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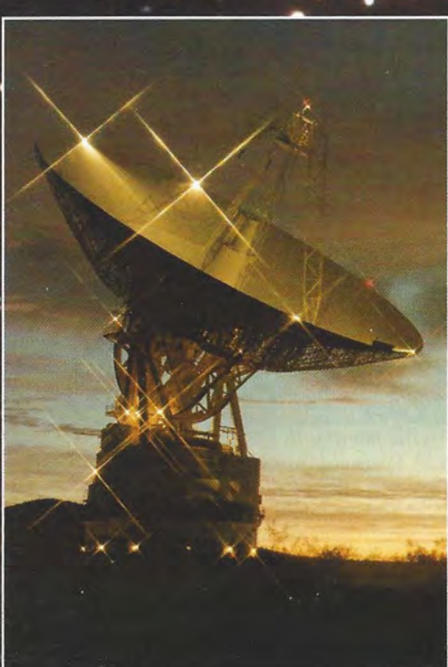

Life in the Universe

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COVER: Life, as we know it, is a chemical process. The elements that make up living things were created deep within giant stars. In the stars' death throes, these elements are released to space, where they can combine into the dark molecular clouds strung among the stars (seen here as dark streaks in the Trifid Nebula). On Earth, we find wonderfully diverse manifestations of living chemistry (clockwise from top left): densely crowded coral reefs; rich, extravagant rain forests; and intelligent, language-using dolphins. We also find a species that has questioned how life began and is now using its technology to search for answers among the planets and stars.
Photos: Clockwise from top left, Carl Roessler, Brian Parker and Ed Robinson: Tom Stack and Associates; JPL/NASA; background, National Optical Astronomy Observatories

Eleanor Helin Discovers Another Comet

PLANETARY SCIENTIST ELEANOR HELIN of the Jet Propulsion Laboratory has discovered another comet, the second found in her continuing search for asteroids and comets that pass close by Earth. Comet P/Helin, 1987w, is a short-period comet (hence the "P" before the name) that orbits the Sun every 14.5 years. It travels an elliptical path that takes it from beyond the orbit of Mars to near the orbit of Saturn.

Helin found the tell-tale track of the comet on a photographic plate taken on August 24, 1987 for the Palomar Sky Survey II with the 1.2 meter Schmidt telescope (now called the Oschin Telescope) at the Mount Palomar Observatory.

On August 25, a member of Helin's team, Steve Singer- Brewster, found another interesting object, Amor asteroid 1987 QB. Amor asteroids follow orbits that cross Mars' orbit but stay outside of Earth's.

Planetary Society members helped make these discoveries possible. The observations were part of Helin's Planet-Crossing Asteroid Search (PCAS), which is supported by our members' donations to the Asteroid Search Fund. Her work is also funded by NASA and the World Space Foundation.

Helin recently expressed her appreciation for the Society's support by naming an asteroid for Sasha Sagan, the daughter of Society President Carl Sagan and his wife, Ann Druyan. Sasha's pleased parents accepted the honor at the Society's Hawaii Conference in August.

This is not the first time Helin has "given" an asteroid to the Society. In 1985 she "donated" (3129)1979MK2 and we held a contest to name the asteroid. From hundreds of entries, we chose the name "Bonestell," in honor of Chesley Bonestell, the undisputed dean of space artists. Mr. Bonestell was thrilled by this honor, and the Society staff was pleased and grateful that he was able to enjoy his asteroid before his death in 1986.

Life IN THE UNIVERSE

by Donald L. DeVincenzi

Throughout the ages, humanity has searched the stars for clues about its origin and destiny. Our generation is the first able to do something tangible to answer questions like: How did life begin? Why is life the way it is? Are we alone in the universe? We are now at a point where scientists can devise experiments to address these most fundamental questions about life.

In this special issue of *The Planetary Report* we will take a look at exobiology, the study of life in the universe. Scientists in this multidisciplinary research effort seek to understand the origin, evolution and distribution of life and life-related molecules throughout the cosmos. Their laboratory experiments, analyses of Earth's rock and fossil record, planetary exploration, deep-space observations and analyses of meteorites and cosmic dust have all been integrated into a scenario describing the events leading to life on Earth. It suggests that life arose through a series of physical and chemical processes initiated with the formation of the universe itself.

Briefly, the scenario is this: First, the elements required for life — carbon, nitrogen, hydrogen, oxygen, phosphorus and sulfur — originate in the formation of stars. Then they evolve into larger organic (carbon-based) molecules in space between the stars. In primitive planetary environments, they combine into the building blocks of life, evolve into enzymes and the genetic code, organize into complex and stable cell-like structures, develop self-replication processes, and grow from simple to complex living things. Both the rate and direction of these processes were influenced by the chemical and physical environments in which they occurred. These connections with the solar system and planets make questions on life's origins central to space science and to research on the origin and evolution of the universe.

Although we have strong evidence for our short scenario, many pieces of the origin-of-life puzzle require more data that can only be gathered through space exploration. We need to know more about: the chemistry occurring in interstellar space, clouds and dust; the relationships among dust, comets, meteorites and asteroids; the delivery of ready-made chemical building blocks for life to primitive planets by comets and meteorites; the possibility for other planets to support chemical evolution and life; the potential of both the early and present Mars to sustain life; and the existence of planets and life beyond our solar system.

Over the past few years, the scientific community has evaluated how planned missions and projects can expand our knowledge of life in the universe. From missions in low Earth orbit to solar system exploration missions to Earth-based projects, we have a rich suite of opportunities to advance our understanding of life's origin and distribution.

For example, the "great observatories" that NASA plans to orbit may include the Hubble Space Telescope, the Space Infrared Telescope Facility and the Astrometric Telescope Facility. These observatories will give us unprecedented opportunities to study the elements and molecules found between the stars, the chemical evolution of planets, comets and asteroids, and the existence of planets beyond our solar neighborhood.

NASA's proposed space station may carry devices to capture and study interplanetary dust in pristine condition, undamaged and uncontaminated by passage through Earth's atmosphere and collection by high-altitude aircraft.

Several planned solar system exploration missions will teach us more. The Comet Rendezvous Asteroid Flyby (CRAF) mission will study particles and dust released by a comet, and analyze them for life-related chemicals.

The joint NASA-ESA (European Space Agency) *Cassini* mission will probe the atmosphere of Saturn's moon Titan to determine its structure, chemical composition and other properties. The *Voyager* mission revealed that extensive chemistry is occurring on Titan; *Cassini* will add to our knowledge about Titan and the early solar system, and allow us to make deductions about chemical evolution on the primitive Earth.

We are now vigorously studying missions to Mars beyond the *Mars Observer* mission (to launch in 1992). Under particularly intense scrutiny is a Mars rover-sample return mission to examine Mars' surface and to return martian material to Earth. The possibility that Mars once supported chemical evolution will be a prime objective.

The Soviet Union is planning an ambitious Mars program. In 1988 they will launch the *Phobos* mission to study Mars and its small, dark moons rich in carbonaceous material. *Phobos* will be followed by a lander mission that may launch instrument-carrying balloons to explore the planet. Even more ambitious sample return missions may follow. And, at the recent Spacebridge held by The Planetary Society, Soviet scientists explicitly stated that one of their major goals is to continue the search for life on Mars.

NASA may soon formally approve and fund a Search for Extraterrestrial Intelligence (SETI) project which would be the most comprehensive ever undertaken. If this happens within the next year, the first operational unit could be constructed, installed and tested at the Arecibo Observatory in Puerto Rico by October, 1992.

Meanwhile, The Planetary Society's Project META continues to search the sky visible from Harvard University's Oak Ridge Observatory in Massachusetts. Although it has yet to find a recurring extraterrestrial signal, this project is only two years old, so the search has just begun (see the July/August 1987 *Planetary Report*).

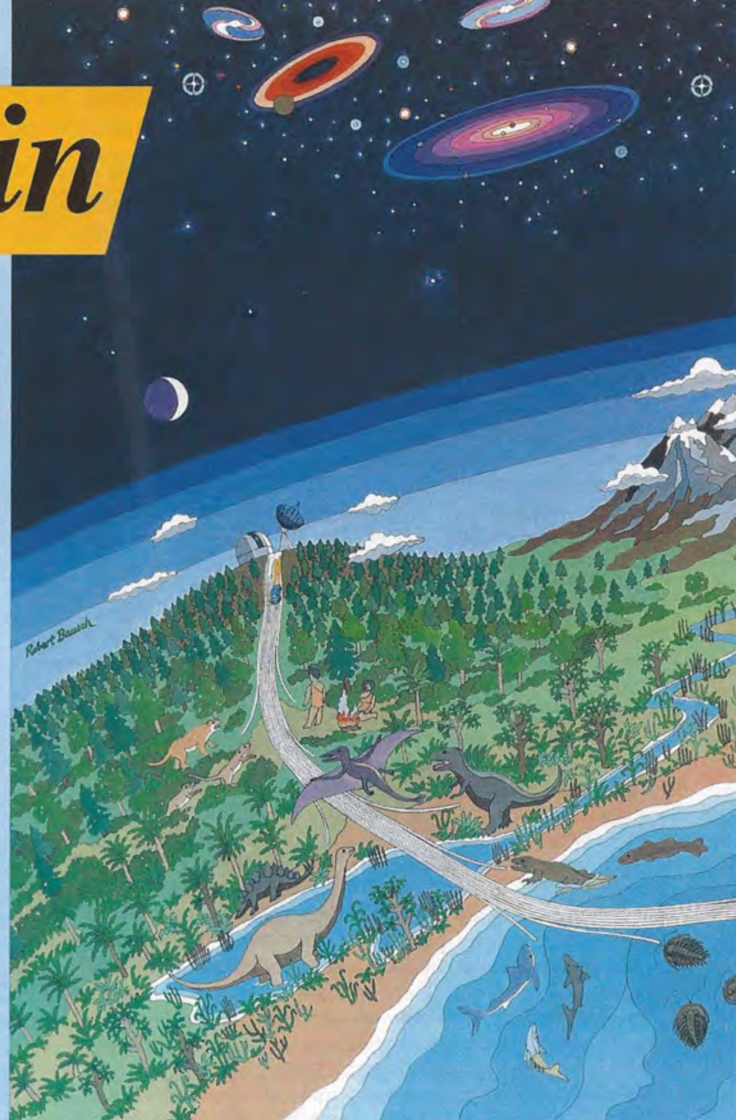
In this special issue, we present the best current thinking and future plans on pre-life chemical evolution, the origin and distribution of life, and the planetary and astrophysical conditions that govern these processes. We have emphasized the ways continuing space exploration can help clarify our theories about life in the universe. The space missions and Earth-based projects will help answer the most fundamental questions we can ask, questions about the origin of the universe, and of life itself.

Donald L. DeVincenzi, Deputy Chief of the Life Science Division at NASA's Ames Research Center, is the guest technical editor for this special issue of The Planetary Report. *He returned to Ames recently after seven years as Discipline Scientist for the Exobiology Program at NASA Headquarters.* *Vera M. Buescher, from the SETI Institute, Los Altos, California, provided invaluable assistance in the production of this issue.*

Life's Origin

The Cosmic, Planetary and Biological Processes

by T. Scattergood, D. Des Marais and L. Jahnke



From elements formed in interstellar furnaces to humans peering back at the stars, the evolution of life has been a long, intricate and perhaps inevitable process. Life as we know it requires a planet orbiting a star at just the right distance so that water can exist in liquid form. It needs a rich supply of chemicals and energy sources. On Earth, the combination of chemistry and energy generated molecules that evolved ways of replicating themselves and of passing information from one generation to the next. Thus, the thread of life began.

This chart traces the thread, maintained by DNA molecules for much of its history, as it weaves its way through the primitive oceans, gaining strength and diversity along the way. Organisms eventually moved onto the land, where advanced forms, including humans, ultimately arose. Finally, assisted by a technology of its own making, life has reached back out into space to understand its own origins, to expand into new realms, and to seek other living threads in the cosmos.

The Beginning: Evolution of the Cosmos *(upper right)*

Astronomers now believe that the universe began at least 15 billion years ago, when the first clouds of the elements hydrogen and helium were formed. Gravitational forces collapsed these clouds to form stars, as shown in the upper center of the illustration. These stars converted hydrogen and helium into heavier elements, including the carbon, nitrogen and oxygen necessary for life. Exploding stars returned these elements to interstellar space, forming clouds (note nebula in illustration) where simple molecules such as water (H_2O), carbon monoxide (CO) and hydrocarbons (combinations including hydrogen and carbon) were formed. These clouds then collapsed to form a new generation of stars and solar systems.

In at least one solar system — our own — a variety of objects were formed, including comets (believed to be the most primitive objects in our solar system), meteoroids, asteroids and the planets (represented by Saturn here). One of the planets — Earth — formed at a distance from the Sun where conditions were favorable and the necessary chemical ingredients were available (note the infalling comet and dust) for the origin of life.

The Prebiotic Earth *(lower right)*

The final, important events leading to the origin of life are perhaps the least understood chapters of the story. Life began during the first billion years of an Earth history 4.5 billion years long. The illustration depicts an Earth where volcanos, a gray, lifeless ocean and a turbulent atmosphere dominated the landscape. Vigorous chemical activity is represented by the heavy clouds fed by volcanos and penetrated both by lightning and solar radiation. The ocean received organic matter from the land and atmosphere, as well as from infalling meteorites and comets. Here substances such as water, carbon dioxide (CO_2), methane (CH_4) and hydrogen cyanide (HCN) formed key molecules such as sugars, amino acids and nucleotides. Such molecules are the building blocks of proteins and nucleic acids, compounds found in most known living things.

A critical early triumph was the development of RNA and DNA molecules, which directed biological processes and preserved life's operating instructions for future generations. RNA and DNA are depicted in the illustration, first as fragments and then as fully assembled helices. These helices formed some of the living threads shown in the illustration. However, other threads were derived from planetary processes such as ocean chemistry and volcanic activity. These evolving bundles of threads thus arose from many sources, illustrating that life was triggered not only by special molecules such as RNA and DNA, but also by the chemical and physical properties of Earth's primitive environments.

The Early Evolution of Life *(lower center)*

Life's history is dominated by the biochemical evolution of single-celled micro-organisms. We find individual fossilized microbes in

rocks 3.5 billion years old, yet we can identify the remains of multi-cellular organisms only in rocks younger than 1 billion years. The oldest microbial communities often constructed layered, mound-shaped deposits called stromatolites whose structures suggest that those organisms sought light and were therefore photosynthetic. Stromatolites grew commonly in the shallow waters surrounding volcanic islands as early as 3.5 billion years ago. They flourished in a variety of coastal environments, which indicates a remarkably high level of sophistication.

Many important events mark the interval between 3 and 1 billion years ago. As the illustration shows, smaller volcanic terrains gave way to more stable granitic ones as the continents more than tripled their sizes. Organisms (the cyanobacteria or blue-green algae) learned how to release oxygen from water, and life diversified and populated the newly expanded continental shelves. The illustration depicts these events, both in the abundant mound-shaped stromatolites along the shoreline and in the greater variety of filamentous and spherical microbes in the foreground. Finally, between 2 and 1 billion years ago, the eukaryotic cells with their nuclei, complex systems of organelles and membranes developed (note the euglena in the illustration) and began to experiment with multicelled body structures. The illustration shows a primitive jellyfish and two Ediacarian sea pens.

Evolution of Advanced Life *(lower left)*

The evolution of the plants and animals most familiar to us occurred during only the last 570 million years. The illustration shows the familiar progression from marine invertebrates to fish, amphibians, reptiles, mammals and humans. The development of land plant communities is also depicted, showing the ancient clubmosses, horsetails and ferns, and the more recent gymnosperms (for example, conifers) and angiosperms (flowering plants).

Perhaps the most significant evolutionary innovation has been humanity's ability to record and build upon its experience, thus triggering the rise of civilization and technology. These developments bring us to the present and, as the thread of life reaches the summit of a tree-covered hill, we ponder our future.

The Future *(upper left)*

Given the huge number of stars in the universe, life has very likely also developed elsewhere. If this other life can control and transmit energy such as light and radio waves, we just might be able to detect it.

As we develop missions to build a space station and to visit other solar system bodies such as comets, planets and moons, we are responding to humanity's need to return to the cosmos to understand life's origins and to expand its horizons.

T. Scattergood is an Adjunct Assistant Professor in the Department of Earth and Space Sciences at the State University of New York at Stony Brook and conducts his research at NASA's Ames Research Center. D. Des Marais and L. Jahnke are research scientists in the Planetary Biology Branch at NASA Ames. The illustration was painted by Robert Bausch, a freelance artist from Belmont, California.

Chemistry BETWEEN THE STARS

by William M. Irvine

Life — as we know it — is a chemical process, based on water and carbon compounds. Complex organic molecules are made primarily from the biogenic elements — carbon, hydrogen, nitrogen, oxygen, phosphorus and sulfur — that formed deep within massive ancient stars. How did these elements travel from their stellar birthplaces across time and space to make up the life-form that is reading these words? In this article, we'll take a look at the chemical processes that set the stage for the origin of life.

From our perspective on Earth, life is fundamentally a chemical process. All the organisms that we know consist largely of water and complex organic molecules made primarily of hydrogen, carbon, oxygen, nitrogen, sulfur and phosphorus. It seems probable that, if living systems exist elsewhere in the universe, they are also made of these elements. Apart from phosphorus, they are among the most abundant elements in the cosmos and their chemistry is particularly well-suited to the complex structures and functions that characterize living systems. It is surely significant that life has not sought out rare and exotic elements for its basic structures, but rather has used the most common atomic building blocks the universe has produced.

In a universe between 10 and 20 billion years old, our solar system formed only 4.5 billion years ago. The biogenic elements must have had a long and complex chemical history before they were incorporated into life on our planet. In this article, I will briefly discuss the chemical processes that went on before our Earth formed. We do not yet know if these processes played a direct role in the origin of life. However, if we try to understand the nature and evolution of chemical complexity throughout the universe, we will better understand the early chemical state of our own solar system. We will also have a better idea of how often the conditions that led to life here might exist elsewhere in our or other galaxies.

The Primordial Element

According to current theories, the primordial element hydrogen formed in the first millionth of a second after the birth of the universe. All biogenic elements heavier than hydrogen are formed by nuclear fusion in the interior of stars. Within these stellar furnaces, pressures and temperatures are great enough to turn hydrogen to helium, helium to carbon, carbon to oxygen and so on through all the known elements. These elements are released as interstellar gas in one of two ways. Most are gently expelled as stars shed material late in their life cycles. Some are thrown off in the violent death throes of a massive star — a supernova explosion.

Most of the known universe — some 99 percent — is made of the lightest elements, hydrogen and helium. Although within galaxies such as our Milky Way, there are differences in the abundances of the heavier elements, most galaxies seem to have very similar overall abundances. Throughout the entire visible universe, the elemental building blocks of complex organic molecules are present in much the same way that they are in our own solar neighborhood.

Most modern astrophysicists have concentrated their attentions on stars, either as individual objects or as galaxies. A star is made of a gas of individual atoms that have been largely broken up into their constituent electrons and nuclei. Molecules, the compounds formed by joining two or more atoms with chemical bonds, were thought to be a very minor feature of astronomy. A few simple two-atom molecules had been discovered in the space between the stars, but theoreticians were convinced that more complex chemical entities could not survive the harsh ultraviolet radiation of interstellar space.

Then, about 20 years ago, astronomers began to turn sensitive radio telescopes toward dark patches in the sky where interstellar "dust" particles were obscuring the light from more distant stars. In many cases the dust and its accompanying gas were clearly associated with bright young stars. Such dust clouds are probably the environments in which stars form, and so they were obvious targets to investigate.

The radio radiation easily penetrated dusty regions opaque to visible light, and since most molecules can be characterized by their radio frequency emissions, the telescopes could identify molecules within the dust clouds. We can think of a water molecule, for example, as a collection of positive and negative electrical charges that are rapidly rotating as the molecule tumbles through space. This changing electrical pattern generates radio waves in a manner characteristic of the molecular structure, just as alternating electric currents in a radio antenna produce emission at the particular frequency assigned to your favorite FM station.

Molecular Clouds

Much to their surprise, radio astronomers discovered that vast quantities of molecular material drifted in the space between the stars. This material has a clumpy distribution, with the clumps called molecular clouds. In fact, the largest clouds are the most massive molecular objects in the universe, containing up to a million times the matter of our Sun. Some of these clouds are only a few hundred light years away, while others can be seen in the farthest reaches of our own and other galaxies. Some appear dark and quiescent, the ever-present dust mixing with the gas in a cloud whose temperature is only 10 to 20 degrees above absolute zero (-273 degrees Celsius, the temperature at which all molecular motion stops). In others young stars are forming, born from the collapse of parts of the cloud. At least some — and quite likely most — such infant stars are surrounded by flattened disks of material that may be analogous to the solar nebula from which our Sun and planets formed.

The chemistry in these clouds is vastly more complex than astronomers dreamed even two decades ago. The list of currently identified interstellar molecules in Table 1 is surely only the tip of the iceberg. With the recent detection of the first phosphorus-containing molecule (PN) in an interstellar cloud, all the

Table 1

These are just some of the interstellar molecules discovered so far that are building blocks for biological molecules:

Molecular hydrogen (H_2), carbon monoxide (CO), ammonia (NH_3), water (H_2O) and hydrogen sulfide (H_2S) — *constituents of primitive planetary atmospheres and the basic building blocks of most of the biological molecules listed below.*

Hydrogen cyanide (HCN), acetaldehyde (CH_3CHO) and ammonia (NH_3) — *precursors to amino acids, the building blocks of proteins.*

Cyanoacetylene (HC_2CN), phosphorus nitride (PN) and water (H_2O) — *precursors to nucleic acids, the carriers of genetic information.*

Formaldehyde (HCHO), formic acid (HCOOH) and cyanamide (NH_2CN) — *used to synthesize sugars and lipids, which form the membranes essential to life.*

Around 4 billion years ago, showers of comets and meteorites may have carried the basic compounds of life to Earth. During their encounters with Halley's Comet (background), the Vega *and* Giotto *spacecraft detected many of the elements necessary for life. Analyses of meteorites and cometary dust (left) that have fallen to Earth have shown us that these interplanetary objects are often rich in organic material.* *Photos: California Institute of Technology (background); NASA/Ames Research Center (left)*

major constituents of life are present in the interstellar molecular inventory.

The discovery of such familiar molecules as ethyl alcohol (C_2H_5OH — the compound that gives some fermented beverages their punch) prompted some astronomers to calculate the abundance of this boon (or bane) to humankind in a particular molecular cloud located near the center of our galaxy. The result is equivalent to ten thousand trillion trillion fifths of pure ethanol, but the proof is rather low (less than that of "non-alcoholic" beer), and some of the flavorings might not be to everyone's taste — they include ammonia (NH_3) and hydrogen cyanide (HCN)! Of more relevance to our subject, molecules such as hydrogen cyanide, formaldehyde (HCHO), ammonia and water are among the basic units from which chemists can synthesize the nucleic acids, proteins and lipids that form the constituents of living cells.

The processes leading to chemical complexity in interstellar clouds are complicated and still poorly understood, although they certainly involve the condensation of dust around evolved stars, chemical reactions between individual gas molecules in the denser clouds, and interaction between gas and dust. The reactions are powered by the interstellar radiation field and by cosmic rays (the very high energy nuclei present throughout our galaxy, which may originate, in part, in supernovae).

Because their constituent molecules are frozen into a solid matrix, and so do not rotate at identifiable frequencies, we cannot analyze the composition of dust particles by radio techniques. The developing techniques of infrared astronomy, as well as earlier optical and ultraviolet observations, suggest that the dust grains have a composition that ranges from "sand" (silicate particles) sometimes coated with water, carbon dioxide (CO_2) and perhaps ammonia ice, to complex organic polymers.

Surviving Molecules

Did any complex chemical constituents in interstellar clouds survive the formation of our solar nebula, and then the Sun and planets? Until recently, most planetary scientists believed that such material broke up into its constituent atoms and later reformed into new molecules within the nebula. But now there is a growing body of evidence that this may not be the whole story.

Much of this information comes from the study of isotopes — different mass forms of the same element. For example, the lightest element, hydrogen, is known in three natural forms: ordinary hydrogen (H), which has a single proton in the nucleus; deuterium (D) or heavy hydrogen, whose nucleus includes both a proton and a neutron; and tritium, with a proton and two neutrons, which is too rare to be important in this discussion. Evidence from the solar spectrum, the atmospheres of giant planets, and diffuse interstellar clouds indicates that about one hydrogen nucleus in 100,000 is deuterium. Radio astronomers were then greatly surprised to discover that in many interstellar molecules deuterium is vastly more abundant than this "cosmic" ratio. In hydrogen cyanide, for example, the ratio of DCN to HCN is more than 1,000 times greater than we would expect on the basis of the D-to-H ratio itself. The explanation comes from chemical processes that, at the extremely low temperatures of interstellar clouds, concentrate deuterium at the expense of molecular hydrogen.

Sensitive radio telescopes can probe the spaces between the stars to pick out the constituents of molecular clouds. Each element emits radiation at specific frequencies which these telescopes can detect. Scientists have now found all of the elements necessary for life in these massive, dark clouds.
Photo: Five College Radio Astronomy Observatory

In a fascinating development, geochemists have now found striking enhancements in deuterium in some meteorites — those thought to best represent the original composition of the solar system. This meteoritic material seems to be preserved interstellar matter that survived planet formation. Other suggestive evidence has come from the intensive study of Halley's Comet, by the flyby spacecraft, *Vegas 1* and *2* and *Giotto*. Many dust particles blown off the comet's nucleus were extremely rich in carbonaceous material. These small grains match very well some models of the interstellar dust grains. Thus comets may be, in fact, agglomerations of interstellar gas and dust.

Although it is more speculative, we may conclude this chain of preplanetary chemistry by asking how Earth received its volatiles — the water, carbon dioxide or perhaps methane (CH_4), ammonia or molecular hydrogen, and other compounds that contain the ingredients absolutely essential to the terrestrial chemistry of life. Earth seems to be too close to the Sun to have allowed condensation of as much volatiles as it now holds. One possible answer is that, after most of our planet formed, Earth received a veneer of volatile-rich material from impacting comets and primitive meteorites. These objects' orbits might have been perturbed into the inner solar system during the formation of the giant outer planets. Such a scenario might deposit on Earth material from interstellar clouds. Perhaps some of these molecules reached the primordial Earth and helped the chemical evolution that led to the origin of life.

Whether or not comets or meteorites hold interstellar material, they do contain complex organic matter. Delicate chemical analyses of carbonaceous meteorites have revealed a vast array of amino acids, the building blocks of proteins; nucleic acid bases, the building blocks of DNA and RNA; as well as other organic molecules both familiar and unfamiliar to the biochemist. During a brief period, some scientists argued for a biological origin for these molecules. This is now discounted, both by the presence of many amino acids that are not part of terrestrial biochemistry, and by the lack of the "optical activity" characteristic of organic molecules in living organisms. (Optical activity affects polarized light shining through a solution, and depends in this case on the symmetry of the biochemical molecules. It is as if organisms on Earth used only left-handed molecules, rather than both left- and right-handed.)

We don't know if these complex molecules were produced within the meteorites or their precursor bodies, or were incorporated from preexisting (interstellar?) material, or both. Nonetheless, it is clear that the processes acting in space on the most abundant elements of the universe are able to create a high degree of chemical structure. At the least, this indicates that a complex organic chemistry must operate throughout the universe.

The dark, interlaced fingers of molecular material thread through the Lagoon Nebula in the constellation of Sagittarius (background). Within molecular clouds like these scientists have found the chemical components of life. Formed from such interstellar dust, comets are rich in these molecules and probably carried them to the primitive Earth (left).

Photo: National Optical Astronomy Observatories
Painting: Dorothy Sigler, Science Graphics

The Next Steps

What are the next steps in exploring this most astronomically oriented aspect of exobiology? NASA's so-called great observatories have been proposed to study the entire electromagnetic spectrum from long-wavelength radio waves to high-energy X-rays and gamma rays. NASA's Large Deployable Reflector would place a radio telescope in orbit above the atmospheric oxygen and water vapor that block crucial portions of the radio and far-infrared spectrum. In this way, key chemical constituents of interstellar clouds will be revealed. A complementary instrument is the Space Infrared Telescope Facility (SIRTF).

The European Space Agency (ESA) is developing some counterpart missions: the Infrared Space Observatory (ISO) and the Far-Infrared Space Telescope (FIRST), whose acronym presents a challenge to NASA if it is to retain its priority in space. Although only ISO is now an approved mission, all these projects have been studied in detail, and FIRST is among the cornerstone missions contemplated by ESA as the basis for the European Space Science Program for the rest of this century.

Among the solar system missions being considered, NASA's Comet Rendezvous Asteroid Flyby (CRAF) and ESA's Comet Nucleus Sample Return would most directly complement existing studies of preplanetary chemistry. The CRAF spacecraft would fly along with a periodic comet through much of its orbit, measuring its chemical composition in much more detail than *Giotto* and the *Vegas* did during their fast flybys of Halley's Comet. Of course, the most detailed and complete picture of cometary organic chemistry will come from a sample return — certainly a fascinating prospect!

William Irvine is Professor of Astronomy and Director of the Five College Radio Astronomy Observatory at the University of Massachusetts in Amherst. He was cochairman of the NASA-sponsored Exobiology in Earth Orbit Workshops held in 1984 and 1985. Dr. Irvine is a member of the Space Science Board Committee on Planetary Biology and Chemical Evolution.

THE ORIGIN OF *Life*

by James P. Ferris

The atmosphere of the primitive Earth was rich in the biogenic elements that would eventually combine into life-forms. Belching volcanos released many of the compounds into the atmosphere; comets and meteorites carried more of the life-forming elements to the early Earth. The heat of volcanic activity, lightning and ultraviolet radiation from the Sun provided energy to transform simple molecules to the complex organic chains that would eventually replicate themselves and become living. This process was relatively rapid; sometime during Earth's first billion years the transformation was complete. As recorded in the fossil record, by 3.5 billion years ago, life was firmly established on Earth. Here we take a look at the chemical processes of life.

In 1952 a first-year graduate student at the University of Chicago persuaded the Nobel laureate Harold Urey that he knew how to experimentally test Urey's postulate that life originated on Earth in an environment without free oxygen. Stanley Miller's laboratory experiments were the first to successfully investigate the origins of life. He generated amino acids, the building blocks of protein, by passing an electric discharge through a mixture of methane (CH_4), ammonia (NH_3), hydrogen (H_2) and water vapor (H_2O). Miller assumed that Earth's early atmosphere consisted mainly of these gases and that lightning converted them to the precursors of biological molecules.

Urey had developed this scenario for a hydrogen- and methane-rich atmosphere from his study of the chemical processes in the hydrogen-rich atmospheres of Jupiter and Saturn. He had assumed that the primitive Earth harbored similar processes. More recent studies suggest that there were much smaller amounts of methane, ammonia and hydrogen in the atmosphere of early Earth. However, the early experiment of Miller and Urey clearly demonstrated that understanding chemical processes on other bodies in our solar system is an important first step in modeling the chemical events on early Earth.

Our solar system formed about 4.5 billion years ago from a cloud of interstellar gas and dust. The cloud collapsed into a revolving disk of dust and molecules from which the Sun, planets, moons, asteroids and comets condensed. The inner planets — Mercury, Venus, Earth and Mars — contain a much higher proportion of the heavier elements than do the outer planets — Jupiter, Saturn, Uranus, Neptune and Pluto. Higher temperatures near the Sun made it hard for the inner planets to retain hydrogen and the other lighter elements. The massive amounts of hydrogen and helium in Jupiter and Saturn reflect temperatures below -120 degrees Celsius in the regions where they formed. So Jupiter is not a good model for primitive Earth, and the amount of hydrogen, methane and ammonia in Earth's early atmosphere would have been much less than Miller used in his initial studies.

Extraterrestrial Organic Compounds

Researchers are increasingly considering extraterrestrial material as an important source of the organic compounds that triggered life on Earth. Since there is evidence for intense meteoritic bombardment before 3.9 billion years ago, meteorites may have been a major source of chemical compounds on the primitive Earth. Particularly interesting are the carbonaceous meteorites that contain up to five percent carbon. By extracting material from these meteorites with water and dilute acid, we get a variety of organic compounds, including amino acids, some of the bases of RNA and DNA, and other components of biological systems. This suggests that the biological polymers essential for life were formed from molecular building blocks brought to Earth by meteorites.

Interstellar dust particles also may have transported organic material to the primitive Earth. About 10,000 tons of this dust floats through the atmosphere to Earth's surface each year. This "stardust" comes mainly from the disintegration of comets passing near the Sun. Since some of these particles carry organic material, they also may have brought organics to Earth.

Comets also contain organic materials. Those that collided with Earth may have been another source of the organic precursors to life. The *Vega* and *Giotto* spacecraft found that Halley's Comet is larger and richer in organic material than was predicted. One of its identified organic polymers is formaldehyde. This is an especially suggestive finding because primitive Earth simulation experiments indicate that formaldehyde (HCHO) had a central role in forming some amino acids and carbohydrates. Thus cometary impacts on the early Earth may have provided enough reactive organic compounds to start the chemical processes leading to biological polymers.

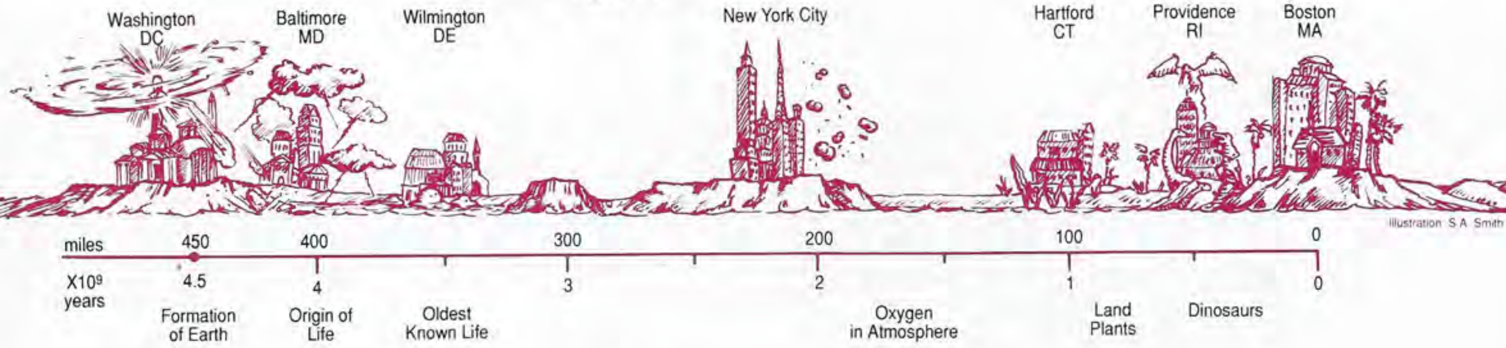
We can learn about conditions on the primitive Earth by sending landers and orbiters to probe the atmospheres and surfaces of our planetary neighbors. Spacecraft sent to Mars and Venus established that their atmospheres are mostly carbon dioxide (CO_2). Both planets have a little water in their atmospheres, and the data suggest that the quantity of water was once much greater than it is today. Because Earth is flanked by Mars and Venus, we can conclude that carbon dioxide and water were also major constituents of Earth's early atmosphere. Thus, several lines of evidence conflict with the methane-rich atmosphere postulated by Miller to demonstrate a possible route to amino acids on Earth.

The Origins of Life

How did life originate on Earth? We don't know the details, but in one view it was a process that moved from simpler to more complex molecules. The chemical reactions leading to life depended on the conditions on the early Earth. Because our understanding of the planet's early history is not precise enough to define these conditions, we must rely on scenarios derived from our current, far from complete, knowledge.

In devising a scenario, the first question to be considered is: When did life originate? We don't know exactly but some events on the timeline in Figure 1 will help define the time period. Since Earth is about 4.5 billion years old, we can correlate a 450-mile trip from Washington, DC to Boston with a 4.5-billion-year trip through time. Each 100 miles is equivalent to a billion years.

Figure 1



Imagine starting out in Washington 4.5 billion years ago when our solar system had just formed. As we proceed on our imaginary time trip from Baltimore to Delaware we can see the earliest life on Earth flourishing near Wilmington. Microbial life is all that we see as we travel the next 2.5 billion years from Wilmington to Hartford, Connecticut. The kinds of fossilized life that we see in many museums, such as reptiles and dinosaurs, evolved less than half a billion years ago, close to Boston. The most primitive form of humankind does not appear until we reach the vicinity of Harvard Square, just outside Boston. It's a short trip from there to the more highly evolved forms in the Boston Common at the center of the city.

Fossils of the oldest known life, present on Earth 3.5 billion years ago, look like filamentous algae and represent a complex and highly evolved form of life. This complexity suggests that the first simpler forms must have originated before 3.5 billion years — well before Wilmington, Delaware on our time line. We can define the time more specifically with the help of astronomers. They tell us that Earth underwent an extensive meteoritic bombardment about 4 billion years ago, around Baltimore on our imaginary trip. If bombardment was very intense it may have prevented life from evolving or killed off what life already existed. If we assume that the end of the bombardment was the earliest possible date for the start of life, and the 3.5-billion-year-old microbial fossils was the latest possible date, then we can conclude that life originated a little less than 4 billion years ago (at the Maryland-Delaware border).

What was Earth like 4 billion years ago? Our ideas have changed since the early experiments of Miller and Urey. We now believe it had an atmosphere consisting mainly of carbon dioxide, water vapor and nitrogen, with little or no methane, ammonia or hydrogen. The sea sediments, permeated with water and minerals, trapped organic compounds from the surrounding medium. The temperature extremes were probably not much different from those on Earth today.

How did the complex molecules of life form in this environment? The exact process is not known, but it probably started by reactions among simple molecules brought to Earth by interstellar dust, comets and meteorites, as well as substances formed by electric discharges, ultraviolet light and other energy sources acting on Earth's primitive atmosphere. These simple compounds condensed either in water — or more likely on the surface of sediments — to form amino acids and nucleotides, and then protein and nucleic acids. The condensation reactions may have been driven by reactive compounds formed in Earth's atmosphere by ultraviolet light and electric discharges. Hydrogen cyanide and other reactive derivatives are among the energy-rich compounds being investigated as such chemical drivers.

Alternating wet-dry cycles, similar to those in deserts on contemporary Earth, have also been studied. In this scenario the polymer building blocks formed by electric discharges and ultraviolet light are washed into a lake which is then dried by the Sun's intense heat. The condensation reactions could occur in this dry, hot environment. Then more rain comes, bringing additional organic material to the lake. A later dry spell leads to the growth of larger polymers from these new building blocks. This repetitive sequence could eventually form the large molecules that organized into the first life.

Catalysis (the tendency of chemical reactions occuring on a substrate to yield particular products) would have been an essential part of this condensation process. Random chemical reactions would have formed a variety of organic compounds, many of which could not have led to life. Unproductive chemical diversity may have been limited by catalysts that favored the synthesis of specific molecules important for life. These catalysts

(continued on page 28)

Life as we know it is a chemical activity.
A few of the more important elements in the game are:

Amino Acids: *A type of large molecule containing carbon, nitrogen and hydrogen atoms. Twenty are found in living tissue where they serve as the building blocks of protein.*

Carbohydrates: *Organic compounds consisting of a chain of carbon atoms to which hydrogen and oxygen are attached.*

Catalysts: *Elements and molecules that greatly accelerate chemical reactions.*

Condensing Agents: *Compounds that facilitate the joining together of molecules.*

DNA (Deoxyribonucleic Acid): *The famous "double helix" molecule that carries genetic information.*

Energetic Compounds: *Molecules that are able to activate other molecules and facilitate their chemical reactions.*

Nucleic Acids: *Complex polymers built up of nucleotides which embody the genetic code (DNA) and assist with its transmission (RNA).*

Nucleotide: *Compounds of carbohydrate, nitrogen and phosphorus that serve as the building blocks of nucleic acids.*

Organic Molecules: *Complicated molecules composed principally of carbon and hydrogen. Some are the products of living processes.*

Polymer: *Long chain-like molecules formed by the linking together of small units.*

Protein: *Complex polymer built of amino acids. Essential constituents of all living cells which carry out the cell's chemical reactions.*

RNA (Ribonucleic Acid): *A family of molecules that aid the transmission of genetic information from one cell generation to another.*

Figure 2: *DNA (left) and protein (center), the polymers central to contemporary life, are very different in structure. RNA (right) provides the link between the two in activity and shape.* Illustration: S.A. Smith

Life on Mars?

TWO VIEWS OF THE QUESTION

Some four billion years ago, Mars may have been a world very much like Earth. Recent investigations have revealed that Mars once had a dense atmosphere and warmer temperatures. Then liquid water may have flowed over its surface. During that time, Mars' evolution may have paralleled that of Earth, where the chemical progenitors of life were busily recombining, and life itself may have already begun its long climb to complex, multicellular beings.

The discovery of this "parallel time" has led many scientists to speculate that life may have also evolved on Mars. Under the influence of Percival Lowell and others, the idea of life on Mars was accepted as fact by a great many people up to the time the Viking *results were analyzed. Our investigating spacecraft demonstrated that Mars was an exceedingly cold and dry place where liquid water — a prerequisite for life as we know it — could not exist at the surface.* Viking *found no organic molecules in martian soil samples —*

MARS, THEN AND NOW

by Norman H. Horowitz

For centuries before spacecraft transformed our understanding of the solar system, almost all the planets were believed, with varying degrees of conviction, to be inhabited. This belief conformed to the Copernican world view, in which Earth is not unique among the planets. When the Space Age opened in 1957, the evidence for indigenous life was strongest for Mars — almost conclusive, on the face of it — and from the beginning the search for life on Mars became a major goal of the United States' space program. The result was the historic series of spacecraft that began with *Mariner 4* in 1965 and ended with *Vikings 1* and *2* in 1976.

Unfortunately, no life was found on Mars, and it seems clear that no life exists on Mars today. How Mars' early promise turned to disappointment is the subject of this article. Even in the cold light of reality, however, Mars is a planet of much interest, thanks to the findings of the *Mariner* and *Viking* missions. And some important questions about Mars are still to be answered.

Lowellian Mars

The picture of Mars that prevailed in the early 1960s, when spacecraft began to explore the planets, was very different from the picture we have today. It was based on the ideas of Percival Lowell, the American amateur who established the Lowell Observatory in 1894 for the express purpose of studying Mars and who convinced himself and much of the public that Mars was inhabited by intelligent beings.

Seen from a distance, Mars is remarkably Earthlike in appearance. It has a nearly 24-hour day, and because of the tilt of its spin axis, it has seasons like our own. It has polar caps that wax and wane with the seasons, and large areas that change color seasonally. All of this proved to Lowell that Mars harbored life: The caps were water ice, and the color changes demonstrated the response of vegetation to seasonal variations in the availability of water.

To this, Lowell added what was for him convincing evidence that Mars also had intelligent life: the famous canals. These consisted of a network of straight, thin lines covering the surface of the planet. These markings, Lowell believed, were bands of vegetation bordering irrigation canals built by intelligent Martians. By 1908, 585 canals had been identified at the Lowell Observatory. Even in Lowell's day, these were regarded by skeptics as figments of his imagination, and we know today that they do not exist.

Lowell was tireless in promoting his Martian fantasy with the public through books, articles and lectures, but when he died the heroic race of Martians that he had created also died, except in science fiction. The rest of Lowell's picture of Mars — including the icecaps, the seasonal movement of water, and the vegetation — survived, however. Amazingly, these pieces of Lowell's Martian romance — all of them conveying a Mars suitable for life and all of them illusory — were corroborated by later generations of planetary astronomers. When the Space Age opened, these ideas were part of the accepted view of Mars.

The first important Martian discovery of the Space Age was that the Lowellian picture of Mars was false. How this picture came to be—how it was possible for a fictional Mars to be endorsed by modern science — may be the ultimate Martian mystery. It is a question for human psychology, however, not planetary science, and will not be pursued here.

The Real Mars

The downfall of Lowellian Mars did not begin with the observations of spacecraft but with a single infrared spectrogram of Mars taken at the Mount Wilson Observatory in 1963. This plate showed that there was something badly wrong with a key element of the Lowellian story: the pressure of Mars' atmosphere. On a dry planet the atmospheric pressure is important because water evaporates faster under a low pressure than under a high one. Lowell knew, of course, that Mars had little water — that is why his Martians built vast water projects. In 1908, Lowell had estimated Mars' atmospheric pressure at 64 millimeters of mercury (compared to 760 millimeters for our planet), and this value was still accepted in 1963, although by then Lowell's name was no longer attached to it. The value had been "confirmed" by later observers, along with the rest of Lowell's model, but Lowell was an embarrassment

During late winter at the *Viking 2* landing site, traces of frost lie on the red ground. This may be water ice condensed from the martian atmosphere.

Image: JPL/NASA

but did find an oxidizing agent that would destroy any organic compounds that might have formed or been deposited by meteorites.

Some scientists now believe that life could no longer exist on Mars, but we should continue to study the martian chemistry and perhaps look for fossilized life that may remain from Mars' wetter, more clement past. This view is here presented by Norman Horowitz. However, other scientists argue that Viking *ruled out life only at the landing sites. The mysterious oxidant may be missing in some places, and there may be hidden niches that could support life. After all, life on Earth is found in such inhospitable places as inside rocks in the dry valleys of Antarctica. Harold Klein here presents this more optimistic view.*

Although they don't agree on the question of life on Mars, both authors do argue that we need to go back to Mars to investigate the question further.

to modern students of Mars, and his name was rarely mentioned.

The Mount Wilson observation showed that Mars' true pressure was much lower than Lowell thought, and we now know, from measurements made from spacecraft, that Mars' average atmospheric pressure is only 4.5 millimeters of mercury. Under a pressure of 64 millimeters water boils at 43 degrees Celsius, while at 4.5 millimeters it boils at 0 degrees. On Earth, the boiling point of water is 100 degrees Celsius at sea level. (Mars' situation is actually much worse than these figures suggest, since there is far too little water vapor in the atmosphere for liquid water to form on the surface; in short, there is no water to boil off.)

By 1969, just six years after the publication of the Mount Wilson findings, a flood of new observations from Earth and from *Mariners 4, 6* and *7* completed the "delowellizaton" of Mars. The atmosphere was found to be mostly carbon dioxide; the icecaps were frozen carbon dioxide, not water ice and there was no seasonal transfer of water across the planet; the evidence for vegetation was illusory. By 1970, Mars presented so unpromising a scene biologically that it would have been hard to argue rationally that a search for life should be the grand theme of the planned landers on Mars.

A change took place in 1971, the year that *Mariner 9* orbited Mars. *Mariner 9* found that Mars had been geologically active in the distant past. Large extinct volcanos were found — and clear evidence of ancient streambeds. (Since they cannot be seen from Earth, these features have no relationship to Lowell's canals.)

The evidence that liquid water existed on Mars, even if only in the remote past, improved the biological outlook significantly. Liquid water is essential to life as we know it, and it may well be essential for life anywhere in the universe, since no other substance shares all the remarkable physical and chemical properties of water. Its role is not simply that of a solvent. It also has an active part in cellular chemistry — as active a part as, say, sugar or DNA. Water is not a rare substance in the universe; on the contrary, it is abundant. What is rare is *liquid* water on a planetary surface, where it is exposed to sunlight, the ultimate energy source for living things. This arrangement, we believe, is essential for the existence of life on a planet — so much so, that any planet found to have water on its surface should automatically be considered a promising object for biological investigation. Conversely, dry planets are not attractive biological targets.

The Viking *Mission*

If water ran on Mars in the past, then life may have originated there too. If so, it was conceivable that it still survived. It was agreed that the search for life would be the major theme of the *Viking* mission.

Most readers of *The Planetary Report* are probably aware of the outlines of this famous mission: two spacecraft, each consisting of an orbiter and a lander, and carrying identical sets of instruments. (See the July/August 1986 *Planetary Report.*) One lander put down in Chryse Planitia in the northern hemisphere of Mars, the other in Utopia Planitia, 1,500 kilometers farther north and on the opposite side of the planet. The biologically important observations consisted of global temperature and water-vapor measurements from the orbiters and, from the landers, close-up photography, organic analysis of surface samples, and attempts to detect metabolic activity of soil microorganisms.

The cameras sent back memorable landscapes of a desolate, rocky Mars. Careful study of these pictures revealed no traces of life. This was no surprise, since only microbial life seemed possible for Mars, and the *Viking* cameras could not have detected it. Organic analysis of the soil was more likely to be informative, although it

"I'm afraid, Stanley, this party's like what they say about Mars. We may have chemistry, but we do not as yet have biology."

Drawing by Opie; ©1976 The New Yorker Magazine, Inc.

was recognized that even a lifeless Mars would probably have organic matter (compounds of carbon and hydrogen with or without other elements) in its soil.

There are non-biological sources of organic matter, and one of them is meteorites. Mars is near the asteroid belt, where meteorites originate, and should have accumulated enough meteoritic material over the ages to register a signal on the sensitive *Viking* instrument. The actual result — no trace of organic matter at the parts-per-billion level of detectability — was the single most important result of the *Viking* mission. It essentially excluded the possibility of life in these soils.

Of the three microbiological experiments, two were Lowellian in the sense that they assumed that Martian organisms, if any, lived in an aqueous environment. These experiments brought martian soil into contact with aqueous solutions of organic compounds and measured the metabolic response. The third experiment was designed to search for life under actual martian conditions. It employed gases known to be present in Mars' atmosphere (carbon dioxide and carbon monoxide) as probes of metabolic activity; no liquid water was used.

All three experiments sent positive signals from Mars. Given the fundamentally different assumptions of the experiments, it seemed clear that they could not all be detecting the same Martian life. The question was whether any of them had found life — a finding that would be hard to reconcile with the failure to detect organic matter in the soil — or whether they had discovered a chemically reactive Mars. The latter turned out to be the case. The aqueous experiments were, in all probability, responding to OH radicals (or peroxides derived from them) in Mars' soil.

OH is produced from atmospheric water vapor by solar ultraviolet light. On Mars it would diffuse into the dry soil and there act as a strong oxidizing agent. Its presence on Mars had been predicted before the *Viking* mission. Its oxidizing power can explain not only the results of the aqueous experiments, but why organic matter is missing, and why Mars is a rusty red color.

As for the dry life-seeking experiment, post-*Viking* laboratory simulations indicate that it was probably measuring a reaction between carbon monoxide and certain iron-containing minerals on Mars. (*Viking* found that Mars' surface contains 13 percent iron.)

The two sites that *Viking* sampled were very similar in their surface chemistry. This similarity reflects the importance of global forces in shaping Mars' environment, forces like the extreme dryness, the pervasive short-ultraviolet radiation, and the planetwide dust storms. *Viking* found that Mars is even drier than was previously thought. The highest abundance of atmospheric water vapor was found around the edge of the north polar icecap in midsummer. Equatorial latitudes, where temperatures rise above freezing and which for this reason were thought, in pre-*Viking* days, to be favorable for life, are desiccated — the driest part of the planet. The dryness alone would suffice to guarantee a lifeless Mars; combined with its radiation flux, Mars becomes almost Moon-like in its hostility to life.

The idea sometimes heard, that there may be an oasis on Mars, a Garden of Eden where Martian life is flourishing, is a daydream. The oasis would reveal itself in photographs by a permanent cloud above it and by snow on the ground. Nothing like this has been seen, and it is most unlikely that such a place exists or can exist on Mars.

Looking Ahead

The picture we now have of Mars is coherent and, we think, realistic, but it needs to be confirmed and expanded. This can best be done with samples collected by automated spacecraft and returned to Earth, where they can be examined in terrestrial laboratories. The active chemicals in the surface material — radicals, peroxides or whatever — require identification. There may be surprises here since it is likely that the plume from the spacecraft retrorockets destroyed the most reactive molecules at the *Viking* landing sites. Samples returned from Mars should also include a deep core to be analyzed for organic material; if any is found, it should be characterized to determine, if possible, whether it is of biological or non-biological origin. The core ought to be examined for fossils, as well.

Everyone should understand, however, that the question of early Martian life is more likely to be answered by a comprehensive study of the geological history of Mars than by a shot in the dark. This will be the challenging task of mobile robot missions of the future.

Norman Horowitz is Emeritus Professor of Biology at the California Institute of Technology. He is a member of the National Academy of Sciences and was a member of the Viking *Biology Team. Dr. Horowitz' recent book, "To Utopia and Back," is available from The Planetary Society.*

BIOLOGY AND THE EXPLORATION OF MARS

by Harold P. Klein

Mars has been an object of great interest for most of this century. We are all familiar with many examples from early science fiction filled with the activities of "little green men" or other sentient Martian creatures. Such fanciful tales still intrigue many people, and films, television and books still project these images. In some subtle way, these notions are probably related to our deep desire to understand our own origins and evolution.

To biologists interested in these questions, Mars holds a special importance because there we can test many aspects of the theory of chemical evolution for the origin of life. (See page 10.) In this theory, life on a planet arises when the so-called biogenic elements produced as stars evolve (notably the cosmically abundant elements hydrogen, nitrogen, carbon and oxygen) combine to form increasingly more complex molecules under the influence of natural energy sources. The resulting organic compounds are then spread through the interstellar medium to newly forming planets. Given a planet with a hospitable environment, the process continues until self-replicating organic molecules form, constituting life. Once started, a living system depends on the capacity of the life forms to adapt to changing environmental conditions.

In considering this theory, Mars is particularly significant for many reasons. First, it formed at about the same time as Earth, and from the same nebular cloud of dust and gas. From Earth-based astronomy and from spacecraft measurements, we have a superficial understanding of the current physical environment of Mars. The biogenic elements are there today in the martian atmosphere and, as at Earth, solar energy and planetary heat are available to drive chemical reactions. Second, the evidence strongly suggests that Mars may have had an early history similar to Earth's. Various scientists studying the *Viking* Orbiter images have concluded that liquid water once flowed across Mars. For certain flow features to have formed, Mars must have had a much denser atmosphere and higher global temperatures than it does today.

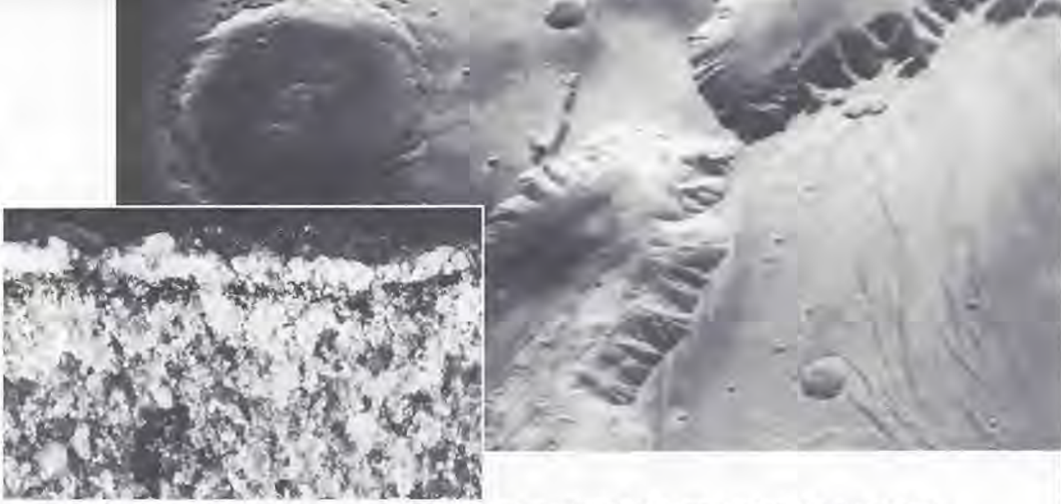
This is an important concept, since many lines of evidence indicate that living organisms were flourishing on Earth within its first billion years — at a time when the environment on Mars may have been very similar. Thus, it is not unreasonable that chemical evolution leading to complex organic compounds, and even to replicating molecules, also took place on Mars in its early history. Finally, its chemical and physical characteristics make Mars an extremely attractive target for biologists — a target accessible by spacecraft.

How Much Do We Know?

Our knowledge of Mars can best be described as paradoxical. Most of what we know has come from the two *Viking* Landers that studied Mars during 1976 and 1977. The mission investigations covered a broad range of possible ways to detect signs of chemical evolution, from the organic analysis instrument, designed to characterize organic compounds, through the biological instruments, intended to measure metabolic activity of micro-organisms, to the imaging system that could have detected direct or indirect visible signs of life.

The most surprising data were the absence of *any* detectable organic compounds at the two landing sites. Before the mission, we anticipated that, at the very least, meteorites from the neighboring asteroid belt would have supplied some organics. But none were found. On the other hand, *Viking* did indicate that the surface contained unidentified strong oxidant(s) that could account for the absence of organics. We still do not know the identity and distribution of this material. In the samples tested, its apparent concentration varied over a 10-fold range and was inversely correlated with the water content of the samples. That is, the highest oxidant concentration was found at the driest site. If this inverse correlation with water content is correct, we should identify other sites on Mars where the oxidant is presumably absent — such as the "wet" polar regions — and probe there for organics.

As for the possibility of *replicating* systems on Mars, after analyzing hundreds of Lander images, the imaging team saw no signs suggesting life. Nor was there unequivocal evidence for metabolic activity in any surface samples tested by the biology instrument. Some of the data from the metabolic experiments are consistent with a biological interpretation, but only if we ignore all the *Viking* results and the Earth-based studies that were carried out in efforts to understand them.



ABOVE: The Viking 1 *Orbiter imaged Hebes Chasma, a canyon within Valles Marineris, the rift in the martian surface that stretches one-fifth of the way around the planet. The central plateau of layered deposits within Hebes Chasma has attracted the attention of some scientists, who believe that it could have formed within an ancient lake.* Image: JPL/NASA

INSET: Life has managed to penetrate every conceivable niche on Earth, and even some that seem inconceivable, such as within rocks found in the dry valleys of Antarctica. To find shelter from the extreme weather, life-forms have colonized minute spaces between the mineral grains. Some scientists have speculated that martian life might be as tenacious and opportunistic. Photo: NASA/Ames Research Center

What Questions Remain?

In contemplating future missions to Mars, we are almost completely ignorant of questions fundamental to biology. What was the course of chemical evolution on Mars? Did organics survive long enough to grow into biologically significant molecules? Did such a process ever form replicating systems, perhaps early in Mars' history? If so, was the resulting life able to adapt to changing conditions as the planet gradually lost most of its atmosphere, dried out and became inhospitable? Are there any specialized ecological niches on Mars where indigenous organisms may still thrive?

The Soviets, in describing their plans for Mars exploration (at the Spacebridge sponsored by The Planetary Society) appear to place a high priority on looking for such biological oases and in searching for living organisms at such sites. We should remember that the *Vikings* sampled material from broad, essentially featureless plains. Recognizing the variety of the planet's topography and the implied potential for different micro-environments, we cannot confidently extrapolate the *Viking* results to the entire globe.

On Earth, some microorganisms have retreated inside rocks in Antarctica, where they have created, or helped create, an environment sufficiently different from their surroundings to allow them to grow. Others have adapted to life in total darkness, far from the sunlight that drives photosynthesis, in or near submarine hot springs that vent at scalding temperatures from the ocean floor.

These examples dispose us to ask whether conditions *anywhere* on Mars can still support organisms — if life ever existed there. Certainly our current picture of Mars — of an extremely arid and oxidizing environment — seems to make it unreasonable to think that complex, replicating, organic entities exist on Mars. However, without a more complete picture of the phases and global distribution of water on Mars, of the nature and global distribution of the mysterious oxidant(s), and of the nature and distribution of any organics, it's premature to close the book on this question.

To many biologists, another scenario seems more plausible: Chemical evolution on Mars may well have produced living organisms under earlier, more benevolent conditions, but these organisms couldn't adapt to worsening conditions over geologic time and became extinct. So, while Mars may now be a dead planet, it may still hold evidence of life from its early history. This evidence may exist — as it does for the early Earth — as fossils, the preserved or modified organic remains of life, or as carbon-, nitrogen- and sulfur-containing materials that show isotopic ratios characteristic of biologic processes.

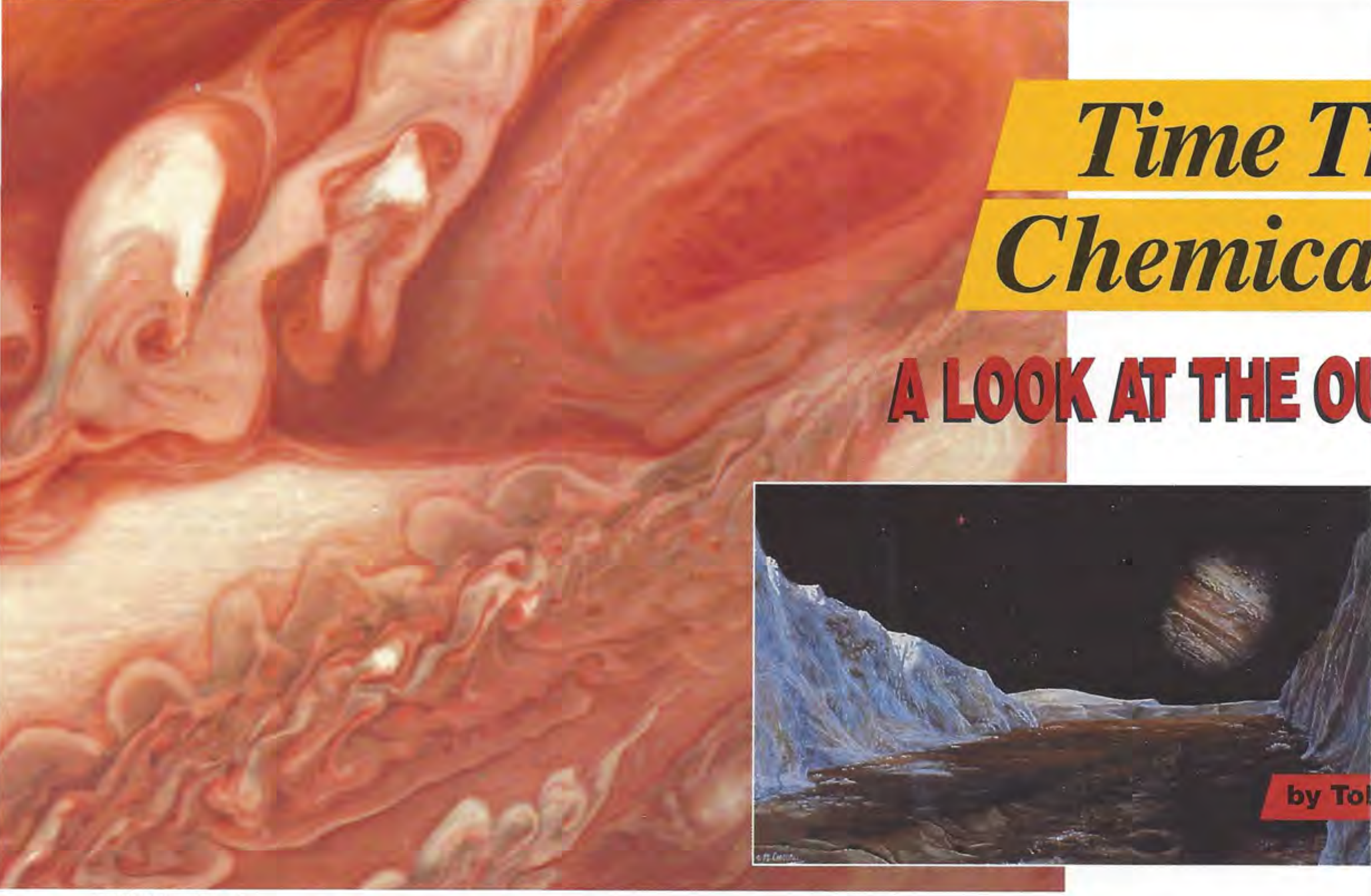
Of course, in this scenario the time-span available for biological development and diversification is critically important. If Mars' primordial atmosphere was quickly lost, the evolution and distribution of life forms would have been short-lived. However, if suitable conditions lasted for even a billion years, life could have been widely dispersed. Within Earth's first billion years, microbial ecosystems became well-established and well-distributed, as we know from complex, fossilized stromatolite communities from Australia and southern Africa. If vestiges of an early biologic era remain on Mars, we will need to do considerably more exploring to find them.

While large areas of Mars appear, from *Viking* images, to have been covered recently by volcanic material, much of the surface seems to be ancient, dating back to the first billion years of the planet's evolution. Subsurface samples from these areas would be useful to study. Other features indicate that flowing water cut numerous channels into the martian surface. Extensive networks of valleys also appear to be extremely old. Moreover, some canyons within the giant Valles Marineris seem to be made of layered sediments, suggesting that they were deposited in standing bodies of water. Evidence of early biology may yet exist in this region, and it is a prime target for investigating the chemical evolution of Mars.

Other Approaches

We will need many missions to Mars, and many different approaches, to test adequately our theories about chemical evolution on this neighboring world. We may find that the forces of nature took a course on Mars consistent with our ideas about how life evolved on Earth. This would, of course, be extremely important verification of our ideas. Conversely, we may find no persuasive evidence to support the theory. In this case, we may learn — or deduce — why the process was prevented or aborted on Mars, and we would then be left with an essentially unverified theory. In the end, we may find nothing to support the theory — without identifying any contravening factors. While we don't anticipate this, such a conclusion would be valuable anyway: It would call into question the premises upon which we have based the theory of chemical evolution.

Harold Klein is Scientist in Residence at Santa Clara University in California. From 1968 until his retirement from NASA in 1984, he was Director of Life Sciences at Ames Research Center. Dr. Klein was the Viking *Biology Team Leader, and now serves as chairman of the National Academy of Sciences Committee on Planetary Biology and Chemical Evolution.*



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A LOOK AT THE OU

by To

ABOVE: The colors of the streaming, swirling clouds of Jupiter provide scientists with evidence of the planet's chemistry. Life-related molecules may be responsible for many of the pastel tints.
Image: JPL/NASA

INSET: A few speculative scientists have proposed that the icy surface of Europa, one of Jupiter's largest satellites, may cover a warm ocean of water. Since life on Earth has colonized even the deep ocean floor, they suggest that life within Europa might be possible.
Painting: Michael Carroll

Many space scientists think that the chemical conditions today on planets and moons of the outer solar system are similar to conditions on Earth soon after it formed. If so, we can learn much about the chemistry that led to life on this planet. We can also speculate about exotic habitats that might have given rise to other types of life. And if we are able to discern the chemical reactions now occurring in the outer solar system, we may be able to extrapolate these rules to other solar systems, and so define the habitable zones around other stars where the potential for life is high.

When we study the solar system beyond the asteroid belt, we are engaging in a kind of cosmic time travel. By examining the outer planets and their satellites today, we are investigating chemical conditions, as well as physical and chemical processes, that may have existed in the inner solar system during the earliest stages of its formation. We are thus given the opportunity to test, in a variety of natural laboratories, our ideas about the chemical evolution that must have preceded biological evolution on Earth.

Unfortunately, none of these laboratories comes close to duplicating the environment hypothesized for the primitive Earth. On the other hand, chemical systems that we find on these distant planets do resemble some thought to have played an important role on our planet.

As we move across the asteroid belt from Mars to Jupiter, a remarkable change occurs in the composition of planetary atmospheres. An obvious manifestation is the difference in the dominant carbon compound in the atmospheres of the inner and outer planets. Mars, Earth and Venus all have atmospheres containing carbon dioxide (CO_2). It is the dominant gas on Mars and Venus, and would be on Earth as well if our planet did not have its oceans of water and abundant life. But from Jupiter outwards, the carbon in atmospheres is predominantly present as methane (CH_4).

There are two reasons for this difference. Hydrogen is by far the most abundant gas in the atmospheres of Jupiter, Saturn, Uranus and Neptune. Thus in normal conditions, carbon will combine with hydrogen to form methane. But hydrogen is only a trace constituent in the atmospheres of Titan, Triton and Pluto, yet methane is still the dominant carbon compound. Here the explanation lies in the absence of available oxygen. The most abundant oxygen compound is water, and at the low temperatures far from the Sun, water is frozen out of the atmospheres of these small, distant bodies. Thus there is no chance for water vapor to be broken apart by solar ultraviolet light, providing the source of oxygen that could convert the methane to carbon dioxide.

In contrast, the warmer inner planets all have water vapor in their atmospheres — even Mars and Venus which have no liquid water on their surfaces. The small masses of these bodies allow lightweight hydrogen to escape easily. The combination of available water vapor and rapid escape of hydrogen means that even if the inner planets began with hydrogen-rich atmospheres, they would inevitably become oxidized over geologic time, as indeed we find them today.

JUPITER

Let's look at Jupiter. Even a small telescope shows us that this planet has some interesting chemistry. The clouds in Jupiter's atmosphere exhibit pastel shades of color which would not be present if these clouds were simply formed

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l Evolution

UTER SOLAR SYSTEM

bias Owen

ABOVE: The subdued, butterscotch clouds of Saturn reflect a chemistry different from Jupiter's. Image: JPL/NASA

INSET: To those interested in organic chemistry, Saturn's moon Titan is one of the most exciting places in the solar system. Its atmosphere is composed mainly of nitrogen, as is Earth's atmosphere, with a healthy portion of methane (CH_4). Ultraviolet light from the Sun could have transformed this substance into various organic molecules. Scientists are anxious to send a probe to Titan to see what has developed there. Painting: Ron Miller

from crystals or droplets of abundant gases condensed out of the atmosphere. We do find some white condensation clouds that are probably made of ammonia (NH_3) crystals — the jovian equivalent of the cirrus clouds drifting in our own blue skies. But the pale yellows, browns, blue-grays, ochres and salmon tints seen on Jupiter require a different explanation.

Today we don't know the substances responsible for these colors. Sulfur compounds seem a likely source of the yellows and browns, but efforts to detect sulfur in any form spectroscopically have proved fruitless. The absence of hydrogen sulfide (H_2S) seems to rule out photochemical reactions involving this molecule as a source of the colors. Phosphorus has been found in the form of phosphine (PH_3), and phosphorus compounds can also provide a variety of colors. John Lewis and Ronald Prinn have suggested that red phosphorus (P_4) might be responsible for the distinctive color of the Great Red Spot. It's possible that C-N-H compounds contribute some of the hues we see, as demonstrated in the laboratory by Cyril Ponnamperuma and Fritz Woeller many years ago.

This possibility is especially interesting since such compounds are a common product of laboratory experiments designed to simulate conditions on the primitive Earth (see page 10). Unfortunately, we've yet to find the spectral signatures of these compounds on Jupiter, and so we cannot yet discriminate among these hypotheses.

How do we move past the present impasse? The colors of Jupiter have been an important astronomical puzzle for half a century, yet we still do not know what causes them. The *Galileo* spacecraft with its atmospheric probe should help. The orbiter carries a near-infrared spectrometer that can identify or rule out specific compounds. The *Galileo* probe will carry a mass spectrometer to detect trace constituents and a nephelometer to locate the various cloud layers. Together, these two instruments should greatly improve our knowledge of jovian cloud constituents.

We already know something about the chemistry on Jupiter from Earth-based studies of the atmospheric gases and from the *Voyager* spacecraft. In addition to the constituents expected in a hydrogen-rich environment, we find unexpected gases such as acetylene (C_2H_2), ethane (C_2H_6) and hydrogen cyanide (HCN). These gases form through photochemical reactions in Jupiter's upper atmosphere and by lightning discharges within the cloud deck.

Other energy sources available to drive jovian chemistry are the descent of charged particles into the auroral zones, where unusual concentrations of trace constituents have been detected, and the release of primordial heat from the planet's interior. At depths where the temperature reaches about 1,200 degrees, for example, methane and water are converted to carbon monoxide (CO) and hydrogen.

All of these energy sources were available on the primitive Earth. Jupiter is a poor terrestrial analog, however, because it has no solid surface and it has such an excess of hydrogen. So there will be a limit to the complexity of compounds produced, as there is no sheltered place where molecules can survive, concentrate and perhaps eventually grow into replicating systems. Instead, they will be part of a continuous cycle in which new species are created only to be converted back to methane, ammonia and water. It remains to be seen what complexity is achieved under these steady-state conditions.

Before leaving Jupiter, we should pause to consider its curious satellite Europa. This small moon has a remarkably smooth, icy surface that *may* cover a layer of liquid water, tens of kilometers deep. If it does, an intriguing possibility explored by Ray Reynolds, Steve Squyres and Chris McKay is that sunlight could filter through cracks in the ice, providing energy to drive chemical reactions in the water below the ice. Internal heat generated by the strong jovian tides acting on Europa's interior is another potential source of energy. (On neighboring Io, the tides of Jupiter drive the vigorous sulfur volcanos.)

Taken to the extreme, a terrestrial analogy that leaps to mind is the manifestation of life around the deep submarine vents recently found scattered across our planet. There communities of strange life-forms thrive that are not dependent on the conversion of sunlight to chemical energy through photosynthesis. Instead, they derive their energy from bacteria that process hydrogen sulfide released from the vents. But these life-forms still have the same genetic system as other life on Earth — they did not evolve separately. And they make use of oxygen dissolved in seawater. These forms are not independent of the rest of life on Earth, and the question of whether life could actually originate in such environments — or under Europan oceans — remains open.

Such considerations broaden our perspective, however, as the authors point out. They force us to realize that in contemplating habitable zones around other stars, we need to enlarge our definition of what conditions make an environment habitable.

SATURN, TITAN AND BEYOND

Moving on to Saturn, we find a subdued version of Jupiter. Its lower temperature and lower gravity conspire to make a thicker layer of ammonia cirrus. While there is a yellow tint to these clouds, some differences in their absorption of ultraviolet, and some occasional colored spots, there is nothing like the swirling, surrealistic cloud patterns we find on Jupiter. Even on Uranus, twice as far from the Sun as Saturn, *Voyager 2* revealed evidence of atmospheric photochemistry driven by solar ultraviolet light. Neptune's atmosphere will probably exhibit similar phenomena. But again we anticipate that the visual drama of Jupiter will be lacking. In the saturnian system, our interest is drawn instead to Titan.

This satellite is only slightly smaller than Jupiter's Ganymede and is larger than the planet Mercury. What marks it out, however, is not its size but its atmosphere. Titan is surrounded by an atmosphere with a surface pressure 1.5 times the sea level pressure on Earth. This atmosphere is composed primarily of nitrogen, like ours, but the next most abundant constituent is methane, not oxygen. Ultraviolet light from the Sun, plus bombarding electrons from Saturn's magnetosphere and cosmic rays from the galaxy, are constantly breaking these molecules apart. The fragments recombine to form a rich variety of new molecules including some polymers not yet identified.

The evidence for polymers is again indirect, as for the colors in the clouds of Jupiter. For all its interest as a natural chemical laboratory, Titan is disappointingly dull in the *Voyager* pictures, shrouded by a thick layer of brownish smog. Unlike Jupiter or Saturn, Titan has a solid surface on which these aerosol particles can collect as they fall out of the atmosphere. Indeed, the surface of this satellite may include lakes or oceans of ethane, as suggested independently by Mike Flasar and Jonathan Lunine, Yuk Yung and David Stevenson.

Once again, we need a new mission to follow up *Voyager* to find out just what the chemistry of Titan is really producing. Such a mission is now being studied jointly by NASA and ESA (the European Space Agency), and is called *Cassini* after Jean Dominique Cassini, the first director of the Paris Observatory who made many discoveries in the saturnian system. This mission involves an orbiter, to be built by NASA, and a Titan probe, to be built by ESA. The probe will make measurements of surface materials, if it survives the landing. Since it will descend gently on a parachute, chances of survival seem good, whether the surface at impact is solid or liquid.

Long before the *Cassini* mission reaches its targets (it is not yet approved as a new start by either NASA or ESA), *Voyager 2* will show us another unusual satellite that may have liquids on its surface. This is Neptune's Triton, to be encountered in August 1989. We already know Triton has an atmosphere that contains methane, and Dale Cruikshank has found an absorption in Triton's spectrum that could be caused by pools of liquid nitrogen on its surface. If so, the atmosphere is clearly much more transparent than Titan's. Why the difference? What chemistry is occurring there? *Voyager 2* will be able to provide only an introduction to these puzzles.

COMETARY NUCLEI

The nuclei of comets seem to be coated with carbon-rich material (if Halley's is at all representative) as do the satellites and rings of Uranus, the outermost asteroids, and Phoebe, the strange little moon orbiting Saturn backwards. This is not all the same suite of compounds, however, since the spectral reflectivities of these various objects differ. Nevertheless, we seem to be confronting organic matter in the outer solar system once again, this time produced without the benefit of an atmosphere. Did all this dark stuff form in the solar nebula before these objects accreted? Or was some of it processed later at low temperatures as a result of cosmic ray bombardment or ultraviolet irradiation? What are these compounds?

The next big step in our continuing effort to answer these questions will be taken by a mission called CRAF, Comet Rendezvous-Asteroid Flyby. CRAF will make a close rendezvous with a comet nucleus and deploy a penetrator to make on site measurements of composition and physical state. The spacecraft will carry a variety of instruments including a gas chromatograph and a mass spectrometer to analyze the gases given off by the nucleus as it moves around its orbit.

In our study of a comet nucleus we are pushing our time travel back to the origin of the solar system and possibly beyond, since unmodified interstellar grains may be frozen in these cometary ices. In the early solar system, cometary impacts with Earth were more frequent than they are today, and they would have delivered a healthy helping of volatile elements (such as hydrogen, oxygen and nitrogen) to Earth and the other inner planets. We could regard this as some celestial seasoning for the famous primordial soup. Whether there was more to it than this depends on what kinds of organic materials are really in the comets and which ones would survive impact with Earth.

Contemplating chemical evolution in the outer solar system, we find ourselves in the state nicely described by St. Paul: We see through a glass darkly. The colors of Jupiter's clouds, the brownish smog of Titan, the black coatings on comets — it is as if there is a tarnish on the whiteness we expect to encounter in the icy realm beyond the asteroid belt. It is precisely this darkness that we want to investigate — what are the compounds that cause it and how are they related (if at all) to the origin of life on Earth? If the missions planned for the next decade are actually launched and successful, we shall surely have more of the answers we seek.

Tobias Owen is Professor of Astronomy at the State University of New York at Stony Brook. He is the American chairman of the NASA-ESA Joint Science Study Team for the proposed Cassini *mission. Dr. Owen is also a member of the* Voyager *Imaging Team and the Mass Spectrometer Team for the* Galileo *mission.*

News & Reviews

by Clark R. Chapman

In the September 27th *New York Times Book Review*, Bob Coleman traces the history of science writing and finds its modern practice wanting. "Taken together, modern scientific writing, both the popular and the professional type, makes science look far more precise and reliable than it really is," Coleman writes. It is crucial, he continues, "to understand accurately scientific fallibility or infallibility. . . . A frank, humane discussion of errors, troubles and limitations was once considered essential to objective scientific writing. The revival of such discussion might make us all more comfortable with the course and uses of science in the late 20th century."

Certainly professional scientific journals have evolved to prohibit honest, complete accounts of research projects. Papers by 19th century scientists often described in detail and in comprehensible language the pathways, including culs-de-sac, to their discoveries. But now page-charges and modern style require scientific articles to be written in precise, progressive, logical and terse form. Discussion of errors is permissible, even encouraged, if cast in statistical terms, but there is no place for expressing philosophy, morality, doubts or anything about the human side of research, nor even for completely describing the progress of an experiment. A journal article must present an important advance in assured, rigorous words, otherwise referees will recommend revision — if not rejection — or editors will require shortening to the bare essentials.

Why should *popular* science articles portray a similarly fraudulent view of science? Some, of course, are by scientists who have learned to write. But even articles by professional writers who have learned some science often describe the logic and results, rather than the practice and human context, of modern science.

Ross Taylor's competent article on the origin of the Moon (September/October *American Scientist*) is an example. A lunar scientist from Australia, Taylor writes (in words accessible to most *Planetary Report* readers) of today's facts about the Moon, and about the recent consensus that the Moon probably was formed by impact of a Mars-sized planet with Earth. Taylor carefully notes that not everyone agrees. But facts are facts to Taylor, and he expresses few doubts about lunar knowledge nor does he doubt that we are closer than ever before to a true understanding of the Moon's origin.

Dabbling with Venus

Where can a scientist publish personal accounts of his or her research? Well-constructed, readable articles may be accepted by *Scientific American, Technology Review* and *American Scientist*, but there are few venues for modern would-be followers of the 19th century style. Therefore, it was a delight to find David Allen's personal account of his exposure to the planet Venus at the Anglo-Australian Observatory where he works. I met Allen one night nearly 20 years ago when we were both observing on Mount Wilson; our paths have rarely crossed again, since he deals with planets so rarely.

But in the October *Sky & Telescope*, Allen reports on his introduction to Venus. With none of the I-know-it-all hubris of most scientists, Allen admits his ignorance about Venus, and tells of his imperfect approach to studying the planet's cloud structures from infrared maps of the nightside. David Allen is surprised, but pleased, that simple Earth-based telescopic observations, which any astronomer could have made a decade earlier, can still outrun the planetary probes sent to our sister planet by the United States and the Soviet Union. It is refreshing that he can admit to his naivete as he aimed the telescope at Venus. And I am glad that *Sky & Telescope* has shed traditional stuffiness and given a place to this kind of writing.

Mysteries of Pluto

David Allen is not alone in exploiting the power of Earth-based telescopes. Tiny Pluto, near the solar system's edge, yields its secrets sparingly. In the last couple of years, however, it has tantalized us with a series of eclipses and other "mutual events" as its moon Charon crosses in front of Pluto, then passes behind, and so on. The critical geometry for these events occurs only every 124 years. Fortunately they are happening now, a decade *after* Charon's discovery, rather than a few years before, when the instruments to obtain the data existed, but nobody would have known to look.

The power of Earth-based astronomy, supplemented by a few critical measurements by the Infrared Astronomical Satellite, is enabling us to learn much about Pluto. The September 11th *Science* has two dry, technical articles on Pluto, comprehensible only to specialists. Fortunately, they are lucidly summarized in a one-pager by Jonathan Eberhart in the September 26th *Science News*.

All three articles fail, however, to provide a realistic picture of the uncertainties and rivalries among the various research groups attempting to exploit this unique plutonian geometry. Although a first-person article may not appear until after 1990, when the mutual events are over, Kelly Beatty does a superb reportorial job in the September *Sky & Telescope*. He lays out all the mysteries about Pluto and Charon, what they are made of, how they differ, whether they have atmospheres and so on. And he goes beyond the pure science to hint at battles among the researchers: unseemly, perhaps, for objective scientists, but a real motivator for many discoveries. Beatty may have crossed a few lines himself, in reporting results not yet released in the professional journals. But overall it is a very good account of what's really happening in Pluto's corner these days.

Cometary Catastrophes

A few scientists do take an introspective view of their science in its historical and social context, notably Stephen Jay Gould, columnist for *Natural History*. In his September piece, he reconsiders William Whiston, a 17th century philosopher who viewed Earth's history in terms of impacts (or near-misses) by comets. Without overstating Whiston's prefigurement of the Alvarez cometary theory for extinctions, Gould reminds us of the cultural context for scientists' evolving views about the relative roles of stability, gradual change and catastrophe in shaping our planet and its biosphere.

The evolutionist Gould, who rejects the idea that human beings are the pinnacle of biological evolution, sees science as an evolutionary process, he is wary of judgements that old, rejected views are necessarily wrong, or that modern science is an objective accumulation of truth. While in *American Scientist* Ross Taylor dryly reports a new view of lunar origin that would have seemed crackpot a few years ago, it takes the rare genius of writer-scientist Gould to teach us how to question scientific "truth".

Clark R. Chapman is preparing to celebrate the tenth anniversary of the last planetary launch by the United States — Pioneer Venus, *August 8, 1978.*

Finding and Studying Other Planetary

Life as we know it is a planetary phenomenon — the conditions necessary for chemical and biological evolution have so far been found only on a solid body (with abundant liquid water). But we do not yet have unequivocal evidence for planets around other stars. Current theories of star formation suggest that planetary systems should be the rule rather than the exception. And since life-related molecules are widespread throughout the universe, we might expect that some other planets have the conditions necessary for life. The detection of other planetary systems is a prime objective of the comprehensive study of life.

Living systems, even in their simplest forms, are a marvelous manifestation of chemical and biological evolution. On Earth, nature used chemical evolution to take the basic elemental building blocks of living systems — elements whose origins can be traced to the infernos deep within all stars — and brought them together to form living things.

Chemical evolution goes on in the dark, cold clouds that fill much of interstellar space and serve as the birthplaces of stars. Equally complex chemical evolution no doubt occured in the earliest stages of our solar system's formation. However, the existence of living systems depends critically on an environment with the conditions necessary for these systems to evolve. Such conditions are found principally, if not solely, on solid bodies such as planets and their satellites. Searches for extraterrestrial life in our solar system are focusing on Mars and the outer planets and their satellites.

Current efforts to detect life beyond our solar system concentrate on finding intelligent, communicating life-forms (see page 23). In this broader perspective of life in the universe, planets play a special role. All estimates of life's abundance in the galaxy start with a guess as to the abundance of other planetary systems.

Our current theoretical understanding of solar system formation suggests that it is a relatively common occurrence in the galaxy. However, we now have *no* unequivocal observational evidence for another planetary system. This is presumably because we don't have the appropriate observational facilities, and does not necessarily reflect a reluctance on Nature's part to produce analogs to our solar system.

Over the past decade, several studies have outlined methods for detecting and ultimately characterizing planetary systems around most — if not all — stars within a few tens of light years. Many of these methods were described in the September/October 1984 issue of *The Planetary Report*, so I will only highlight them here.

Detecting Planets

We naturally would like to take a picture of another planetary system. Usually we see astronomical images in visible light, as most spectacular photographs of our neighboring planets have been taken. Detecting other planetary systems by direct visual observation is a difficult task. It's difficult because even a very bright planet like Jupiter is nearly a billion times dimmer than the star it orbits. To directly detect a planet requires astronomers to both suppress light from the bright star without also suppressing any faint light from planets that might revolve about it and to avoid creating false signals from scattered light within a telescope. The situation is much better in the infrared part of the spectrum, where the contrast between planet and star is more like ten thousand to one.

If we do directly detect planets about other stars, what can we hope to learn? After enough observation (ranging from months to years, depending on the system under study) direct observation would teach us about the planets' orbits. Perhaps the greatest potential scientific return would come from spectral information about the planets' atmospheres. Such information would be particularly useful to searches for life. But any images taken with systems now under study would show only a faint, unresolved point of light. With the first generation of space-based direct detection systems, we could not see any planetary surface features.

To detect another planetary system indirectly, we would look for periodic variations in the properties of a star that can be attributed to planets revolving about it. The two most widely considered techniques are spectroscopy (the precise measurement of star colors — wavelengths of light) and astrometry (the precise measurement of the apparent positions and motions of stars). Spectroscopy is particularly well-suited to detecting planets close to their parent star, and astrometry is better for finding planets farther away from their star.

An appealing aspect of spectroscopic searches is that we can do much with Earth-based facilities. Newly developed instruments at the University of Arizona and at the Dominion Observatory in British Columbia permit spectroscopic observations of several nearby stars with enough accuracy to detect Jupiter-sized companions to those stars. Indeed, very intriguing preliminary results from these programs have already been published.

Although these indirect techniques do not provide us with images, they are actually richer in scientific content than the first generation of direct detection techniques. Indirect techniques can characterize in detail both the orbits and the masses of planets found in other systems. These properties are important for testing models of the solar system's origin.

The Astrometric Telescope Facility, to be mounted on NASA's proposed space station, would be able to detect Uranus-sized planets orbiting any star within 33 light years of the Sun. If current theories of planet formation are correct, there should be enough planets out there to keep the telescope very busy. Painting: JPL/NASA

Systems by David C. Black

Scientists believe that planets form naturally as swirling clouds of dust and gas condense into stars (above). Stars are being born throughout the universe in "stellar nurseries" such as the great nebula of Orion (right). These clouds of hydrogen, helium and heavier elements are the raw materials from which gravitational forces create new stars.
Painting: Hayden Planetarium; Photo: National Optical Astronomy Observatories

Prospects for Detection

As we look to the near-term future of planetary detection (where "near-term" means the next 10 to 20 years) the prospects look promising. The first major instrument designed primarily for detecting other planetary systems is the space-based Astrometric Telescope Facility (ATF), now being studied by a team of researchers from NASA's Ames Research Center, the University of Arizona and the Allegheny Observatory at the University of Pittsburgh. The ATF should be able to detect relatively small planets (about the size of Uranus) around any star within 30 light years of the Sun. This system will work in concert with precise Earth-based spectroscopic and astrometric systems that will begin operating within the next five years.

Prospects for direct detection are also exciting, but less certain because of the difficult technical problems in controlling stray light in telescopes. Studies at the Jet Propulsion Laboratory are promising, and may lead to an optical telescope that could detect large planets about some of the nearest stars to the Sun. One of the key facilities in NASA's planned Great Observatories program, the Space Infrared Telescope Facility (SIRTF), may directly detect Jupiter-like companions to nearby stars.

Extraterrestrial Life

The rationale for finding and characterizing other planetary systems is that the results would be: 1) essential to understanding the origin of our solar system, 2) extremely valuable to modeling star formation, and 3) able to provide constraints on searches for life elsewhere in the universe. Items 1 and 2 typically receive more attention than does 3, but here we will focus on how a planetary detection program might influence searches for extraterrestrial intelligence (SETI).

The most direct influence would be to affirm (or deny) the basic assumption of most SETI activities: that planetary systems are numerous. Failure to detect planets around the nearest few hundred stars would not imply that there are no planetary systems elsewhere in the galaxy, but it would cast doubt on that assumption. Detection of planets around many nearby stars would affirm the assumption. Either outcome would profoundly affect SETI strategies. In particular, if planets are discovered about nearby stars, we would expect SETI efforts to focus on them.

Aside from developing a catalog of planetary systems, a comprehensive detection program would teach us about the properties of other systems. An important characteristic would be the orbital architecture of those systems, that is, the orbital periods (time to make a complete orbit) and eccentricities (an orbit's departure from a circle). These orbital parameters would give us clues to the thermal environments of the planets. For example, are the thermal conditions conducive to the formation and evolution of life? Indirect detection techniques, such as astrometry, also provide estimates of planetary masses, and mass is a very important parameter in determining the composition and structure of planets.

One of the more exciting outcomes of these searches is that we may be able to determine, through spectroscopic observations, the relative abundances of key constituents in planetary atmospheres. If we can, we will gain valuable insight into the likelihood that living systems evolved on those planets. Spectroscopic studies might even provide direct evidence of living systems; the relative abundances of nitrogen, oxygen and methane in Earth's atmosphere are a sure sign of life.

An intimate, perhaps causal relationship exists between the search for life and the search for other planetary systems. And the search for life is one of the most significant challenges yet undertaken by humanity.

David Black is Chief Scientist for Space Research at NASA's Ames Research Center in California. He has just returned to Ames after two years in Washington, DC as NASA's Chief Scientist for the Space Station. Dr. Black was the guest technical editor for the September/October 1984 Planetary Report *devoted to extrasolar planets.*

SOCIETY *Notes*

NEW MILLENNIUM COMMITTEE SCHOLARS ANNOUNCED

The Planetary Society has announced its 1987 New Millennium Committee scholarship winners: Lisa Boehmer of Los Angeles, California and Elan Grossman of Staten Island, New York. Each student received an award of $2,500. Ms. Boehmer, a graduate of Marlborough School, attends Harvard-Radcliffe University; Mr. Grossman, in his first year at Wesleyan University, is a graduate of Port Richmond High School.

The topic of this year's contest essay was: If you were asked to organize a scientific program to search for extraterrestrial life, how would you plan and conduct that search? Ms. Boehmer wrote:

"I would propose to have at least two radio telescopes synchronously searching the Milky Way 24 hours a day. If a 'sighting' were reported, one observatory could confirm the other's findings. Data from these telescopes would be recorded so that a sighting could be reconfirmed by the further analysis of another group. This analysis group would then attempt to decode the message, while alerting a committee that . . . would develop a policy of action."

"This systematic approach would lead to an organized search for extraterrestrial intelligence, and be able to deal with this intelligence in an intelligent way."

Elan Grossman envisioned a radio telescope in space:

"The basic problem encountered in designing a radio telescope is to construct one as large as possible, but at the same time maintain that parabolic shape to within a certain fraction of the wavelength that it is designed to detect. A single parabolic dish could be built on the order of five kilometers across, heightening its sensitivity far beyond anything presently existing on Earth. The structure could be light, composed of a geodesic frame costing only about one-tenth to one-twentieth of the cost of an equivalent installation on Earth."

New Millennium Committee scholarships are available each year to high school seniors who are members of the Society or are nominees of members. The 1988 scholarship competition will be announced in the January/February 1988 issue of *The Planetary Report*.

We would like to thank Society Advisor Philip Morrison for reviewing the finalists' applications. Dr. Morrison is Institute Professor at the Massachusetts Institute of Technology and one of the founders of the modern search for extraterrestrial life.

MEMBERS FUND MARS BALLOON STUDY

Part of our members' contributions to the Mars Fund is financing a study of using balloons to explore Mars. (See the May/June 1987 *Planetary Report.*) Bruce Murray, Society Vice President, is leading the cooperative effort among The Planetary Society, the NASA Jet Propulsion Laboratory and the California Institute of Technology, working with the Centre National d'Etudes Spatiales to design and test a payload system for the balloon.

The study team includes leading US planetary scientists, along with several balloonists and aerospace engineers. The Society has awarded Ball Aerospace a contract to design a television camera to ride on the Mars balloon, and JPL, with NASA support, has a contract with Titan Systems, Inc.

At the Case for Mars III conference last July, members of the study team flew a demonstration balloon for an interested crowd. During the International Astronautical Federation (IAF) annual meeting in Brighton, England in October, team members reported on their analysis and test results to NASA, CNES (the French space agency) and Intercosmos (the Soviet-led space consortium).

A CHALLENGE TO MEMBERS

Society member Richard W. Gorney of Chicago has challenged all Society members to help increase our membership: "If each current member would either solicit a new member or give a gift membership, the Society would easily double overnight, thus providing *both* funds and clout!"

Mr. Gorney sent in two solicited memberships and gave memberships to US President Ronald Reagan and USSR General Secretary Mikhail Gorbachev to commemorate the signing of the US/USSR space agreement of April 15, 1987. He also challenges the Society's Boards of Directors and Advisors to talk and write about the Society so our important goals will become widely known.

MARS INSTITUTE STUDENT CONTEST ANNOUNCED

The Planetary Society's Mars Institute has announced its 1988 student contest. This year's topic will be: Consider the search for evidence of life (past or present) on Mars, including why life may have existed or does exist, where the evidence might be found, and how human explorers or robots could find that evidence. Entrants will be asked to submit an essay detailing their proposal, which will then be judged by a distinguished panel of planetary scientists and engineers. All high school and college students are eligible for the prize of $1,000.

If you would like more information on the contest, please write: Mars Student Contest, The Planetary Society, 65 N. Catalina Avenue, Pasadena, CA 91106.

PLANETARY ARTWORK DONATED TO SOCIETY

From August 31 to September 19, The Planetary Society held a workshop for educators in Mexico City. We'll report in detail on this extremely successful program in a later issue of *The Planetary Report*, but we'd like to share now a gift to our members from a workshop participant.

Inspired by what she had learned, architect Socorro Velasco created a lighted glass sculpture of Jupiter's magnetosphere. She has now presented this beautiful work toThe Planetary Society, along with this letter:

"It is my honor to contribute this grain of sand to that Society whose noble object is to disperse scientific knowledge to the people. The unity of human efforts among all the countries of the world is one of the greatest hopes to preserve humanity on this planet Earth.

"I consider this work to have a particular symbolism since it has been used to demonstrate in this planetary science course that science and art must go together. On the other hand, it is to show how grateful I am to all of you for the efforts you've made to disperse knowledge of space to the Mexican people."

AWARDS GIVEN AT HAWAII CONFERENCE

The Planetary Society gave several awards to outstanding individuals and organizations during the Hawaii conference last August:

The *Challenger* Center was given a grant to help establish educational programs. Dr. Kathryn Sullivan, NASA astronaut and member of the Board of Directors of the center, was on hand to help present the award. It was given in memory of *Challenger* astronaut Ellison Onizuka, who was a resident of Kailua-Kona, site of the conference. Accepting the award were Cynthia Onizuka for the family, and Arthur Kimura, Hawaii's Teacher-In-Space.

Senator Spark Matsunaga (D-HI) was given an award at the University of Hawaii by Society President Carl Sagan, for leadership in the US Congress advancing international cooperation and the goal of human flight to Mars. Senator Matsunaga has initiated legislation that led to renewal of the space cooperation agreement between the US and the USSR and to the establishment of the International Space Year.

The Windows of SETI—

Frequency and Time in the Search for Extraterrestrial Intelligence

by Bernard M. Oliver

On Earth intelligent life evolved as a natural consequence of the events set in motion when the planet formed over 4 billion years ago. Since chemical evolution and solar-system formation appear to be occurring throughout the universe, we theorize that our universe may be rich with planets populated by intelligent beings who, like us, can search for evidence of other technological civilizations. Terrestrial civilization now has this capability. But if we do not begin the search soon, we'll lose the opportunity to do it from Earth as interfering signals of Earthly origin rapidly close the microwave window.

Some 5 billion years ago, as the Sun condensed from a dirty cloud of hydrogen and helium, it left behind about one seven-hundredth of its mass in the form of orbiting planets. We believe most Sun-like stars do the same. The remarkable thing is not that planets form, but that so little of the original mass is involved. On Earth, life began almost as soon as the planet was cool enough to form seas. If this is typical, there may be as many as 10 billion Earth-like planets in our Milky Way galaxy alone. Today we contemplate a universe teeming with life, some of which may be intelligent. But will we be able to find other civilizations? Three windows significantly reduce the cost of the Search for Extraterrestrial Intelligence (SETI). We are letting one of them slip by.

It's nice to have scientists come to believe what science fiction fans have known all along, but the latter group is going to have to change its thinking too. We are not going to make contact with extraterrestrials by physical interstellar travel. Nor are they going to hop in their spacecraft and visit us. Not this year. Not this century. Not ever. Interstellar travel is not physically impossible but, unless some unimaginable breakthrough occurs, it is economically impossible on the time scale of a human lifetime. (See Figure 1, next page.) Very few voyages are worth thousands of years of a planet's energy consumption. So much for the so-called Fermi Paradox: Where are they? Their appropriations committees, like ours, reject proposals requiring thousands of years or their planet's entire energy budget.

Are we then doomed to isolation, never to know the fantastic variety of intelligent life-forms and societies the galaxy has engendered? Here the answer is no. Communication with extraterrestrials would enrich our lives fully as much as travel to their exotic worlds. After all, only a few dedicated astronauts would sacrifice their lives to the journey. Most would have to depend upon communication anyway.

To communicate we must send some form of energy or matter across space. If we assay all known alternatives — gravity waves, neutrinos, charged particles, photons and so on — we rapidly conclude that photons (electromagnetic waves) are best. Gravity waves have yet to be detected from events on a cosmic scale. Neutrinos could easily pass through a light year of lead and are therefore fantastically difficult to intercept. Charged particles are deflected by magnetic fields and are absorbed by matter in space. Photons have mass only in flight at the speed of light. Any particles having mass at lower speeds or at rest require much more energy per particle. The kinetic energy of an electron traveling at half the speed of light is millions of times greater than the total energy of a microwave photon. The transmitter must supply this energy.

The Frequency Window

Electromagnetic waves are the common waves of radio, TV, heat, light and X-rays. They cover a wavelength from thousands of meters to billionths of a meter. Microwaves, used in radar and satellite communication, range from about 30 centimeters to a few millimeters and so are not the shortest electromagnetic waves; they are merely the shortest we could use for radar during World War II. The name is historical.

Not all electromagnetic waves are equally suitable for interstellar communication. Of particular interest to SETI is the region from about 1,000 megahertz to 60,000 megahertz, or from wavelengths of 30 centimeters down to about 1/2 centimeter, known as the free-space microwave window (see Figure 2).

At the lower frequencies (longer wavelengths) the background noise increases with decreasing frequency. This is the radiation caused by electrons being whipped around in the galactic magnetic field. It is the radio noise first observed in 1932 by Karl Jansky and which led to the whole science of radio astronomy.

At higher frequencies (shorter wavelengths) the other noises drop away and we are left with noise due to the granularity of the radiation itself. Electromagnetic radiation is emitted and absorbed in discrete quanta, called photons. The energy per photon is proportional to frequency — so with increasing frequency a given amount of energy is received in fewer, larger lumps. As the fine mist of arriving light particles turns into larger and larger hailstones, the background noise increases with frequency.

In between these two walls is a silent valley where the only important noise is that due to the cosmic background. This is the relict radiation of the Big Bang, greatly cooled and dropped in frequency by the expansion of the universe. Sensitive radio receivers can still pick up this echo from the cataclysmic event that engendered our universe. The limit on our radio sensitivity in the microwave window is set by the (much attenuated) glare of creation.

It is important to note that the three noise sources that define the microwave window appear much the same to radio-engineers anywhere in the galaxy. The galactic radiation is probably greater near the galactic center than near the rim, but the microwave window remains.

On Earth the absorption by atmospheric oxygen and water vapor renders the top half of the free space window nearly opaque. However, for many reasons the long-wavelength end of the window is preferred. Antenna collecting area is cheaper since the surfaces, which must be accurate to a fraction of a wavelength, need not be so precise. Transmitter power per device can be greater. Receiver noise is lower. Frequency shifts and drifts, due to relative motion of the transmitter and receiver, are proportional to the frequency used, and so are less at the low end of the window. Thus the signals we are searching for seem likely to be in the lower half of the window, and this is the

Figure 1: Nature's Price for Interstellar Travel

Although there is no air resistance in space and, once set in motion, a vehicle will continue in motion indefinitely, we still have to provide kinetic energy to the vehicle to get it moving in the first place. For velocities up to about one-fifth the speed of light, the kinetic energy is approximately one-half the mass of the vehicle times the square of its velocity.

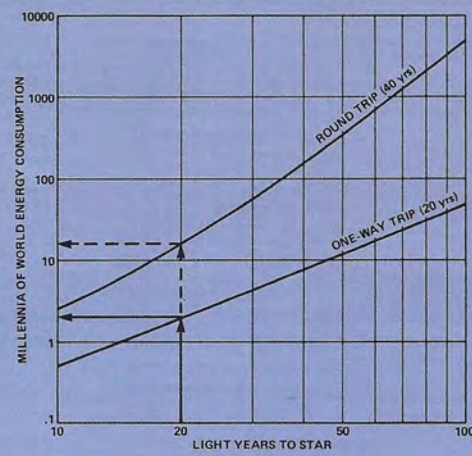
To get a two-ton car up to 60 miles per hour requires one-fifth of a kilowatt hour — enough to light a 100-watt lamp for two hours. This is already a significant amount of energy — about equal to that needed to propel the car for half a mile — and is dissipated as heat in the brakes when we stop. This wasted energy is what reduces gas mileage in stop-and-go traffic. But now make the mass 3,600 tons (the smallest interstellar craft we can imagine) and make the speed 134 million miles per hour (one-fifth the speed of light) and the stored energy becomes:

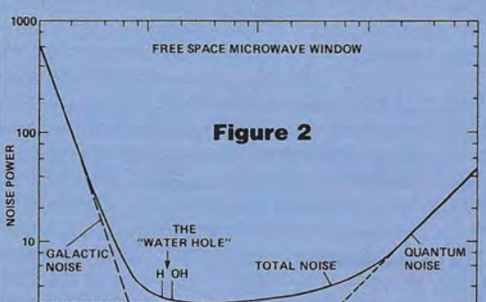
$$\frac{3,600}{2} \times \left(\frac{134,000,000}{60} \right)^2 = 9 \text{ quadrillion}$$

times as great, or 1.8 quadrillion kilowatt hours. This is the amount of energy the world consumes in 20 years.

But our vehicle must not only start, it must stop at our destination, start back and stop when it arrives back at Earth. So far as the rocketship is concerned, stops are the same as starts, and the total energy is therefore four times as great. In addition, each start must accelerate the fuel needed for later starts. This adds another factor of four, bringing our total to 320 years of world energy consumption to visit a star four light years away, and return in a human working lifetime.

The curves of Figure 1 take into account relativistic corrections to the simple theory above. -- B.M.O.





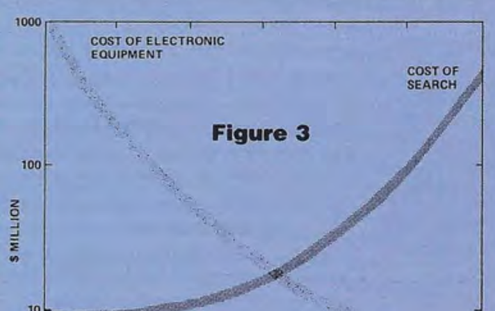


***FIGURE 2:** Between the emission lines of hydrogen and the hydroxyl radical lies the "water hole," the quiet window where interstellar communication may be taking place.*

***FIGURE 3:** The cost of SETI hardware has dropped dramatically. Now the costs of conducting the search are rising because of increasing interference. These are the years for the search.*

***BACKGROUND:** The nearby galaxy of Andromeda is often called the "sister" to our Milky Way. From intergalactic space, our galaxy would appear like this — a possible home for many diverse civilizations.*

Photo: National Optical Astronomy Observatories part that should be searched first. The terrestrial microwave window extends from about 1,000 to 10,000 megahertz.

The Water Hole

By pursuing the principle of reducing the energy required for contact, we have abandoned travel in favor of communication, chosen a particular form of radiation, and identified a best region of the spectrum. Of course we will use the largest antennas we can. Yet we still have to search thousands of megahertz of spectrum looking for artifact signals that may be only a hertz or less in intrinsic bandwidth. Is there anything further we can do to narrow the region of the spectrum we must search?

In 1959, Giuseppe Cocconi and Philip Morrison, having followed much the same path of reasoning we have outlined, suggested we search near the frequency emitted by neutral hydrogen in space. At the time this was the only known spectral feature in the microwave window. The aliens, knowing our astronomers would be actively observing at this frequency, would naturally choose it for their transmissions. Since then the hydroxyl lines and dozens of other spectral lines have been found, so the hydrogen line has lost its uniqueness.

Cyclops, the 1971 NASA/Ames Summer Study Faculty Fellowship program, studied the design of a SETI system. During this study, Charles Seeger pointed out that the hydrogen and hydroxyl lines bounded a band in which there were no other known lines. Since spectral lines themselves are noisy, it would be better to search in this quiet band between the two lines than to search the lines themselves. The Cyclops team found this suggestion appealing:

"Nature has provided us with a rather narrow band, in this best part of the spectrum, that seems especially marked for interstellar contact. It lies between the spectral lines of hydrogen (1420 megahertz) and the hydroxyl radical (1662 megahertz). Standing like the Om and the Um on either side of a gate, these two emissions of the disassociation products of water beckon all water-based life to search for its kind at the age-old meeting place of all species: the water hole."

This is SETI's second window, or perhaps it is only a brighter pane in the larger microwave window. In either case, it appears that a little poetry applied to physical phenomena may reduce our search space by 30 times. Of course, we mustn't ignore the spectrum outside the water hole; they may not have our sense of the poetic! But at least our search can start there.

The Time Window

SETI has a third window, one that few people appreciate. This is a window in time that includes the next dozen years. It reflects a combination of two factors: our recently acquired ability to compress enormous amounts of signal processing equipment into a reasonable size and a reasonable cost on the one hand, and the threatened loss of the microwave window to Earth-based services on the other. If we are to do SETI cheaply, we must begin now.

Until radio astronomy flowered in the wake of World War II, and until high-powered transmitters had been developed for radar and other microwave uses, we did not have the capability to signal across the vast distances to the stars. Think of it. For all of human history no signal we could generate, no flash we could produce, could be detected at even the nearest stars. Then in the middle of this century the war-born microwave technology rolled back the curtains to reveal our window on interstellar communication. For the first time in all human history we could realistically dream of contacting life around other stars. Had we stumbled, with fantastic luck, across an extraterrestrial signal as early as the late 1950s or early 1960s, we could have begun communication then and SETI would not still be seeking adequate support.

But it soon became apparent that we were going to have to search some 10 billion channels in the microwave window for steady signals or pulses that might arrive from millions of distinguishable directions, signals that might drift slowly in frequency because of accelerations along the line of sight either of the source or of Earth — acceleration that is the natural result of planetary rotation. Such tiny signals, such an enormous haystack! The search is beyond human capabilities; only a special purpose computer is up to the task. Only a computer can search untiringly after months or years of negative results. So SETI had to wait out the micro-electronics revolution, had to wait until we could put whole computers on a single chip and put thousands of such chips on duty in our search army.

In 1960 an adequate signal processing system would have cost well over $2 billion. In Cyclops' day the cheapest solution was analog processing using photographic film at a capital cost estimated at $200 million. Today the entire hardware cost is estimated at $15 to $20 million. Well, this is great! All we have to do is delay SETI until the equipment cost stabilizes, some 10 or 20 years from now. The problem with that solution is that our precious microwave window won't be there anymore!

While we've been learning how to search it, the window is becoming occupied by other services that emit a wide variety of signals. TV, communications and reconnaissance satellites, radar for aircraft protection, military radar, over-the-horizon links, weather balloons — these are only a few of the horde of services that are eating away at the microwave window. The Global Positioning and Geostar navigational satellites are right smack in the middle of the water hole. The radio frequency interference (RFI) generated by these services is in general thousands to millions of times stronger than the ETI signals we are looking for. The latter have crossed tens of trillions of miles, the former only thousands.

Many portions of the window are already lost to us. Others can be searched only at certain times or from certain locations. The growing radio interference problem is decreasing the completeness and extending the time required for the search. Not only do portions of the spectrum have to be searched repeatedly before they are found free of interference, some will never be free. Moreover, an elaborate series of tests must be applied to all candidate signals to make sure they are not local interference.

Thus while the cost of the equipment has been dropping, and will continue to drop, the cost of doing the search itself will increase. (See Figure 3.) Soon the equipment cost will be negligible compared with the cost of the search. Already the equipment cost is only about one-quarter to one-third of the total budget of the proposed NASA SETI program. Incidentally, the proposed program would increase NASA's annual budget at most in the third decimal place. From now on, without doubt, the total cost of doing SETI will increase.

The proposed NASA SETI program will use existing radio astronomy antennas. The program essentially proposes to test the hypothesis that these are up to the task. If the program succeeds we will have succeeded the cheap way. But we will only succeed if other civilizations are radiating signals that, by our standards, are very high powered or else are beaming signals in our direction. Thus, failure to detect a signal would not mean that extraterrestrial intelligence does not exist, it would merely prove that we need greater antenna collecting area to detect less powerful signals — the kind we ourselves radiate.

A large collecting area is easy to achieve with an expandable phased array of antennas. If we were to build antennas at a rate of, say, 10 per year, the annual cost would be less than one shuttle launch. The search could go on as the array was built and building could stop as soon as the first signal was detected. Thus, the array would never be larger than necessary.

It would be very sensible to begin constructing such a dedicated SETI facility now. In 10 years we would have 100 times our present sensitivity. This would greatly increase our chance of success before the microwave window is closed by the interfering signals of Earthly origin. Can we afford to risk our chances of contact by acting too late?

Bernard Oliver is Chief of the NASA SETI Program, a joint effort between the NASA Ames Research Center and the Jet Propulsion Laboratory. He was Vice President for Research and Development at Hewlett Packard Corporation for over 25 years, retiring in 1983. In 1986, Dr. Oliver received the National Medal of Science.

Terraforming:

Making an Earth of Mars

by Christopher P. McKay

As we understand more about life on Earth and about the chemical and biological potential of other planets and objects in our solar system, it's not too much of a leap to consider creating a habitable environment on another planet. Scientists have begun to ponder the possibility of transforming Mars, the most Earthlike of the nearby planets. Various scenarios have been proposed, and in many ways these scenarios duplicate the processes that transformed the early Earth. Here we look at some of the possibilities.

Is it possible that someday humans will walk beside a rushing river cascading down a lush green mountainside underneath a dark blue sky — on Mars? Such is the vision behind planetary ecosynthesis — terraforming, or turning another planet into an Earth. The objective of terraforming is to alter the planet to improve the chances for indigenous life — or if there is no native life, to allow the survival of Earthly life-forms, including humans.

Of all the planets and natural satellites in our solar system, Mars is the only possible target for terraforming in the foreseeable future. Mars is a small, cold, dry planet with a thin atmosphere, but it is still the most hospitable planet, besides Earth, in our solar system. Although the *Viking* results imply that there is now no life on Mars, all the elements necessary to support life have been found on the planet in some accessible form. It is the most likely candidate for human exploration and settlement.

Many of Mars' physical features seem custom-made for terraforming. Its rotation rate and axial tilt, which we can't alter and which would control the daily and seasonal cycles of life, are within five percent of the values for Earth. Even Mars' smallness is an advantage in terraforming, since in the lower gravity, maintaining a breathable pressure requires about three times the atmospheric mass as it does on Earth. This thicker atmosphere would be warmer, partly compensating for the planet's greater distance from the Sun.

So Mars seems ripe for terraforming. But before we consider how to transform the planet, we must find out if there are enough of the key materials needed to build a biosphere to support life. Since it is beyond any foreseeable technology to import the needed materials, our first step is to determine the amount, distribution and chemical state of three important compounds: water, carbon dioxide and nitrogen.

These compounds primarily form Earth's biosphere and are the components of life as we know it. Water is the essential medium in which the biochemical processes of life occur. Carbon dioxide is the source of oxygen via photosynthesis and is the primary source of carbon, which forms the backbones of biomolecules. Nitrogen is used in the construction of proteins and other essential biomolecules. Life, from microorganisms to blue whales, needs these molecules. Terraforming Mars means rearranging these compounds into the desired state.

Unfortunately, we don't know the inventory of these volatile compounds on Mars. We know that there's very little in the present-day atmosphere. However, in the past, conditions were much different. Large amounts of liquid water once flowed over the planet. This implies that ancient Mars had a thicker, probably carbon-dioxide-rich atmosphere. If water and carbon dioxide were abundant, then theories of planetary formation suggest that nitrogen should also have been plentiful. Mars may once have had an Earth-like environment, and terraforming could be viewed as a restoration project.

This wet and warm early environment didn't last long, and the volatiles are no longer abundant. But they didn't leave the planet. Current theories suggest that most of the water is tied up in the soil as permafrost; there is also water in the permanent polar icecaps. If the planet were warmed, the water in these reservoirs would be released. We think the carbon dioxide reacted with water to form carbonates, a type of sedimentary rock. It would be difficult to liberate the carbon dioxide from the carbonate rocks. But large amounts of carbon dioxide might be held in the soil as absorbed gases — much like a sponge holds water. This carbon dioxide would be much easier to get at.

Nitrogen is the essential element about which we know the least. Mars may have lost most, if not all, of its nitrogen to space, or the initial nitrogen may be buried as nitrates along with the carbonates. The *Mars Observer* mission should help us understand the water and carbon dioxide, but it can't detect nitrogen in any form. We may have to wait for a rover/sample return mission that can drill into the martian surface.

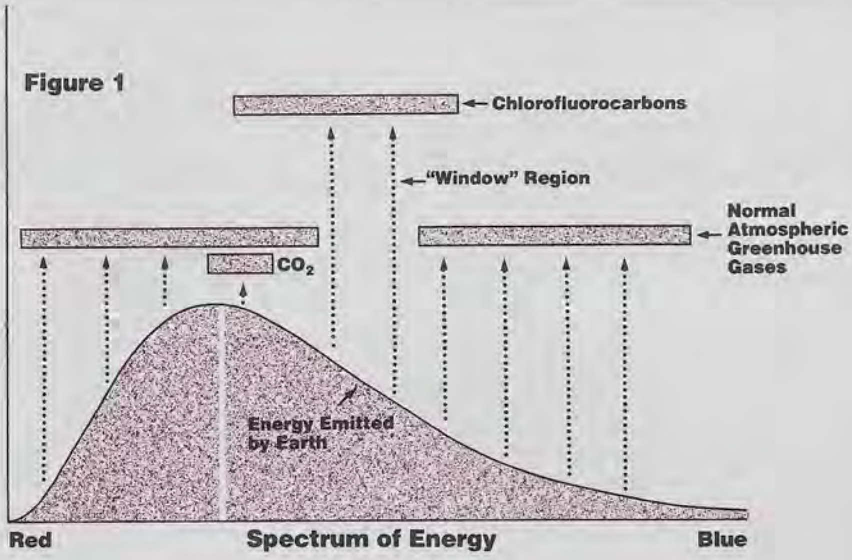
If there is not enough water, carbon dioxide or nitrogen on Mars, then terraforming becomes a remote dream. If there are enough of these volatile elements, then we can consider what the planet would be like if they were brought back to the surface. Let's consider two cases.

In Case I the atmosphere is composed of carbon dioxide and nitrogen. For this composition, climate calculations show that, if we could bring the atmospheric pressure to about twice that on Earth, then the average temperature would be above freezing. With the small amount of oxygen produced naturally by sunlight dissociating the carbon dioxide, this would be an ideal environment for Earthly plants. We could cover the martian surface with a rich green flora, slowly consuming the carbon dioxide and making oxygen.

Humans and other animals with vascular systems, however, could not survive on this world. Carbon dioxide is lethal in high concentrations. In such an environment humans could move about only with the aid of breathing apparatus, something like scuba equipment.

Let's now consider Case II. Here the atmosphere would have exactly the same level of oxygen as Earth's atmosphere. The oxygen would come from the carbon dioxide. The rest of the atmosphere would be nitrogen and carbon dioxide, which would be kept below toxic levels. The total pressure would be twice Earth's, but this atmosphere would be perfectly suited for breathing by humans and other animals. Unfortunately, climate models indicate that it would be much too cold, nearly 40 degrees Celsius below zero.

I have explored an idea first suggested by James Lovelock for resolving this dilemma. He suggested that a trace amount of specially prepared gases containing fluorine, chlorine or bromine could augment the greenhouse effect on Mars. To understand how these gases could warm a planet, we must consider how energy leaks from the Earth (or a terraformed Mars) to space. Figure 1 shows the energy coming out from Earth and how the greenhouse gases, water and carbon dioxide, block the energy's escape. A lot of Earth's energy is lost through the region of the spectrum where none of these gases absorb, known as the window region. Earth would be a much warmer place if we introduced molecules into our atmosphere that absorb in that region. (Actually, many scientists have speculated that the carbon dioxide released into the atmosphere by the burning of fossil fuels might already be warming Earth.)



Greenhouse gases, such as water (H_2O) and carbon dioxide (CO_2) warmed the planets Venus and Earth and may someday help to warm Mars. This graph shows how the energy emitted by a planet can be trapped by the primary greenhouse gases. If future terraformers wanted to warm Mars "quickly," they might plug the spectral window where energy might escape by introducing chlorofluorocarbons into the martian atmosphere.
Chart: S.A. Smith

We can apply this technique to Mars. I have chosen a set of four compounds that could make a suitable "cocktail" of greenhouse gases. As seen in Figure 1, the combination of C_2F_6, CF_3CL, CF_2Cl_2 and $CBrF_3$ (chlorofluorocarbons, like those suspected of depleting the ozone (O_3) layer on Earth) does a good job of plugging the window region. They also absorb elsewhere, adding to the effect. In Earth's atmosphere, these molecules are long-lived, lasting about 500, 400, 110 and 100 years, respectively. On Mars, the elements that make up these compounds are probably available.

To estimate the amount of these gases we'd need to warm Mars, I've adapted the results of calculations for Earth's atmosphere. V. Ramanathan and coworkers have determined that these four gases, if each were at the one part per billion level in Earth's atmosphere, would increase the temperature by 0.65 degrees Celsius. To make the breathable martian atmosphere warmer, we'd need a much higher concentration. To warm Mars by 40 degrees Celsius, we'd need between 60 and 1,000 parts per billion. This works out to a mass of between 9 million and 1.4 billion tons. If these gases must be replenished once every 300 years, then each year we must supply between 30,000 and 4 million tons. While it may be impossible to ship that much material to Mars from Earth, producing this much gas on Mars is probably not beyond the ability of a moderately sized, self-sufficient civilization. For perspective, note that the city of San Francisco produces almost a million tons of garbage each year with no concerted effort.

With a simple energy analysis, I have estimated the time it would take to make Mars habitable. The Sun is the only energy source capable of providing the energy for terraforming Mars. (Note that the solar energy in sunlight beaming down onto Mars' surface every afternoon exceeds the US/USSR nuclear arsenal of about 10,000 megatons.)

The process of warming Mars and altering its atmosphere naturally divides into two steps, corresponding to Cases I and II. In the first step, the planet would be heated by a warm, thick carbon dioxide atmosphere. This would be done by exploiting the properties of a carbon dioxide atmosphere. If the surface temperature were increased, say by warming the poles with giant mirrors, by spreading black soot over the polar caps or by introducing greenhouse gases, then the atmospheric carbon dioxide would also increase. This would warm the atmosphere still further, releasing still more carbon dioxide, making it warmer still, and so on. The energy to complete this step would be about one million joules per square centimeter. Assuming that this process could be triggered and could use one percent of the solar energy falling on Mars, it would take about 200 years.

The second step would be to convert the atmospheric carbon dioxide and soil nitrates to the desired oxygen and nitrogen mixture. The only known mechanism that can change a planetary atmosphere is life. (We have an example of the process close at hand: Earth. Between 4 and 2 billion years ago, photosynthetic cyanobacteria changed Earth's original carbon dioxide atmosphere into what we breathe today.) The energy needed is about 10 times more than that required to warm the planet. Furthermore, biological systems are not very efficient converters of energy to biomass, and so step II could take up to 100,000 years. However, a biological system could function autonomously for the entire time.

It's clear that life will play a major role in any terraforming of Mars, and that terraforming will be a gradual, evolutionary process — duplicating in many ways the early evolution of life on Earth. Microorganisms, the hardiest of Earthly life-forms and biochemically the most versatile, will do most of the biological processing. At a very early stage, we might release on Mars specially engineered microorganisms that could adapt to the extreme cold. As the planet warms and the atmosphere thickens, hardy species of grasses and shrubs might be introduced, followed by flowering plants, trees and food crops. After the oxygen concentration rose above the limit for respiration, invertebrates, insects (but please not mosquitos!) and the like could survive. Finally, when the oxygen approaches the desired value, reptiles, birds and mammals would complete the system.

Perhaps it is unrealistic to expect that terraforming Mars could be done by Earth's nations. While the expense may not be prohibitive, the timescale may be forbidding and the benefits intangible. Space policy makers may never make a conscious decision to terraform Mars, but the first step is already being seriously considered — the establishment of a self-sufficient Mars settlement.

If humans established themselves on Mars, self-sufficiency would be imperative to the long-term health of the settlement. Over the years a distinct group of Martians would certainly develop. To them the benefits of terraforming Mars would be quite tangible — the survival of their civilization.

Chris McKay is a Research Scientist at NASA's Ames Research Center. He is a member of the Mars Sample Return Science Steering Group, interdisciplinary scientist for exobiology on the Comet Rendezvous Asteroid Flyby (CRAF) mission, and co-investigator on its radiometer experiment. Dr. McKay is also Coordinator for The Planetary Society's Mars Institute.

The Origin of Life *(continued from page 11)*

may have been organic compounds formed either on Earth or by accretion from extraterrestrial sources.

An even more abundant source of catalysts would have been the reservoir of minerals and salts on Earth's surface. Clays and other minerals formed by the weathering of rocks are known to absorb and catalyze reactions of organic compounds today, so it is likely that they catalyzed reactions on the primitive Earth. The massive task of investigating the catalytic properties of minerals that may have abounded on the early Earth has only just begun.

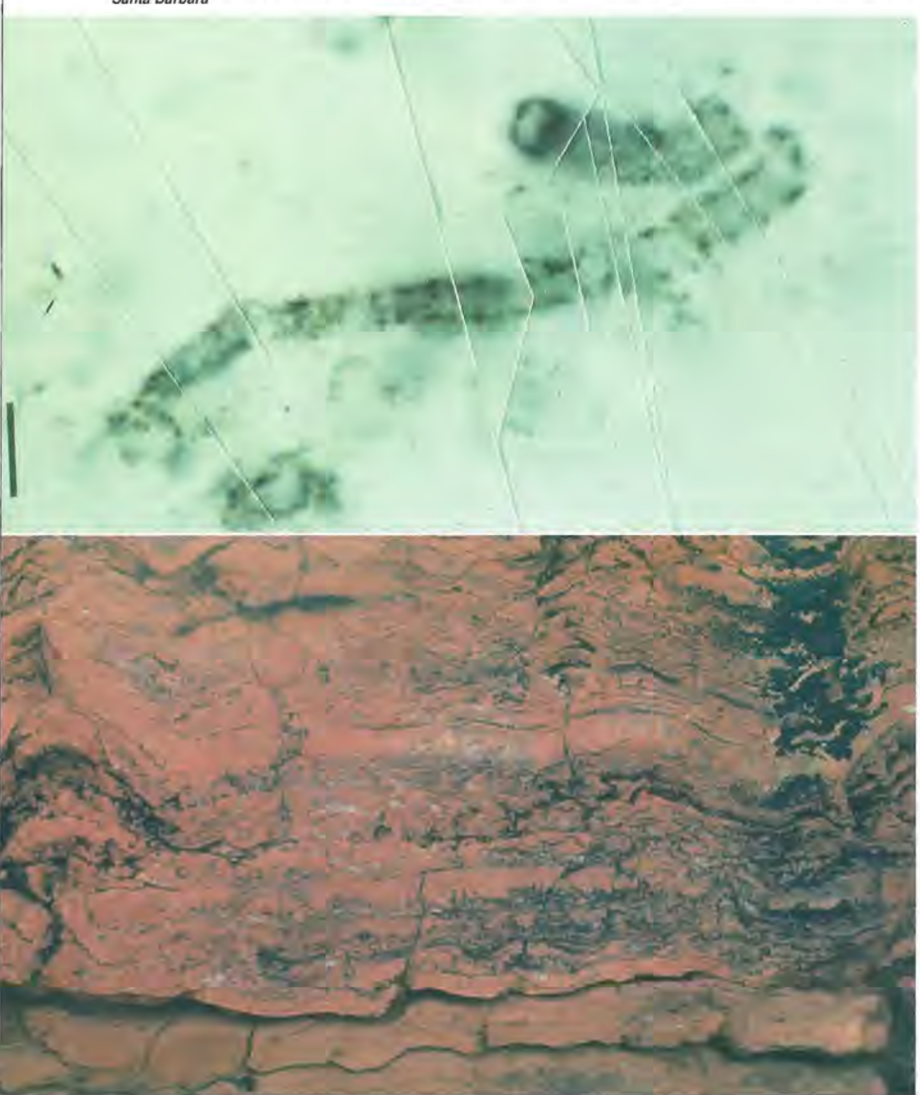
Life requires the interaction of polymers (molecules of many repeating units) and monomers (those single, free units) in a restricted environment that segregates the biological molecules from substances or environmental conditions that can prevent the cooperative interaction found in living systems. This cooperative interaction may have been inhibited on the primitive Earth by harmful chemical reactions with other compounds ("poisons") in the environment, by the dissolution of a fragile molecular complex due to the downpour of rain, or by excessive solar ultraviolet light.

One approach of nature to solving these problems may have been to bind the organic molecules of life to a mineral surface, much in the same way that moss binds to a rock. The food for this first life may have been dissolved in water that washed over the bound molecular complex. If this niche were submerged, it would have been shielded from much of the destructive solar ultraviolet light. And, since this life was bound to a mineral surface, it would not have been washed away in a downpour. But we don't know how this first life would have been protected from environmental poisons.

In an alternative scenario, the compounds constituting life may have been surrounded by membranes that shielded them from environmental hazards. This feature is very successful in protecting present-day microbial life. Only a few experimental studies have been performed to test this hypothesis, and it is not clear whether or not a membrane would spontaneously form around polymers under primitive Earth reaction conditions.

Filamentous fossils (top) of cyanobacteria (blue-green algae) are the earliest known evidence of life on Earth, dating back at least 3.5 billion years. These photosynthetic life-forms populated shallow ancient seas where they sometimes "constructed" stromatolites (bottom), stubby mounds built up, layer by layer, as generations of these bacteria grew toward the life-giving light. Cyanobacteria are probably the hardiest life-form known; although Earth is now covered by legions of competing forms, cyanobacteria still flourish.

Photos: Stanley Awramik, University of California at Santa Barbara



RNA — The First Biopolymer?

A fundamental concern in the field of life's origins is what molecules were essential for the first life. DNA (deoxyribonucleic acid) and protein are the central biological polymers in contemporary life. DNA stores the genetic information in chromosomes so that similar characteristics are carried from one generation to the next. The information in DNA is expressed in proteins. Protein performs the structural and catalytic functions that are characteristic of a particular species. Thus, in living systems, DNA is the director and protein is the doer.

DNA and protein have very different structures, as shown in Figure 2 (see page 11). DNA has a very conservative double-stranded structure that is ideal for information storage. All DNA looks pretty much the same. But because each protein must perform a different function, each one has a different structure. The twists and turns of the protein shown in Figure 2 illustrate the variety of structural units in protein, in contrast to the monotonous double helical structure of DNA.

RNA (ribonucleic acid) provides the link between DNA and protein in contemporary life. RNA carries the genetic information encoded in DNA to the molecular machinery in the cell that synthesizes protein. The main role of RNA is that of a messenger which helps in the synthesis of protein.

For many years scientists studying the origins of life argued over which structural type was more important in the first living systems, protein or DNA. The problem with this chicken-or-egg argument is that neither structural type alone can fulfill all the requirements of a living system.

Recently some of these scientists have changed their thinking on life's origins. This new direction was inspired by the recent observation that RNA has catalytic properties similar to those of protein. This finding, coupled with earlier studies showing that genetic information could be stored in RNA, indicates that RNA could carry out the functions of both DNA and protein. The similarity of RNA to DNA is evident in its structure (Figure 2). RNA is formed from building blocks almost identical to those of DNA, but its three-dimensional structure resembles that of protein. And, like the proteins, each RNA has a different three-dimensional structure.

These and other observations suggest that RNA may have been the first biological polymer. Life eventually switched over from RNA to DNA and protein because these molecular specialists are better able to perform the tasks of information storage and catalysis. This important conclusion not only removes the problem of which came first, protein or DNA, but it also focuses attention on the prebiotic synthesis of RNA. Several research groups are now investigating whether it could have been likely for RNA or RNA-related structures to have formed spontaneously on the early Earth.

We've made remarkable progress in our understanding of the origins of life since Miller's pioneering experiments some 35 years ago. We're still a long way from understanding the exact processes that led to the first biological polymers, but we've bettered our understanding of the pathways for the synthesis of the precursors to these polymers. Using both laboratory studies and spacecraft probes, we will rapidly advance this fascinating field of research.

James P. Ferris is Professor of Chemistry at the Rensselaer Polytechnic Institute in Troy, New York. He is Editor of the journal Origins of Life, *and was Chairman of the 1987 Gordon Conference on the Origin of Life.*

World Watch

by Louis D. Friedman

MOSCOW: On October 4, 1987, the 30th anniversary of *Sputnik*, a remarkable international space forum was held in Moscow. More than 350 American, Western European and Japanese participants joined approximately 500 Soviets and Eastern Europeans in the forum. Planetary Society President Carl Sagan and Director Thomas Paine were among a dozen leaders addressing the plenary sessions.

The sessions focused on international cooperation in space exploration, with principal sessions on space science, economics, international activities, piloted flight and Earth applications. In space science, participants reported on the *Kvant* mission's observations of the recent supernova in the Large Magellanic Cloud.

A tour of the Cosmonaut Training Center in Star City brought together the largest group of people ever assembled who have flown in space. Forty-one astronauts and cosmonauts took part in the exciting event. The US participants were Kathy Sullivan, Owen Garriott, James van Hoften, John Fabian, Stuart Roosa, Richard Gordon and Charles Walker. Mexico's Rudolfo Meri, who flew on a US mission, also joined in. The impressive Soviet group included such notables as General Vladimir Shatalov, Commander of the Training Center, General Alexei Leonov of the *Apollo-Soyuz* mission, and Valentina Tereshkova, the first woman in space. Society Executive Director Louis Friedman asked a question that launched the assembled space fliers into an interesting debate on the merits of artificial gravity for human flight to Mars versus traveling weightless. The verdict? Most voted that weightlessness was the way to go. Then, in response to Owen Garriott's request, the audience (mostly space scientists and engineers) voted — just the opposite!

Human flight to Mars was the principal topic of discussion for many of the forum's participants. As Tom Paine put it, the world is waiting to see the United States and Soviet Union get together on this.

The Planetary Society played a major role in helping American participants with travel arrangements and communications. In the plenary session both Sam Keller, leader of the NASA delegation, and Roald Sagdeev, chairman of the forum, cited and complimented the important role of the Society. Two principal groups whom we helped were American ex-astronauts and a delegation of space artists, who held an exhibition in connection with the forum. The art exhibition featured works by American artists Jon Lomberg, Ron Miller, Pamela Lee, Don Davis, Michael Carroll and Kim Poor, with the participation of many Soviet artists. The successful show generated plans for future international exhibitions, which the Society will help sponsor. One big Society event will be Planetfest '89, to be held during *Voyager*'s Neptune encounter in August, 1989.

At the closing session, the official US delegation leader, Dr. Thomas Rona of the White House Office of Science and Technology Policy, announced a follow-up conference in 1988 on the impact of space science on humanity to be hosted by the United States.

WASHINGTON: As we went to press, the US planetary exploration program was getting a lift from various congressional supporters, including the House Science and Technology and Senate Appropriations Committees. Money was added to the Reagan administration's budget request for space science missions. In particular, the *Mars Observer* received a much-needed boost. Although the possibility of a 1990 launch was irrevocably lost when NASA ordered all work stopped on an expendable launch vehicle (ELV), the extra money will enable some important mission improvements, including the possibility of an ELV launch in 1992. Although the House Committee wants that option, NASA is still fighting it. NASA has, however, argued in favor of additional spacecraft procurements as back-up for launch failures and for possible future use on a Lunar Polar Observer.

NASA also favorably reviewed both the Comet Rendezvous Asteroid Flyby (CRAF) and Advanced X-Ray Astronomy Facility (AXAF) and recommended both missions to the Office of Management and Budget as new starts in fiscal year 1989. CRAF's main objective is to fly alongside and thoroughly study Comet Tempel 2 beginning in October 1996. After measuring the mass of its nucleus, the spacecraft will make a detailed map of the comet's entire surface. On its way to Tempel 2, CRAF will travel through the asteroid belt and do similar studies on a large asteroid named 46 Hestia.

MOSCOW, PARIS, BRIGHTON: The Planetary Society reported on its cooperative Mars Balloon study at the Institute for Space Research, Moscow; the Centre National d'Etudes Spatiales (CNES), Paris; and the International Astronautical Federation Congress in Brighton, England. The study was organized in cooperation with the Jet Propulsion Laboratory, the California Institute of Technology and CNES, and included personnel from these organizations, several universities, Ball Aerospace Corporation and Titan Systems Corporation. The study validated the dual thermal-helium balloon concept (see the July/August 1987 *Planetary Report*) through computer-modeling and flight testing, defined a payload container to meet mission requirements, and considered a feasible imaging approach for the balloon camera. The report was well received and now appears to be having considerable effect on Soviet, French and American planning for balloons in the exploration of Mars.

At the International Space Forum meeting the Soviets indicated that their Mars balloon mission is now scheduled for 1994. One mission description, called *Colomb* (for Columbus), states that the mission would include a 30 kilogram (66 pound) rover.

BRIGHTON: At the annual meeting of the International Astronautical Federation, the leaders of the Soviet and American planetary exploration centers reported on new plans for missions to Mars in the late 1990s. Dr. Lew Allen, Director of NASA's Jet Propulsion Laboratory and Dr. V. M. Kovtunenko, Scientific Director of Glavkosmos' Babikan Space Center, presented remarkably parallel papers about Mars sample return and rover missions.

The two directors discussed launch options, orbital rendezvous, entry into Mars orbit, sampling strategies, rover operations, Earth return and sample analysis, and options for international cooperation in space. Dr. Allen answered a Soviet question about the realism of US/USSR cooperation by saying, "It would be unrealistic not to plan on such cooperation; the question is how much and what degree of interaction will occur." He also contrasted the more balanced US program of planetary exploration with the Soviet focus on Mars.

Other papers at the Mars session covered topics ranging from the Soviets' 1988 *Phobos* mission to possible human settlements on Mars in the next century.

Louis Friedman is the Executive Director of The Planetary Society.

The Solar System in Pictures and Books

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Jon Lomberg designed The Planetary Society's logo and recently served as art director for "Death of a Star," a program in the NOVA series seen on the Public Broadcasting Service.

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