragments recycled into younger sedimentary rocks by normal erosive processes or by impacts into Hadean-age targets; and directed sampling of the Lunar regolith for Hadean-age material ejected from Earth and preserved on the Moon.

(2) The Archean to early Paleoproterozoic (3.9 to 2.2 billion years ago). For most of this time the atmosphere of the Earth was oxygen-free and the ocean iron-rich. Understanding the nature of the surfical environment and the biota it supported will greatly inform the development of ambitious experiments like the NAI's Virtual Planetary Laboratory. This NAI team is attempting to build a numerical model of a complete planet, which can be "observed" remotely, by connecting existing codes for core and mantle circulation with coupled ocean-atmosphere models

(3) The remainder of the Proterozoic (2.2 to 0.5 billion years ago). This second steady state in Earth history, dubbed by one investigator as the "boring billion", is increasingly seen to have been very different from both the modern and the Archean worlds. In particular, the chemistry and biology of the oceans during this time seems to bear the fingerprint of an extended transition from an anoxic to a fully oxygenated atmosphere.

Tools that may be used to address these questions are principally geochemical, geological, and paleobiological. The results obtained by the geosciences communities then need to be transferred in a connected collaborative fashion, via the earth system sciences community, to the planetary and astronomical communities. This is a recommendation for an interdisciplinary research and analysis initiative within the astronomical and geosciences communities to address fundamental questions that bear on the detection and characterization of habitable and inhabited worlds.

PRELIMINARY PLANNING DOCUMENT 5
CHEMISTRY, DIVERSITY, ORIGIN AND SYNTHESIS OF LIFE

This topic is new to the planning table but is clearly an area in which the NAI has deep and wide multidisciplinary interests. Contact: Peter Ward, argo@u.washington.edu

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Evolution and Chemistry of Life

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Introduction: The frequency of life in Solar System, let alone the galaxy remains one of the greatest unanswered questions facing humankind. Is the emergence of life (or its seeding from elsewhere) a very rare event in the Cosmos, or will we find that life had emerged on most planets or moons within the Habitable Zone? (defined here as a region where a planet has had temperatures allowing the long term existence of liquid water). An equaling pressing question, and one that directly affects the frequency of life question, concerns the possible chemical diversity of life that might exist. If, for example, it can be concluded that only a small number of plausible biochemical strategies exists for any life to exist, e.g. all life requiring information molecules such as DNA and, further, that this chemistry is inextricably connected to early Earth environmental conditions, then the number of Earth like planets that exist will approximately dictate the frequency of life in the Universe. If, on the other hand, there are a broad variety of potential biochemistries permissible for life (unlike life as we know it) then on bodies with temperatures either much higher or much lower than those on Earth, (such as the high temperatures on Venus, or the very low temperatures on the moons Europa and Titan), we may find that life will be abundant indeed. As it currently stands we do not have a robust theory for the origin of life on Earth, let alone a universal theory that would allow us to place restrictions on the extent of life in the Solar System beyond the obviously most inhospitable environments.

The Chemistry of Life: As the only example of known life, the history of how Earth life first evolved, and then diversified, is crucial in understanding larger questions about the frequency of life. Approaches to this question include the study of the ancient Earth, in order to better understand the chemistry and location of life's first formation on Earth, as well as to constrain the morphology of early Earth life from fossils where possible. But a second methodology is through laboratory attempts to create the building blocks of life, or even primitive life itself through simulations of the early Earth's atmosphere and energy sources. This second approach can also be used to examine alternatives to Earth life, or DNA life, by perturbing components of extant life, such as experiments in which DNA is chemically altered into forms that are not now known on Earth, but which remain functional.

The highly successful missions in recent years to Mars, the Jupiter neighborhood, and to Titan have greatly enhanced our understanding of environmental conditions on these three bodies, which appear to have the highest chance of having life in our Solar System beyond Earth. For each we can ask: 1. Are there environments now (or in the past) that have a range of conditions that could sustain Earth-like life, and if so, what kind of Earth life? 2. Even if such conditions exist, are there pathways or environments under which life could conceivably evolve on a given planet or moon? 3. For any planet or moon in the Solar System beyond Earth, are there mechanisms by which life might be transported from another planet or moon through the mechanisms collectively known as Panspermia? 4. If Earth life conditions are not found, is there a conceivable chemistry intrinsic to a given planet that may have provided for a form of life unlike that on Earth.

While progress has been made towards addressing aspects of these questions much remains to be done. It is now clear that within the atmospheres and oceans of early terrestrial planets, chemistry could have occurred to provide key molecular building blocks of life, e.g. amino acids, alpha keto acids, and possibly nucleobases. Recently it has been shown that the synthesis of ribose may naturally occur in environments with borate minerals; thus removing a major obstacle in certain theoretical models about the origin of life on Earth as well as leading to a hypothesis about specific environments on Earth where life may have evolved (e.g. impact craters in desert regions). The problem of spontaneous synthesis of peptides from amino-acids has been circumvented by the recent discovery that carbonyl sulfide (a common gaseous product of volcanic exhalations) catalytically acts as a condensing agent. Breakthroughs in the artificial synthesis of RNA as well as the artificial formation of cell membranes now give hope that the synthesis of life in the laboratory is a problem now limited only by funds, not by mechanisms. Finally, new chemical models of viable alternatives to DNA, carbon life have raised the possibility that not only Earth life, but also alternative chemistries of life can be artificially created in laboratory settings.

Exploration and Experimentation: The progress made in laboratories and field studies of ancient strata lends new hope to the search for life beyond Earth, and can and should be a central part of the NASA Astrobiology research mission, but presents substantial challenges as well. The artificial synthesis of life can teach us much about how life began on Earth, as well as potentially being of beneficial use in medical fields. If we find that life can indeed be transported across vast distances of space, then we must be even more vigilant against not infecting other planets or moons with Earth life via contamination by our various space probes. Finally, the study of alternative forms of life might show where and how in the Solar System to conduct our search for life. For example, it may be that our current paradigm, essentially one of looking for an abundance of water, is unnecessarily limiting.

What is becoming increasingly clear is that future missions to the surfaces and atmospheres of extraterrestrial bodies must include scientific instrumentation capable of addressing questions regarding organic inventories and potential biochemical signatures of life. The community of scientists under the broad umbrella of Astrobiology are providing critical guidance to the Mars exploration program guiding the conceptual development of the Astrobiology Science Laboratory. Similarly, numerous proposed missions to smaller solar system bodies include extensive consideration into the in-situ analysis of the organic constituents of these bodies, e.g. comets and asteroids, with the ultimate goal of establishing the organic chemical inventory within the solar system and, from this, a better assessment of the extent and limits of life in the Solar System. As part of NASA’s vision for Space Exploration it is imperative that question of the limits of life remain both a question of premier scientific importance, but also one of astronaut safety and extraterrestrial environmental preservation.

PRELIMINARY PLANNING DOCUMENT 6
SUBSURFACE LIFE, EXTREME ENVIRONMENTS, AND THE EXPLORATION FOR LIFE

This was one of the core outcomes of the Jackson Hole NAI retreat.
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Subsurface Life on the Earth and Planets:
A White Paper in Response to the Nov. 5, 2004, Call for Input

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Introduction. A major theme running through the Exploration Vision and Initiative is the determination of the potential and actual distribution of life in the solar system and beyond. Of necessity, we use our one known example of life in the universe to understand the environmental requirements necessary for the origin and the continued existence of life, the interactions that can occur between organisms and their planetary environments, and the locations on planets and satellites that we might explore in searching for evidence of past or present life. Terrestrial evidence indicates that the metabolism of organisms that are deeply rooted in the tree of life can be sustained by subsurface geochemical reactions (such as reactions between water and rock), and that such reactions might even have led to the origin of life. Thus, understanding the nature of subsurface environments on the Earth and planets, the ways in which organisms live in those environments, and the means by which we might search for life in those environments are central to the scientific aspects of the Exploration Initiative. By taking an interdisciplinary approach that involves both terrestrial and planetary studies, and by integrating terrestrial geology, geochemistry, geophysics and microbiology with planetary geology, geochemistry, geophysics, atmospheric chemistry and, potentially, exobiology, we can provide the intellectual underpinnings that can drive both the robotic and human exploration programs.

The results of an integrated, interdisciplinary research focus on subsurface life would be broadly applicable to exploration within the solar system, especially to Mars, Europa, and even Titan, and also are relevant to extrasolar investigations such as Terrestrial Planet Finder. Given present mission timelines, such research efforts are immediately needed in the context of Mars exploration, and the following research areas are identified primarily in that regard.

Themes in exploring subsurface life on Mars. Over the past 15 years research into Earth's subsurface life has encompassed a broad range of scientific disciplines. With recent advances in martian planetary processes, a compelling set of scientific issues related to planetary exploration emerge. Below, we highlight six areas for which new efforts involving interdisciplinary research could make substantial progress in understanding the potential for life on Mars and how to search for it.

(i) Terrestrial drilling and implications for planetary protection. As we plan missions that will search for life on Mars, getting into the subsurface will be key to accessing locations that have been protected for extended periods or that have the potential to harbor life today. This could involve drilling meters, tens of meters, or hundreds of meters, depending on environment and physico-chemical factors. Drilling missions might be done robotically, or they might involve humans. Developing expertise in drilling in terrestrial environments that are similar to possible martian ones is imperative for designing drilling technologies that will minimize spread of biological contamination while enabling autonomous, directed drilling, and thereby improve the chances of mission success. Of special interest will be drilling in martian-analog permafrost, development of drilling fluids, removing contaminants from the drilling apparatus and borehole, and designing down-hole sensing technologies or sample-retrieval systems for

life detection and composition determination. These issues are especially relevant in that they allow us to prepare for martian operations and simultaneously improve our ability to explore subsurface microbial environments on Earth.

(ii) Identification of biomarkers for use in searching for life elsewhere. Any search for martian life necessarily will involve examining characteristics of martian materials and deciding whether they could be uniquely biological in origin (as opposed to having both a biological and a geochemical mechanism). The Viking and ALH84001 experiences underscore the difficulty of identifying characteristics that are solely biological. Additional detailed analysis of terrestrial environments and biosignatures and of martian processes that could mimic them is necessary in order to be able to interpret results from upcoming missions. This will require broadbased analyses on Earth of the types of processes that might occur on Mars, even of those that are purely abiotic, in order to be able to distinguish biosignatures from geosignatures from ambiguosignatures. Just as important is the ability to distinguish biosignatures of terrestrial organisms that might be inadvertently transported to Mars from those of indigenous martian organisms.

(iii) Surface-atmosphere exchange of gases and energy. The ongoing debate over the possible detection of methane in the martian atmosphere and whether it could be biological demonstrates the need to understand exchange of gases between the subsurface and the atmosphere. And, just as methane from the subsurface can diffuse into the atmosphere, oxidants produced in the atmosphere (such as O_2 and hydrogen peroxide, H_2O_2) can diffuse into the subsurface where they can react with methane. This is a specific example of a general category of processes involving surface-atmosphere exchange in many different environments, by many different processes, and involving fluxes of many different molecules that also can carry energy. There is a compelling need for a fully coupled model of photochemical processes and chemical reactions in the atmosphere, diffusive exchange with the subsurface, physical and chemical processes in the subsurface, and the potential role of outgassing of juvenile gases from the deep interior. Our understanding of terrestrial processes again will be important in constructing models, comparing with observations, and interpreting results. This exercise will identify key biosignature compounds that could be detected from orbit and used to direct the search for life on and beneath the surface.

(iv) Microbial lifestyles in near-surface environments on Earth and Mars. Very little is known about the terrestrial microbes that live in extremely dry, near-surface environments such as the Antarctica dry valleys or the Atacama desert. We can study these terrestrial environments in order to understand the potential for life in similar martian environments, and to understand the range of physico-chemical properties in martian environments in order to understand whether terrestrial organisms (or ones with similar lifestyles) might be able to live there. In particular, we need to determine whether organisms living in these niches on the Earth depend upon any input of energy or chemical species from photosynthesis, and whether these near-surface microbial communities produce a gaseous or mineralogical biomarker (such as a desert varnish) that would be discernible from space or on the ground.

(v) Habitability and the subsurface realm. Understanding habitability in the broadest possible sense is critical not only in the search-for-life aspects of solar-system exploration, but also in the planetary protection aspects (To what extent is the subsurface of Mars or Europa habitable by terrestrial organisms? To what extent might the terrestrial subsurface be habitable by organisms from elsewhere?). There are many aspects of habitability that we usually do not consider in terrestrial studies because they are seldom relevant to the surface biosphere. But in the subsurface, organisms have a distinct and discrete requirement for energy (in terms of both flux and level), and an obvious requirement for raw materials (C, N, P, S, micronutrients). These considerations may be highly limiting to the potential distribution of subsurface life. To quantify and generalize these aspects of habitability, we require laboratory, terrestrial ecosystem, and theoretical studies of the biological requirement for energy and material flux, in concert with field and laboratory studies that address the ability of subsurface geochemical processes to meet these needs.

(vi) Environmental differences between Earth and Mars and the potential for martian life. Discussion of the potential for life on Mars has centered on the environmental similarities between Earth and Mars and its implications. Although there are numerous similarities, substantial differences exist, and

these might have a tremendous impact on biological potential. Present-day differences include atmospheric composition, pressure, and temperature, geochemistry of surface and subsurface materials, nitrogen abundance, spatial and temporal distribution of liquid water, the absence of martian plate tectonics, and the absence of a martian ocean, just as examples. Each of these could have a significant impact on the potential for martian life and its temporal and spatial distribution. And, in the past, some of these characteristics may have been different (e.g., a possible martian ocean, or a warmer and wetter early Mars). What are the implications for life and, if life existed previously, how would it have evolved as the climate became increasingly cold and dry?

Summary and conclusions. Each of these areas is important both to understanding the terrestrial environment and the interaction between microbes and their planetary environment and to understanding planetary environments, their potential interactions with microbes, and the potential for life. Their breadth and diversity underscore the importance of interdisciplinary research in addressing the scientific goals, involving purely terrestrial analyses, purely planetary analyses, and detailed combinations of the two at a very deep intellectual level. Without this type of analysis, any search for life or potential habitats on Mars is guaranteed to end in ambiguity and uncertainty.

PRELIMINARY PLANNING DOCUMENT 7
PLANETARY BIOSIGNATURES: THE SIGNS OF LIFE

Several different groups stressed the importance of having NAI input in this area. Closely linked to topic 5. Contact: Steve D'Hondt, dhondt@gsosun1.gso.uri.edu

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Defining and Understanding the Signs of Life
A White Paper in Response to the Nov. 5, 2004, Call for Input

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Introduction— The search for evidence of life across multiple worlds (within our solar system and far beyond it) is a major goal of the new NASA Strategic Vision. To support that goal, we propose that the study of biosignatures and their environmental contexts be a consistent focus for research of the Science Mission Directorate at every level, in exploration of Earth, other bodies in our solar system, and the planetary bodies of other stellar systems.

There is clear potential for strong positive interaction between studies of life on Earth and the search for life and habitability on other planets. Earth is the only inhabited planet that we presently know. Consequently, it serves as our only natural guide to the potential signatures of life and habitability on other worlds. Biological processes and products that characterize the ecosystems of different Earthly environments provide models for potential ecosystems on different planets and in different stages of planetary evolution. For example, Earth's modern anaerobic ecosystems serve as a model for life on pre-oxygenated planets (including early Earth).

Several categories of biosignatures are appropriate to the search for life and habitability on other worlds. Some biosignatures, such as the handedness and isotopic ordering of organic molecules are a direct consequence of fundamental biochemical processes. Other biosignatures are a direct consequence of metabolic transformations. The latter signatures include; 1) evidence of specific catalyzed reactions and 2) the existence and distributions of specific metabolic products. Searches for some categories of biosignatures require direct manipulation of planetary samples and provide an appropriate focus for robotic and human exploration within our solar system.

Signatures of some biological activities can be identified by remote sensing techniques that can be applied to the entire range of worlds identified in the NASA Strategic Vision. To exemplify the importance of studying biosignatures throughout the Science Mission Directorate, the remainder of this document describes potential synergies between study of Earth and the remote-sensing search for extrasolar life.

Earth and the search for extrasolar life—The search for life on planets around other stars provides an unusually powerful focus for interdisciplinary research efforts that involve both Earth and Space Science in support of the Vision For Exploration. Techniques and models originally developed for studies of the terrestrial environment can be adapted to the search for life and habitability within and beyond our Solar System. These techniques include remote-sensing techniques for determining atmospheric thermal structure and composition, surface processes, clouds and aerosols. The models include atmospheric chemistry, climate, carbon cycle, hydrological cycle and biospheric models.

Conducting advanced telescopic searches for Earth-like planets and habitable environments around neighboring stars is one of the cornerstones of the new NASA Strategic Vision. In support of this vision, NASA is developing a series of space-based observatories, including the Terrestrial Planet Finders, to search for life on planets outside our Solar System. To optimize the designs and observation strategies of these missions, and to ultimately interpret the data that they return, we need to be able to recognize habitable worlds, and to discriminate between planets with and without life, using only remotely sensed information.

The potential range of habitable worlds and extrasolar biospheres is likely to go far beyond the planet-wide characteristics of modern Earth. Yet any attempt to search for life or habitability on extrasolar planets must use what we know about the Earth and Earth System processes as ground truth, to inform the models that will take us beyond an Earth-centric view, and to develop the required analysis techniques. Field and theoretical studies have confirmed that signs of life can only be interpreted correctly in the context of their environment. Our ability to remotely characterize the environment of an extrasolar planet is therefore fundamental to our search for life beyond the Solar System.

Enhanced information from Earth studies is extremely valuable for building and validating interdisciplinary models of planets that are broadly quite different from modern Earth. For example, Earth observations allow us to use higher spectral and spatial resolution remote-sensing data to determine the ambiguities inherent in disk-averaged, remote-sensing characterization of individual planets. It would be advantageous to design experiments to determine: 1) the detectability of key characteristics in the Earth's disk-average, and 2) the optimum retrieval methods for determining planetary characteristics, in advance of the Terrestrial Planet Finder missions. In addition, collaborations between Earth scientists, planetary scientists, astronomers and biologists could focus on specific Earthly environments and ecosystems as examples of systems that may occur on other planets. Processes that appear insignificant on Earth could be more significant on another planet. For example, several gases, such as CH_4, N_2O and CH_3Cl, have biogenic sources on Earth but relatively low concentrations in Earth's atmosphere. Although these gases would be extremely difficult to detect in Earth's spectrum using a mission similar to the Terrestrial Planet Finder, recent modeling suggests that biogenic compounds like these could build up to more detectable levels on terrestrial planets around cooler stars than our Sun. Work to quantify biological outputs to Earth's atmosphere could attempt to identify likely biosignatures for other worlds, even if the gases in question have low abundances on modern Earth.

The definition of remote-sensing biosignatures that may be found on extrasolar planets is an inherently interdisciplinary process. For example, to define a *new* atmospheric biosignature, one must first identify a biological product or trace a known atmospheric constituent to a biological source. If one starts by identifying a product, the potential for microbial use of the product and the extent of its net release to the atmosphere must be determined. If the product is released to the atmosphere, its atmospheric lifetime, the processes that remove it, and the nature and lifetimes of its characteristic reaction products must be determined. These lifetimes will depend on the composition of the planet's atmosphere and surface, and the spectral energy distribution of the star. The potential for its production by non-biological processes must be assessed. Finally, if the product is truly a biosignature with little chance of being confused with an abiotic false positive, we must ask if it is in fact *visible* in the spectrum of the planet as seen from space. So attempts to define new biosignatures require the expertise of microbiologists, atmospheric scientists, geologists, stellar physicists, Earth-observing scientists and astronomers.

To define new biosignatures and to understand the plausible range of planetary characteristics and biospheres on other planets, we also need to engage in interdisciplinary efforts to model terrestrial planets. Because biosignatures can only be identified in the context of their environments, these models must combine knowledge and techniques from Earth science and astronomy, and must be informed by data obtained from the exploration of Earth's habitats and ecosystems. The models must be comprehensive and flexible, so they can be expanded to study atmospheres and potential biospheres on planets that circle stars very different from our own.

Concluding statement—The NASA Strategic Vision identifies the search for life across many worlds as one of its principal goals. This objective requires strong efforts to identify biosignatures on Earth, to understand their context, and to search for them throughout our solar system and beyond. It requires direct exploration of Earth, Mars and other bodies in the solar system. It requires remote observation of extraterrestrial planets. It requires robust models of planetary biosignatures on a diverse array of possible worlds.