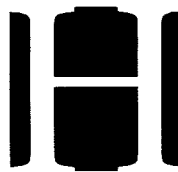


# Overview: Exobiology in Solar System Exploration

N 9 3 - 1 8 5 4 6

Glenn C. Carle and  
Deborah E. Schwartz

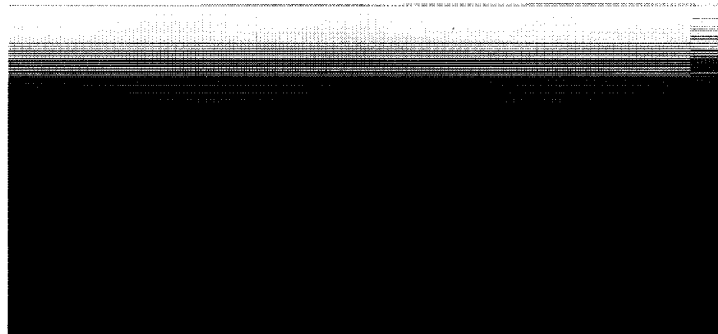


How, why, where, and when did life arise?  
What is the relationship between life and  
ongoing processes in the universe?

These questions are perhaps some of humankind's oldest philosophical inquiries and still resonate today. Philosophers ponder these most difficult and profound subjects from a metaphysical standpoint, while scientists have and will continue to conduct methodical studies of the physical and chemical processes of life in their pursuit to understand its origin, evolution and ubiquity.

Through the science of exobiology, we seek to understand the origin and evolution of life and life-related processes and materials throughout the universe. We know a great deal about contemporary living systems and the way they function, but as we ask about earlier and

PRECEDING PAGE BLANK NOT FILMED



earlier life forms, there are fewer known facts. Much has been learned about exobiology, but considerably more knowledge is left to be gained before the subject is well understood.

Understanding the relationship between the origin and evolution of life and the origin and evolution of the solar system is one of the main objectives of exobiology. Clearly, life is intimately connected with its environment. With respect to the origin and subsequent evolution of life on Earth, the environment played a critical role. When life first arose on Earth, the biogenic elements (carbon, hydrogen, nitrogen, oxygen, phosphorus, sulfur) and traces of many other elements must have been available in appropriate amounts. Temperatures must have been moderate enough for water to exist as a liquid, but not so hot as to destroy organic molecules. The environment must have been conducive to prebiotic organic chemistry (i.e., the evolution of simple chemicals to complex molecules necessary for development of living systems); otherwise, the prebiotic precursors to life could not have formed. Much

about the interplay between environment and prebiotic process remains to be understood. Some of the questions exobiologists seek to answer are: What were the sources and complexities of the prebiotic molecules? What role did the environment play in mediating or directing the chemical evolution that fostered Earth's first replicating system? Is Earth the only place in the solar system (or in the universe, for that matter) where life exists? Could life have originated and survived elsewhere?

While pursuing the answers to these weighty questions, exobiologists extrapolate from the single example they have access to: life on Earth. They study contemporary biology in the laboratory by way of the conventional disciplines such as microbiology, biochemistry, and biophysics. They also study the Earth's geological and fossil record by way of the disciplines of geology and paleontology. Earth itself complicates this work. The ancient rock record, which may have once held the key to chemical evolution and the origin of life, has apparently been destroyed by ongoing geological processes. The oldest fossil evidence of life are stromatolites, which date back to about 3.5 billion years ago. Although only slightly younger than Earth's oldest rocks, these life forms

are very similar to the contemporary microbial mat communities often found in shallow waters. The fossil stromatolites were, as the microbial mats are today, complex communities comprising a number of different types of microorganisms. While the fossil stromatolites are very ancient, they were highly evolved ecosystems and certainly do not represent Earth's earliest life forms.

Given that evidence of the earliest epochs has not yet been discovered and may not be available on Earth, exobiologists have turned outward to the rest of the solar system to understand the conditions that fostered life. Furthermore, in other bodies of the solar system, they may find additional environments where life now exists or where it once existed. Even though the Viking spacecraft found no evidence of life existing on Mars, if early Mars was like the early Earth, life may have begun on Mars, also. Fortunately, substantial areas on Mars have had little or no geological recycling since its earliest period. Sediments containing fossils, or other biomarkers, have not been subducted, ground up, or remelted as they have been

on Earth. Therefore, the possibility exists for a preserved geological record of the origin of life on Mars. In fact, Mars may hold the only existing geological evidence of the origin of life in the solar system. A mission to Mars with exobiology-specific experiments and instruments may find this evidence.

Exobiologists also seek knowledge of the earliest environment on Earth by investigating the role that comets may have played in delivering to Earth biogenic materials necessary for chemical evolution and the origin of life. Scientists ask, What role did cometary impacts play in the origin of life? What was the composition of Earth's atmosphere during stages of chemical evolution and the origin of life? According to one theory, comets introduced essential organics into the atmosphere spurring development of biopolymers. Recent data from encounters with Halley's Comet support these claims, showing that comets contain substantial amounts of water and organic compounds. The exact nature of these organics is as yet unknown and their contributions to chemical evolution are also unknown. Missions to other comets may provide information needed to understand Earth's earliest chemical and physical processes.

## Continuing Inquiries

In 1958, the Congress of the United States enacted the National Space Act. This act validated the importance of exploring space and established, for the first time, an organization that could provide direct access to the solar system. This organization was the National Aeronautics and Space Administration (NASA). In 1984, the Subcommittee on Space Science and Applications reviewed the Space Act and concluded that

*A healthy space science program is essential to continued strength and vitality of the space program...(and that) NASA should initiate enhancements in the space and earth sciences including pursuit of planetary exploration through a renewed commitment to exploration of the solar system, and expansion of human knowledge of the Earth and phenomena in the atmosphere and space.*

NASA has carried out many important steps in this pursuit. Two notable accomplishments are the Apollo Missions with the concurrent search for life on the Moon and the Viking Missions which searched for life on

Mars. While neither investigation found evidence for extraterrestrial life, each gathered a wealth of information about these and other bodies in the solar system. This information is still being interpreted. Today, many new opportunities lie on the horizon. In the United States and the Commonwealth of Independent States (formerly the Soviet Union), as well as in Europe and Japan, missions are being planned to comets, the outer planets and their satellites, and Mars. It is appropriate, therefore, to reassess the current status of knowledge about the bodies of the solar system and identify the role currently planned missions can play in expanding our understanding of exobiology.

In August 1988, the NASA Ames Research Center held a three-day symposium in Sunnyvale, California, to discuss the subject of exobiology in the context of exploration of the solar system. Leading authorities in exobiology presented invited papers and assisted in setting future goals. The goals they set were to:

- Review relevant knowledge learned from planetary exploration programs;

- Detail some of the information that is yet to be obtained;
- Describe future missions and how exobiologists, as well as other scientists, can participate; and
- Recommend specific ways exobiology questions can be addressed on future exploration missions.

These goals are in agreement with those of the Solar System Exploration Committee (SSEC) of the NASA Advisory Council. Formed in 1980 to respond to the planetary exploration strategies set forth by the Space Science Board of the National Academy of Sciences' Committee on Planetary and Lunar Exploration (COMPLEX), the SSEC's main function is to review the entire planetary program. The committee formulated a long-term plan (within a constrained budget) that would ensure a vital, exciting, and

scientifically valuable effort through the turn of the century. The SSEC's goals include:

- Determining the origin, evolution, and present state of the solar system;
- Understanding Earth through comparative planetary studies; and
- Revealing the relationship between the chemical and physical evolution of the solar system and the appearance of life.

The SSEC's goals are consistent with the over-arching goal of NASA's Exobiology Program, which provides the critical framework and support for basic research. The research is divided into the following four elements:

- 1) Cosmic evolution of the biogenic compounds;
- 2) Prebiotic evolution;
- 3) Origin and early evolution of life; and
- 4) Evolution of advanced life.

NASA's program is designed to trace evolutionary pathways of the universe, including synthesis of biogenic elements, evolution of planetary systems, origin of life, and evolution of intelligent life.

To attain these goals, relevant studies of the planets and other bodies of our solar system are necessary. The SSEC's strategy for exploration is to begin with a global view of the solar system bodies, and only later move to detailed observations and measurements in selected regions. Although much information is gained from first generation reconnaissance missions, *in situ* atmospheric and surface measurements and the analysis of returned samples provide the specific details needed for interpretation and understanding. Such missions also assist us in modeling the processes that occur on planets and smaller solar system bodies.

## The Inner Planets

The inner planets and the Moon have been explored more intensely than the outer planets or small bodies due to their proximity and similarity to the Earth. Missions have included flyby and orbiter missions, soft-landings of spacecraft on Mars, probes into the Venusian atmosphere, and manned missions to the Moon with samples returned.

### *The Moon*

The U.S. Lunar Program began in 1964 with Ranger VII's photography-based mission, and culminated in 1972 with the Apollo project. Apollo landed men on the Moon, returned lunar samples from six sites, and permitted a quantum leap in our understanding of spaceflight and lunar evolution. Although life apparently did not evolve on the Moon, studies help us to better understand Earth and conditions and events that occurred more than 3.5 billion years ago.

Compared with Earth, the Moon is depleted of hydrogen, carbon, nitrogen and their simple compounds. Small amounts of water and other volatiles, as well as minuscule amounts of carbon found in fine-grained material, may be vestiges of impacting bodies. No clear evidence of complex organic compounds has been found, but traces of methane and carbide-like species have. This suggests a synthesis from interactions between the solar and the lunar surfaces. In fact, solar wind provides a major portion of the Moon's hydrogen, carbon, and nitrogen. Investigators found that the parts per billion (ppb) amounts of amino acids in lunar soils were not indigenous, but rather produced during analyses from trace amounts of chemical precursors of amino acids. Apparently, solar and cosmic irradiation, meteorite bombardment, and volatile loss have severely constrained the Moon's chemical behavior and the evolution of biochemically significant elements. Questions still to be answered include, How old are the lunar impact craters? Did impacts occur in any particular pattern, or were they random? What are the compositions of meteorites on the lunar surface?

If we plan to use lunar resources to further planetary exploration, we first need to understand the Moon in very close detail. During the proposed Lunar Orbiter Mission, data will be collected to compile a global lunar map. From this data we should be able to deduce the composition of the lunar surface, the presence of condensed water, and other volatiles. It has been suggested that a lunar base would be the ultimate location to study the origin and history of the Moon, which may better help us understand the early history of the Earth. From this base investigations using the radio-quiet far side could search for evidence for extraterrestrial intelligence and conduct other astronomical investigations. Additionally, scientific investigations could take advantage of the Moon's high vacuum and extreme changes in temperature.

## *Venus*

Venus is too hostile today to harbor life; temperatures are very high as clouds cover 100% of the surface. If life did exist, it did so far in the past when conditions were more Earth-like. The United States began studying the planet Venus in 1962 with the launch of the first successful interplanetary probe, Mariner II. In addition to this and Pioneer Venus, various Soviet Venera missions have provided data concerning the properties of the surface of Venus. Although controversial, data collected during these missions suggest the possibility that ancient lakes may have once spread across the surface of Venus. Models also imply that Venus may have possessed a sizable water inventory, as well as a cooler climate, in its early history.

These putative lakes (or oceans) could have remained for several hundred million years, until they boiled away as temperatures rose because of a runaway greenhouse effect. There is also a suggestion that comets, thick with ice, could have replenished

those waters for nearly a billion years. The possible presence of lightning may have been an important energy source for the production of organic chemical compounds. Early environmental conditions on Venus may have been favorable for the development of life, but if the impact flux was as high as it was on Earth, early life on Venus may have been repeatedly wiped out. The study of Venus may give us insight into the physical limitations of the habitability of an Earth-like planet.

Presently, data collected during the Magellan Mission are being used to create a global map of Venus. Magellan entered orbit around Venus in April 1990. The probe's mapping radar has already mapped over 95% of the planet and has revealed that about 85% of the planet is covered by volcanic rocks, mostly lava flows that form the great plains. Detailed studies of the surface features and their characteristics will allow us to address questions on the age, origin, and history of Venus.

## *Mars*

In 1976 and 1977, after several Mariner flybys and after many remote images had been taken of the Martian surface, two Viking Landers touched down on Mars. Because the search for life on Mars was a major driver for this Mission, three microbiological experiments were performed. However, no unequivocal evidence was found for metabolic activity in any of the surface samples analyzed, no organic matter was detected, and no images were returned suggesting signs of life. These data led us to believe the possibility of extant life on Mars was quite slim, unless it existed in hidden, protected niches.

However, even if there is no extant life on Mars, it is still reasonable to hypothesize that life may have once existed there. Geologic and climatologic studies suggest that the early Martian environment may have been similar in many respects to that of the early Earth. Both planets show histories of liquid surface water, warmer temperatures, and cometary and meteoritic impacts, as well as relatively thick carbon dioxide and nitrogen atmospheres and volcanic activity. Therefore, the elements needed for chemical evolution may have been present

on Mars, even though subsequent planetary events did not favor the continuing evolution of life.

Regardless of whether life originated on Mars, the planet may contain within its sedimentary record the early histories of both Mars and Earth. Because of Earth's geologic processes, unaltered rocks that date back to 3.5-4 billion years ago are rare. On Mars, however, over half the planet (the southern hemisphere) dates back to the late bombardment event of about 3.8 billion years ago. Studying Mars, therefore, not only helps us understand events that occurred while life on Earth was originating, it also allows us to investigate the possibility of an extinct Martian biota.

The study of Mars provides us with clues to better discriminate between conflicting theories of solar system formation, revealing to us new clues about how terrestrial planets with atmospheres formed and evolved and allowing us to more fully understand planet Earth. New missions to Mars will study Martian atmospheric and surface materials and processes, and will search below the planet's surface for buried clues of past, and perhaps even present, biological activity.

One planned mission is the Mars Observer Mission (MO), scheduled for launch in September 1992. The Mission will continue more detailed studies of the Red Planet by sending a spacecraft platform to orbit Mars. Remote sensing instruments will observe and map the entire Martian surface and atmosphere for at least one Martian year, collecting data on surface materials, volatiles and dust; topography and the gravitational and magnetic fields; and the structure and circulation of the atmosphere. MO data will constitute a baseline for future Mars missions. MO's most important contribution to exobiology will be improving our understanding of climate change and its consequences on any past biota and biological processes.

The Mars Environmental Survey (MESUR) Network Mission is planned for several launch opportunities beginning in 1999. The Mission objective is to establish a global network of stations on the surface of Mars to concurrently collect and return scientific data over a minimum of one Martian year. The full network will consist of 16 stations providing pole-to-pole coverage of Mars. Each station will be identical, weigh less than 150 kilograms, and house instrumentation to characterize the planet's meteorology, internal seismic activity, and local surface properties. Using data obtained during the Mission, exobiologists will gain insight into the geological and atmospheric conditions in the past and present, and Mars' ability to sustain a potential past biota. MESUR is viewed by the scientific community as the logical, evolutionary step after Viking and before sample return/human exploration missions.

The Mars Rover Sample Return (MRSR) mission is currently proposed for the late 1990s. Recommended by the SSEC and the NASA's Office of Exploration Task Group, chaired by Sally Ride, the MRSR mission will: gather data to better understand the origin and evolution of Mars and the conditions present on very early Mars; search for evidence of former life; and improve our knowledge of the Martian environment in preparation for human exploration. The Rover will sample different materials at different locations and will perform a range of *in situ* measurements. Because the MRSR mission will only return 5-10 kilograms of material, selected samples must represent the planet's full variety. Once returned to Earth, the samples can be analyzed with the benefit of tools and techniques, such as sample dating and trace element analyses, that are too complicated to be performed remotely. Data taken during the MRSR mission will help answer questions about how the surface of Mars evolved, what the structure of the interior is, whether or not life once existed on the planet, what the planet's present thermal and dynamic states are, and what role water played in the evolution of the Martian surface.

## The Outer Planets

The outer planets and small bodies have been explored less intensely than the inner planets and the Moon. A recent accomplishment in space exploration is the successful reconnaissance of Voyager 2 with all the giant planets during its grand tour of the solar system.

The giant planets include Jupiter, Saturn, Uranus, Neptune, and Pluto. They formed in the same flattened disk of gas and dust, the solar nebula, as did the terrestrial planets, but are strikingly different. Thought to have retained much of the original solar nebular material, the giant planets are composed of three basic materials: gas (mostly hydrogen and helium), ice (containing mixtures of water, carbon and nitrogen-containing materials), and rock (mixtures of silicon, magnesium, iron, oxygen, and other heavy elements).

The giant planets are bigger and more massive than the terrestrial planets, and have numerous rings and moons surrounding them. The giant planets themselves exhibit a wide variation in basic properties. Atmospheres, for

example, extend ten thousand to several tens of thousands of kilometers into the planets' interiors, thereby representing a significant fraction of a planet's entire mass. These atmospheres are highly reducing environments, where methane is converted into more complex molecules.

Some exobiologists believe the chemical steps leading to life involved the production of complex carbon-containing molecules from simple molecules in a highly reducing environment. If this is so, then atmospheres of the giant planets represent natural laboratories for observing and understanding initial chemistry that leads to production of organic molecules. Energy sources driving the atmospheric chemistry include solar ultraviolet radiation, lightning, and high-energy charged particles that are precipitated into auroral zones. Lightning may be important in producing certain disequilibrium species such as hydrogen cyanide and carbon monoxide. If carbon and other biologically relevant materials came to Earth from the outer solar system, the giant planets may have played a fundamental role in transferring this material to the inner solar system by virtue of their gravitational interactions with small bodies.



## Jupiter

Our understanding of life as a planetary phenomenon is based upon Earth-like planets. However, there are environments in the solar system where liquid water, commonly believed to be a prerequisite for biological activity, may exist in a distinctly non-Earth-like environment. Such an environment may occur on Jupiter's moon, Europa. There, surface water ice, organic molecules and biogenic elements (available as precursors for the synthesis of biocompounds), are thought to exist along with a continuous supply of energy (either through the dissipation of tidal energy as heat or through hydrothermal activity or solar radiation).

Europa formed from the Jovian nebula, rich in water and other biogenic elements; therefore, early Europa may have been favorable for the capture and *in situ* formation of different organic compounds, including biochemical monomers and polymers. The low-temperature environment may have also facilitated the preservation and further interaction of labile biochemical polymers. Whether these processes proceeded to a more advanced stage is not known; no experimental work has been done at

low temperatures on the protocellular stages of prebiological evolution. Some exobiologists believe that if any European biota exists, it would have to be anaerobic and prokaryotic.

The Galileo Mission will take a close look at Jupiter and Europa. It was launched from the Space Shuttle in October 1989 and follows a complex looping orbit to arrive at Jupiter in late 1995. Once in the Jovian vicinity, it will spend many years examining the Jovian moons and Jupiter's atmosphere.

Laboratory research indicates that Jupiter's copper and gold colors are most likely due to an atmosphere rich in biogenic elements, such as phosphorus, methane, ammonia, and hydrogen gas. Discovery of large storms on Jupiter during the Voyager project set the stage for a natural laboratory for the study of chemical evolution. The Galileo Mission will allow us the opportunity to take advantage of this natural laboratory once again.

The Galileo Mission will also help elucidate questions of exobiological interest: Is there abundant organic material present on Europa? Do the fractures on the smooth, icy surface indicate the presence of liquid water beneath the surface? Are there internal sources of energy that would promote life? Can prebiotic chemistry occur at such cold temperatures? The monitoring of Europa for vapor and frost clouds that could result from fracturing events may reveal whether liquid water lies beneath its icy surface. Radar sounding could also detect liquid water if it is present. High resolution imaging of Europa's surface could elucidate processes involved in the formation of its linear features, as well as in variations of its coloration and albedo.

Future missions using landing spacecraft to penetrate the surface and perform *in situ* surface and subsurface measurements in Europa will be required to find out what actually lies beneath the surface.

## Saturn

Saturn's rings are composed of particles ranging in size from tiny pebbles to large boulders and include a sprinkling of fine dust. The material is mostly icy, and contains impurities of unknown origin. The Saturnian satellites have dark coatings presumed to be carbon-rich organic material. The source of these coatings is unknown, but further analysis may help to elucidate the relationship among icy satellites, comets, and primitive carbonaceous meteorites. By continuing studies of the outer planets and by comparing their structure and behavior, we gain insight into the formation and evolution of the solar system and can learn what chemistry might have taken place here on Earth during the first mysterious years.

Titan is Saturn's largest satellite. Titan is an icy, rocky object that possesses a dense nitrogen-methane atmosphere. Although its size and atmospheric density might stimulate comparisons with terrestrial planets, at such a great distance from the Sun, Titan is much colder and richer in ices. The surface temperature is about 94K, only a few degrees above the melting point of methane. It has been postulated that lakes or oceans of liquid methane or other hydrocarbons might dominate the surface, and that dense methane clouds exist in the lower atmosphere below the visible orange haze.

Although the conditions on present day Titan are quite different from those that are thought to have existed on early Earth, Titan provides a natural setting, on a planetary scale, for the study of processes involved with chemical evolution. The low temperatures found on Titan preclude the existence of significant amounts of water vapor; however, abiotic chemical evolution, leading to complex hydrocarbons and nitriles, can still take place. Also, Titan's hazes and ubiquitous colored clouds indicate the presence of aerosols. These aerosols can interact with the atmospheric gases and with each other, thereby influencing the path of atmospheric evolution. Chemical analyses

of Titan's atmosphere should provide more information about the primordial nebula from which Titan was formed.

Information about material presently impacting Titan may also be obtained. Because hydrogen cyanide has been detected in Titan's atmosphere, syntheses of as yet undetected organics may have occurred in the atmosphere. Clearly, synthesis of some abiotically useful compounds should have taken place, albeit anhydrously. This is likely to have been the case, as evidenced by compounds already detected. Therefore, careful inventories of the various organic compounds in the atmosphere of Titan are essential to expand exobiology's knowledge of prebiotic evolution of the precursor molecules necessary for the origin of life. Many questions remain unanswered: What kind of prebiotic chemistry is taking place in Titan's lower reaches? Do these processes provide clues as to how precursor molecules led to life on Earth?

The Cassini Mission is a vital component of an exciting exploration program. While much of what we know about Saturn's and Titan's atmospheres has come from Voyager flyby data, the Cassini Mission to Saturn and Titan will address fundamental questions about the formation and evolution of the solar system, prebiological organic chemistry, plasma physics, atmospheric dynamics, and virtually every other aspect of space science. Data retrieved from Saturn may provide insight into the dynamics and nature of Saturn's ring particles, Saturn's atmospheric composition and the nature of its magnetosphere. Additionally, Saturn's moons will be explored and the surface composition and geologic history of these moons will be determined. Together with the Galileo Mission to Jupiter, these missions represent a systematic and comprehensive approach to the study of the outer planets and will provide tremendous insight into the formation and structure of the solar system.

The Cassini Mission will consist of two parts. The first will be the delivery of a probe into the atmosphere of Titan. The probe will sample and analyze chemical and physical characteristics of the atmosphere and haze particles in

detail. The probe will be followed by a four year orbital tour of all parts of the Saturnian system, including numerous flybys of Titan and the other main "icy" satellites (Mimas, Enceladus, Tethys, Dione, Rhea, Hyperion, and Iapetus).

NASA will build the orbiter as the second spacecraft in its Mariner Mark II series; these are modular spacecraft designed for exploration of the outer planets and small bodies. The European Space Agency (ESA) will provide the Titan Huygens Probe, which will be launched with the orbiter. The Huygens Probe will begin sampling the atmosphere and transmitting data at an altitude of about 170 km. The descent from this level to the surface will last approximately 2.5 hours. Because of the thick haze layer, the surface of Titan has never been observed; its precise nature will remain unclear until the Huygens Probe is able to resolve it.

## Comets, Asteroids, and Other Objects

Comets are known to contain a relatively large amount of organic molecules. They are vehicles potentially capable of delivering to the planets products of interstellar processes, such as organic compounds produced in space by nonequilibrium reactions (catalysis and radiation processing of condensed volatiles). Despite their apparent diversity, comets represent a population of essentially homogeneous objects that show strong analogy with carbonaceous chondrites.

Comets eventually decay into gas and dust, becoming a source of interplanetary particles containing carbon. Comets may also be a major source of planetary atmospheres. It is believed that Earth may have received most of its ocean and organic molecules from heavy comet bombardment as the solar system formed. These simple and complex organic molecules may still be preserved in comets today. Despite invaluable data gathered from the Comet Halley flyby, many questions remain: What is the complete inventory of organic materials present in comets? How has this material been

synthesized into complex, biologically interesting molecules? Is there any evidence that substantial amounts of material from comets have been delivered to the planets?

The concept of orbital diffusion throws a new light on exobiology. It suggests the existence of a cosmic mechanism, working everywhere, that can transfer prebiotic compounds to ubiquitous rocky planets so as to provide a proper environment to initiate life. However, not enough is known about cometary chemistry for a full understanding. The study of Comet Halley has brought a wealth of new information, but the fast flyby velocity destroyed significant molecules that were thus not characterized. An active, short period comet that has entered the inner solar system only very recently is the best target for exobiology studies. Such a comet should still contain a substantial supply of volatiles, and a high level of activity should assure a sufficient amount of gas and dust reaching the spacecraft for studies.

Exobiology is also interested in the continuing study of asteroids and meteorites. Most asteroids, particularly those toward the outer parts of the asteroid belt, are objects of very low-surface reflectivity. Similarly, the surfaces of cometary nuclei appear to be very black. Some planetary satellites are also black on a global scale or contain black matter mixed with surface ices. Macromolecular carbon, found in meteorites and interplanetary dust particles (IDPs), is a plausible low-albedo constituent of these dark (asteroid, comet, and satellite) surfaces.

The presence of organic matter in cometary dust has been established. How much organic material do asteroids contain? To what extent, and how, has the organic material in asteroids and meteorites been synthesized into complex, biologically interesting molecules? The source of the organic matter in the meteorites and asteroids is unclear, but isotopic composition (deuterium enrichment) indicates formation in low-temperature interstellar molecular clouds. Organic synthesis, in the form of photochemical smog, is currently in progress in some planetary atmospheres (Jupiter, Saturn, Uranus, Titan) and on planetary and satellite surfaces (Pluto, Triton), producing yellow and brown-colored

organic complexes from the methane that is detected spectroscopically. Alteration of these organics to more complex solids by the action of ultraviolet and cosmic ray flux probably occurs. Telescopic searches for the CH spectral signature strongly suggest its presence on dark, hydrous asteroids, but confirmation and further exploration are needed.

Questions still remain about the origin of meteoritic organic matter, particularly concerning the role played by presolar, interstellar processes and factors controlling the extent of chemical prebiotic evolution on different solar system bodies. Using data obtained during the October 1991 Galileo encounter of Gaspra, and the planned, fast flyby of Ida in August 1993, we will gain insight into the nature of asteroids and the composition and source of their low-albedo component(s).

Dust is a ubiquitous component of our galaxy and solar system. Interstellar dust is the predominant form of condensable elements in the galaxy that are not in stars. Grains form in gas outflows from stars and they are processed, destroyed and reformed in the interstellar medium and molecular clouds. Interplanetary dust is debris recently liberated from comets and asteroids within the solar system and is relatively rich in volatiles, a source of abiotic organic molecules. The interstellar medium offers a rich variety of environments in which carbon chemistry can occur. A wide variety of chemical processes provides for the production of rich assemblages of biogenically interesting compounds.

A strong link exists between interplanetary and interstellar dust. Prior to the formation of the solar nebula, most atoms heavier than helium were contained in interstellar grains. Some grains were incorporated into comets and asteroids. Both interstellar and interplanetary dust seeded early Earth with elements and compounds. Collection and analysis of extraterrestrial dust through the use of dust-collection facilities on Earth-orbiting vehicles will provide information about the sources of biogenically significant elements and compounds that

accumulated in distant regions of the solar nebula and that were later accreted onto planets.

Also contributing to the understanding of interstellar and interplanetary dust is the Long Duration Exposure Facility (LDEF). LDEF is a large, reusable, unmanned, free-flying spacecraft accommodating technology, science, and applications experiments for long-term exposure to the space environment. The LDEF was placed in Earth orbit in April 1984 by Challenger, and retrieved from orbit in January 1990 by Columbia. Several experiments on board the LDEF studied the chemistry and morphological characteristics of micrometeoroids and interplanetary dust. Data obtained during those experiments should provide an understanding of the biogenic significance of such extraterrestrial materials.

Due to federal budget cuts, the Comet Rendezvous Asteroid Flyby (CRAF) Mission was canceled in February 1992. If resurrected, the CRAF Mission will perform measurements aimed at a deeper understanding of chemical evolution. It will address fundamental questions about the formation and evolution of the solar system, prebio-

logical organic chemistry, plasma physics, and atmospheric dynamics. This Mission will also help provide evidence as to whether substantial amounts of cometary material have been delivered to the planets, particularly Earth.

CRAF will study a typical short-period comet, Kopff, over more than half its orbit, following aphelion near the orbit of Jupiter through perihelion and beyond. In 2000, CRAF will reach its destination with Comet Kopff and be inserted in an orbit around the Sun that precisely matches that of the comet. CRAF will map the entire surface of Kopff with imaging and spectroscopic instrumentation. It will identify different ices and minerals on the comet's surface, and will use accurate radio tracking to determine the mass of the comet. The spacecraft and comet will then travel together through one or more complete orbits. Detailed analyses will be made of the gas and dust flowing from the comet's nucleus. A year after the spacecraft's arrival, a penetrator carrying a set of instruments will be placed directly into the surface of the nucleus to measure elemental composition, temperature, and surface strength and to determine the physical state and composition of the icy organic mix below any crust on the surface.

En route to comet Kopff, CRAF will fly by and observe a primitive, carbonaceous-type, main-belt asteroid, 449 Hamburga, and make remote sensing measurements. Data obtained will address questions concerning elemental and isotopic abundances, chemical composition, ice phases, and the mineralogic forms and microscopic physical structures of these primitive solar system materials which are of great interest to exobiologists.

The CRAF Mission will provide an opportunity for significant advances in the knowledge of primitive (yet complex) material in short-period comets and the surface of an asteroid. The Mission will obtain new information concerning the early environment of the solar system and the extent of chemical evolution in such environments.

Comparison of data with results of analyses of interplanetary dust and meteorites will elucidate relations between these different solar system bodies, and should give a clearer picture of how primitive bodies, comets, asteroids, and interplanetary debris may have contributed to the origin of life on Earth.

The data anticipated from CRAF will yield much insight on comets, but ultimately a comet sample return mission, such as the proposed Rosetta Sample Return Mission, will be needed to provide the range and detail of analyses needed to definitively characterize a comet nucleus.

## Summary

Many fundamental questions remain about the origin of life, chemical evolution, and the formation and composition of our solar system. A number of spacecraft missions have been proposed that will certainly provide very important clues and answers to some of these outstanding questions. For exobiology, the highest priorities for future missions should include a thorough investigation of a comet and a future cometary nucleus sample return mission. In addition, it is recommended that a comprehensive study of Mars be pursued and that a sample return mission to Mars, with intelligently chosen samples from carefully selected sites, be a high priority.

Future exploration objectives should be to determine the present nature of the solar system, its planets and primitive bodies to understand how the solar system and its objects formed, evolved, and (in at least one case) produced an environment that could give rise to and sustain life. Another objective should be that of comparative planetology: to better understand the Earth by determining the general processes that govern all planetary development and by understanding why

terrestrial planets differ so much from each other.

National goals for space exploration were outlined in the Space Exploration Initiative (SEI). First announced in 1989 and established by the Bush Administration in 1990, SEI provided the basic framework for future exploration: back to the Moon and then a piloted mission to Mars. The 90-Day Study, 1989, contained explicit suggestions for the successful exploration of the Moon and Mars. More recently, the Synthesis Report, 1991, was the first serious look at how to fulfill the President's stated objectives in space. The Report contains the findings of a year-long survey of the U.S. aerospace engineering community and the general public, and features four basic options for returning humans to the Moon and proceeding toward Mars. These options include:

- A trip to Mars in 2014 by six astronauts, with testing of related technology on and around the Moon beginning in 2005;

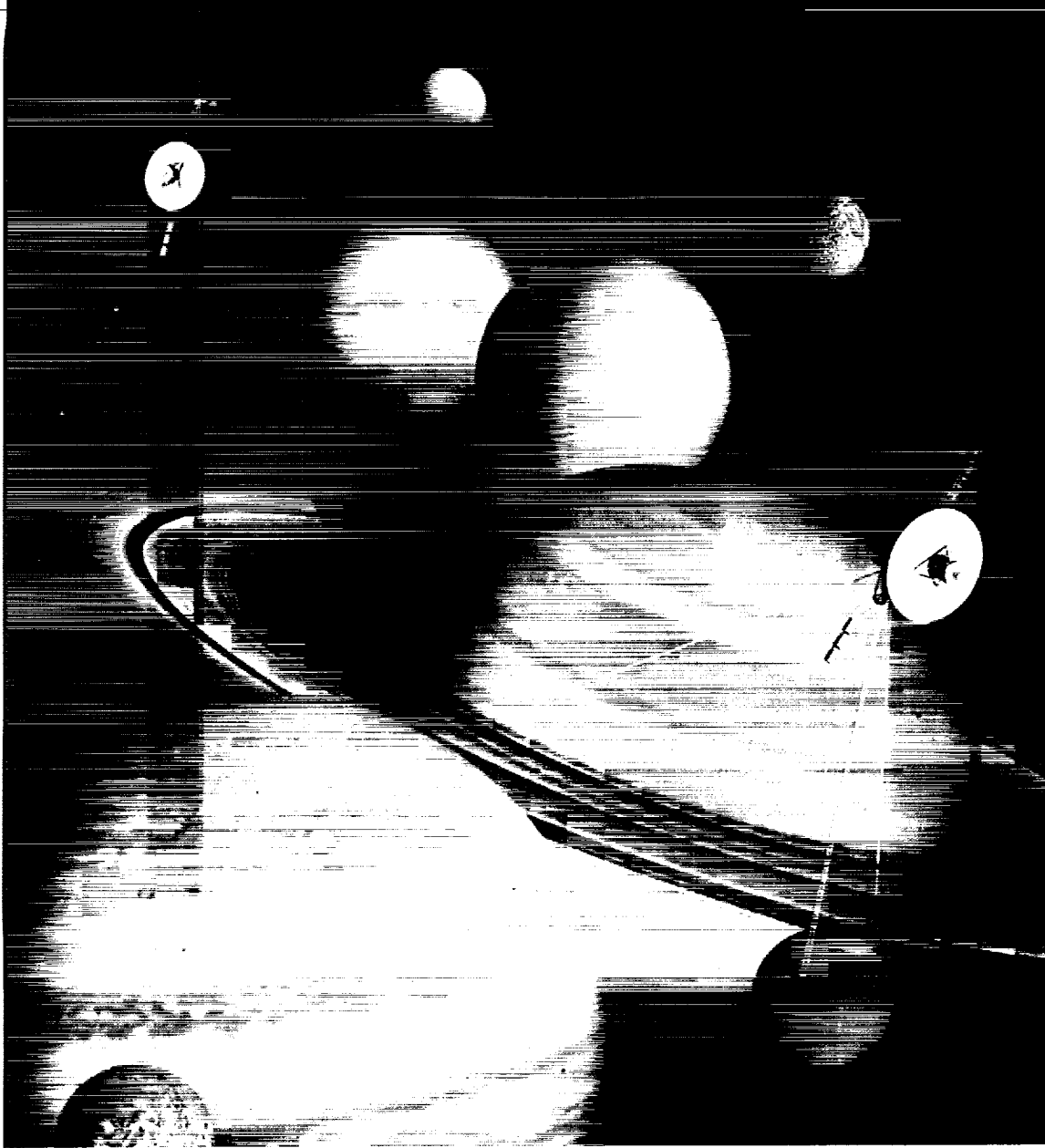
- Scientific exploration of the Moon and Mars, with the first piloted lunar landing in 2003 and extensive robotic activity on both bodies;

- A permanent Moon base followed by human excursions to Mars;

- A Moon-oriented approach toward returning solar energy and other natural resources to Earth, with a self-sufficient Mars base initiated in 2016.

To achieve these objectives and advance exploration of the solar system at the healthy pace recommended by the SSEC, we must strengthen our ground-based planetary science research effort, put energy into major technological developments, build up our research and data analysis capabilities, and increase our potential for telescopic observations and remote analysis capabilities. Additionally, we need to develop and foster relationships with other nations to further international cooperation.

With a national commitment to human presence in the solar system endorsed, and reports such as the Synthesis Report and the Ride Commission Report "Leadership and America's Future in Space" recommending Mission to Planet Earth, future lunar bases, expanded planetary exploration, a series of Mars Sample Return missions, and the human exploration of Mars, we are preparing for a future of national leadership and activity beyond Earth orbit and into the solar system.



ORIGINAL PAGE  
COLOR PHOTOGRAPH

