Earth has it. Mars might have it. What are the chances for life elsewhere in the solar system?

Confined to a layer barely one-thousandth of the Earth's diameter, our planet's biosphere is the home of an extraordinarily diverse range of organisms. Through long cycles of extinction and diversification, billions of species have evolved since life first appeared on Earth. But beyond the sketchy outline provided by the fossil record, many questions remain unanswered about the history of life.

What were the conditions here at the time life arose? Did life begin by seeding from elsewhere or develop from processes limited to the Earth? How did simple organic compounds organize themselves into the complex metabolic systems of living organisms?

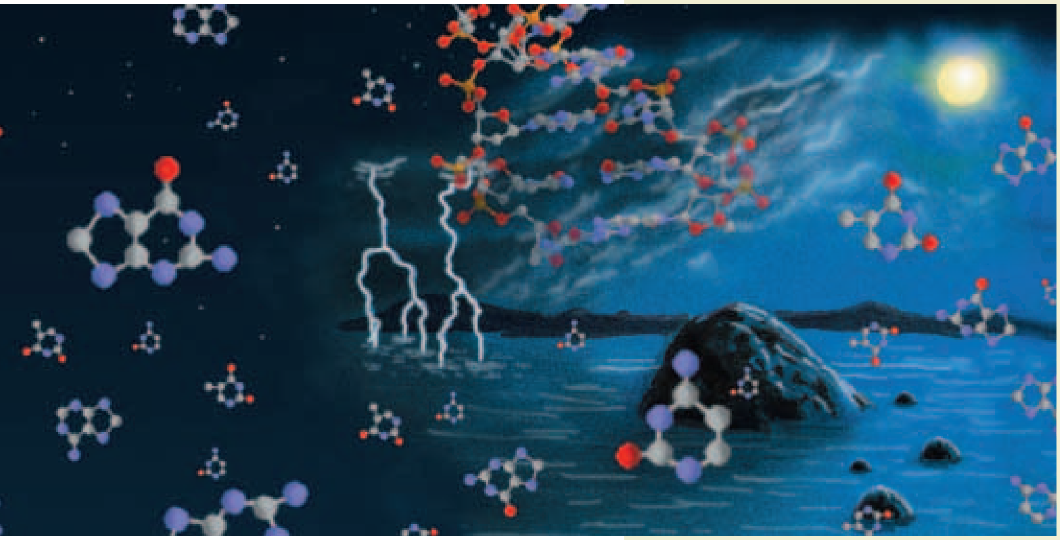


ILLUSTRATION BY JON LOMBERG

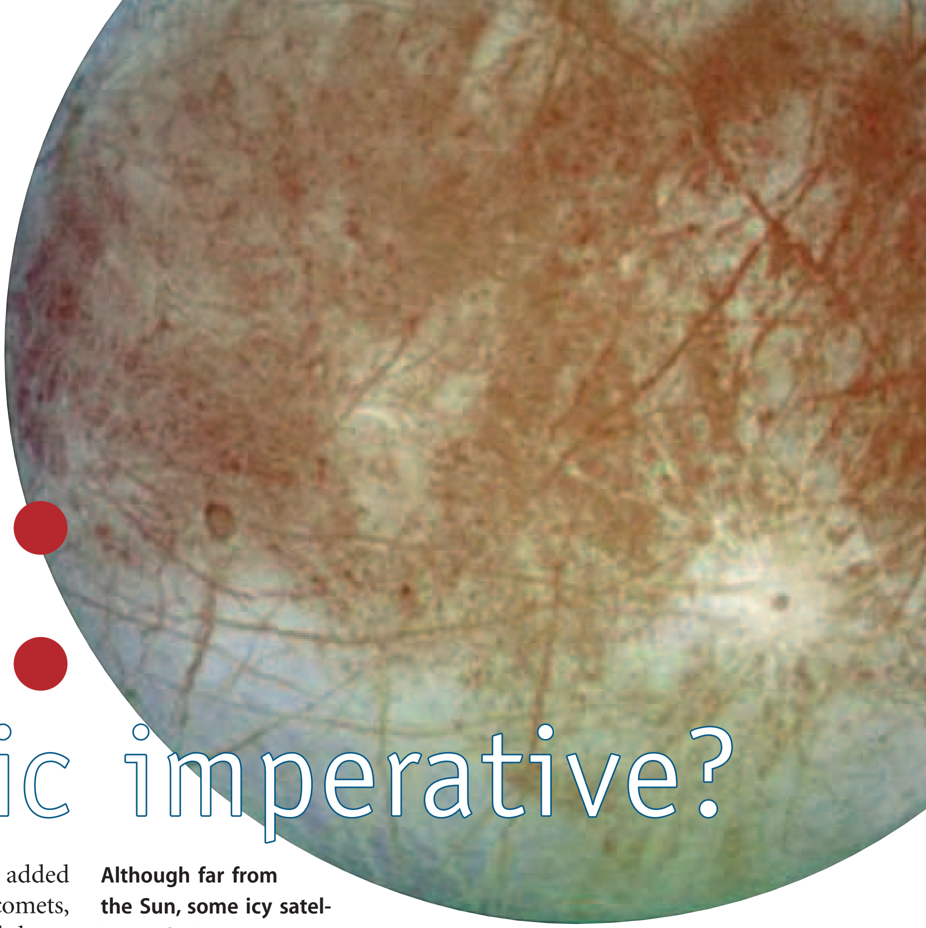
By Yvonne J. Pendleton and Jack D. Farmer

Might we realistically expect conditions suitable for the origin and evolution of life to exist on other planets in our own solar system or in planetary systems now being discovered around other stars?

In short, are we alone in the cosmos, or, as Nobel Prize–winning chemist Christian de Duve suggests, is life a "cosmic imperative," the inevitable outcome of cosmic evolution? These are key questions facing astrobiologists, a newly coined name for researchers who seek to understand the origin and distribution of life in the universe. In this article we will explore some possible answers to these questions, by highlighting new discoveries in this exciting field.

The early history of the Earth was a time of intense bombardment, as the raw materials of the solar system were swept up by

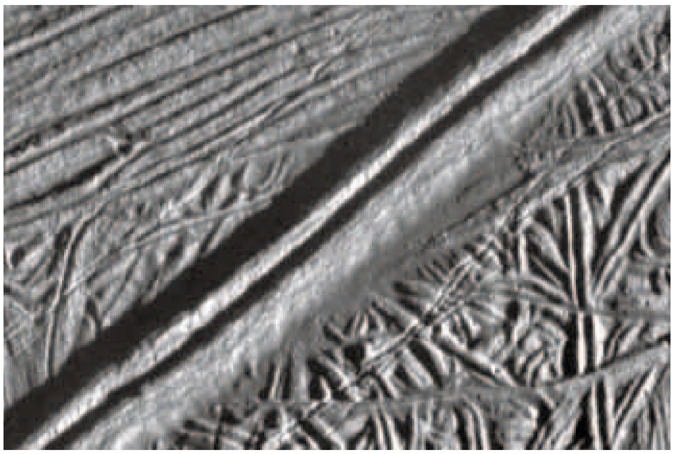
Life: a cosmic imperative?



gravity to form the protoplanets. It was during this period, about 4.5 billion years ago, that the Moon formed, probably by the catastrophic collision of a Mars-size object with the primitive Earth. The Moon, Mercury, and Mars record this cataclysmic period in their cratered surfaces, which indicate the heavy bombardment lasted until about 3.8 billion years ago. The primitive, impact-ridden surfaces of these objects have been altered little since then. Venus and Earth, however, have been nearly completely resurfaced by geologic events — Venus by extensive volcanism and Earth by plate tectonism, weathering, and erosion by water.

On Earth, the early impact history probably had both beneficial and detrimental effects on the beginnings of life. During heavy bombardment, most of the water and many of the volatile biogenic elements (carbon, nitrogen, phosphorus, and other raw materials for life) were vaporized and lost from the accreting planet. The biogenic elements necessary for the development of life were most likely added later, by moderate-size comets, just as the planet cooled down enough to retain them. In addition to water and biogenic elements, it is possible that these late icy impacts contributed simple precursor organic compounds needed to originate life (*S&T:* March 1994, page 36). Estimates indicate that the very early Earth could have accreted as much as 10,000 tons of organic matter per year. Even today, the Earth routinely collects more than 300 tons of organic material per year from space.

A stable supply of liquid water at a temperature less than 100° Celsius (the boiling point of fresh water at sea level) would have been necessary to allow complex organic molecules to form. We think these environmental conditions for the origin of life could have been present on Earth between 4.2 and 4.4 billion years ago — the time when the heavy bombardment began to decline. Certainly life was well established by 3.5 billion years ago, the age of the oldest fossils. Recent chemical evidence suggests that life may have been present as early as 3.9 billion years ago.



Although far from the Sun, some icy satellites of the outer solar system could also support life. Tidal flexing of the moons may heat their interiors to the melting point of water. These Galileo views of Europa, Jupiter's smallest Galilean satellite, suggest that subsurface water has oozed out to fill cracks with dark ice that is perhaps rich in organic material. Courtesy NASA/JPL.

An important control on the habitability of planets in the inner solar system was the energy output of the young Sun. There are good reasons to believe that during this early period the Sun was 25 to 30 percent dimmer then it is today. On the early Earth, because of an atmosphere rich in carbon dioxide, the effect of the faint young Sun was likely offset by a mild atmospheric greenhouse effect that trapped the heat given off by the planet and kept surface temperatures within what is termed the habitable zone, where liquid water is stable. An interesting consequence of

For its first several hundred million years, the newly formed Earth was bombarded by planetesimals left over from the formation of the solar system. After the pummeling subsided about 4 billion years ago, the atmosphere thickened, oceans formed, and the first life emerged. Painting © 1985 Don Dixon.

the cooler young Sun is that the habitable zone may have also extended inward to encompass neighboring Venus.

WATER ON VENUS?

The present surface of Venus is obscured by sulfuric acid clouds suspended in a thick atmosphere of carbon dioxide. Using radar, the Magellan spacecraft penetrated the clouds and returned high-resolution images of the ground. These striking views show a surface almost completely reshaped by extensive eruptions of what are considered to be some of the most unusual volcanoes in the solar system.

Although the Venusian surface is exceedingly hot and dry today, we have indirect signs that water was once present as vapor in the atmosphere and may have even been abundant enough to form oceans. A basic tool used to sleuth out the past climate history of Venus is isotopes, species of an element that have slightly different masses because they have gained or lost neutrons from the nucleus. Many natural processes select one isotope over another during chemical reactions, and this results in changes in the relative isotopic abundance. Such differences comprise fingerprints for particular chemical reactions and can be used to infer past conditions.

During the Pioneer missions in the late 1970s orbiting spacecraft measured deuterium, an isotope of hydrogen, in the upper atmosphere of Venus. The ratio of deuterium to normal hydrogen revealed that Venus is enriched in the heavy isotope more than 150 times relative to Earth. This indicates that a substantial amount of lighter hydrogen was lost to space over time. Researchers believe that as the Sun gradually increased its energy output, hydrogen was split from water molecules and dissipated into space. As volcanic activity continued, carbon dioxide was outgassed into the atmosphere, trapping the Sun's energy and creating a runaway greenhouse effect that raised the surface temperature to its present 457° C.

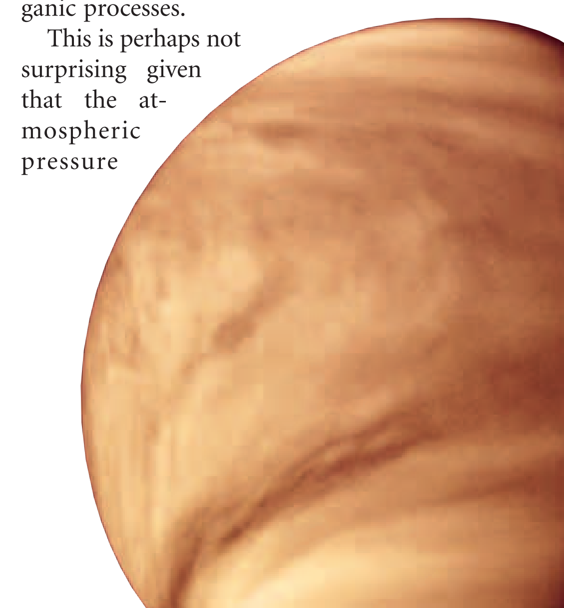
Thus it is quite possible that water was abundant on Venus early in its history and life could have initiated there as well.

However, if life developed on our sister planet it surely would have been extinguished as the Sun's energy output increased, turning the climate of Venus into a hothouse. Unfortunately, the rock record of these early events has probably been lost due to the extensive volcanism and tectonism that have since reshaped the surface. But Venus is not the only place in the inner solar system, outside of Earth, that could have harbored environments for life. Mars may have spent much of its early history within the habitable zone and may yet host liquid water beneath its frosty mantle.

EXPLORING FOR MARTIAN LIFE

In 1976 the Viking missions placed two landers on Mars's surface to search for evidence of living organisms. Their biology experiments approached the question in several ways. The most basic was simply to search for organic molecules within the red soil. This provided the most disappointing result because not a single carbon compound was detected, even though the instruments could have spotted organic molecules at a concentration of one in a billion. Other experiments sought signs of metabolic activity as water and nutrients were added to soil samples. Although some interesting results were obtained during these experiments, they have all since been explained by inorganic processes.

This is perhaps not surprising given that the atmospheric pressure

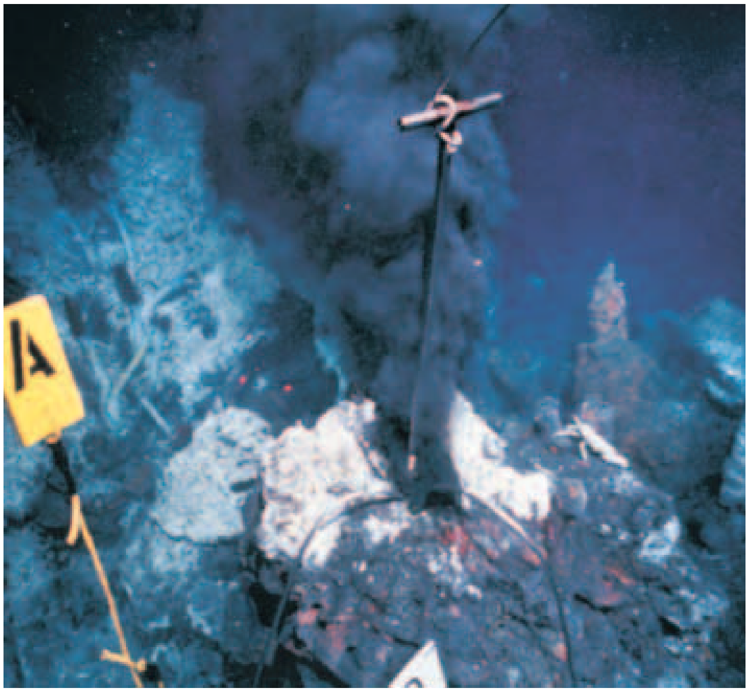


Venus wasn't always enshrouded in clouds. Early in its history Venus may have resembled primordial Earth, with oceans of water that allowed a foothold for primitive life. The buildup of greenhouse gases, however, ended any chance of further development. This view of the planet's cloudtops was taken by the Pioneer Venus Orbiter in January 1979. Courtesy NASA/Ames.

on Mars is less than 1 percent of that on Earth, far too low for liquid water to exist. In addition, there is no oxygen in the atmosphere and therefore no protective ozone layer to shield the surface from damaging ultraviolet radiation. The strong ultraviolet light received by the surface has no doubt been an important factor in producing the red, heavily oxidized surface of Mars. The resulting peroxides in the soil are highly destructive to organic compounds.

The scientific consensus that has emerged since Viking is that the surface of Mars today is likely barren of life, though habitable zones of liquid water could exist deep beneath the surface, where heat and pressure are sufficiently high. One important challenge for future exploration will be to gain access to subsurface environments by deep drilling, an activity that may require human presence.

Pictures from Viking's orbiters and their Mariner predecessors revealed that the older, heavily cratered terrains of Mars were extensively channeled by running water long ago. Thus, as the Viking landers were spelling doom for present-day surface life, orbital mapping opened up new possibilities in the search for ancient Martian life!



WOODS HOLE OCEANOGRAPHIC INSTITUTION

Kilometers below Earth's ocean surface, entire ecosystems evolved, nourished not by the energy of the Sun but by hot, mineral-rich geysers. The first of these "black smokers" was discovered in 1979, leading scientists to reconsider the circumstances under which the first life on Earth appeared. Such hydrothermal vents may have also arisen elsewhere in the solar system.

From the standpoint of habitability, the climate history of Mars was just the reverse of that of Venus. While the red planet may have started out comparatively warm, today it is in continual deep freeze. This seems counter to what we expect given the increase in solar luminosity that resulted in stronger sunlight reaching Mars. But this is where another important factor, namely atmospheric evolution, enters the picture.

On Mars an early dense atmosphere of carbon dioxide and possibly other greenhouse gases kept surface temperatures high enough for liquid water to persist aboveground even during the faint-Sun period. As the atmosphere interacted and combined with the rocks of the crust to form weathering products, atmospheric pressure declined. On Earth, similar atmospheric losses are counterbalanced by the recycling of the crust into the mantle and the release of gases into the atmosphere during volcanic eruptions. Because Mars lacks such a cycle and volcanic activity there is much less dynamic than Earth's, no comparable mechanism existed to replenish the atmosphere after it was drawn down into the Martian crust.

By about 3.0 billion years ago Mars was probably well into a surface deep freeze, with the liquid water having retreated underground, perhaps carrying with it an emerging biosphere. Could life have originated on Mars during the early clement period, when liquid water was at the surface, and then retreated with the habitable zone into subsurface oases, where it continues to evolve up to the present time? Alternatively, could life have originated underground long after Mars lost its surface water? In either case, could a record of prebiotic chemical evolution and/or fossil life have been preserved in crustal rocks?

The Martian meteorite ALH 84001, found in Antarctica in 1984, provides insight into this important question (see page 36). This meteorite contains complex hydrocarbon compounds (polycyclic aromatic hydrocarbons or PAHs) that some researchers suggest were entrapped in carbonate minerals formed as water-bearing fluids percolated through fractures in crustal rock, perhaps as early as 3.6 billion years ago. Then some 16 million years ago, ALH 84001 was ejected into space by an impact and eventually found its way to Earth, falling on the Antarctic ice sheet toward the end of the last ice age about 13,000 years ago.

We cannot yet say with certainty that the PAHs found in ALH 84001 indicate the past existence of Martian life, nor whether they are merely contaminants from Earth. These and related issues are currently being studied by a host of researchers. But if they are shown to be indigenous to the meteorite, their presence implies that complex organic compounds prevailed in the Martian crust.

Unlike Venus, there are extensive tracts of ancient crust preserved on Mars, making it a more probable candidate for a fossil record. In fact, given the ancient age (4.56 billion years) of ALH 84001, the cratered highlands are likely to contain a record of the very earliest evolution of the planet. Information about prebiotic chemistry, crucial for understanding the origin of terrestrial life, may be as important as a discovery of Martian life itself. For this reason, many scientists want to return to the red planet to explore for signatures of past life, an endeavor just renewed with launches of the Mars Global Surveyor orbiter and the Pathfinder lander.

Hydrothermal environments have been identified as key places for the early evolution of life on Earth — and possibly even for life's origin. Such conditions are likely to have been much more widespread early in the history of the solar system, when the crust was hotter and volcanism more prevalent. Interestingly, the "universal tree" that has been constructed by comparing the genetic sequences of living organisms suggests that the last common ancestor of terrestrial life was a sulfur-loving microbe that lived at high temperatures. Good analogs for these conditions today are sulfide-bearing hydrothermal vents, or "black

ily cratered highlands of Mars, areas that date back to the early clement period when liquid water was present.

Furthermore, to drill into the Martian crust to look for possible life-bearing zones of liquid water, we need high-resolution orbital surveys to locate concentrations of water vapor or hydrothermal gases in the atmosphere, where ground water may be close to the surface.

The return of samples to Earth from such sites will help further our search for prebiotic chemistry or fossils. However, planetary protection is an important concern. We must prepare safe methods for sample handling and quarantine to ensure against the release of foreign organisms into Earth's biosphere. These preparations are currently under way and involve the entire international community, but we still have a lot to accomplish before we bring Martian samples back to Earth.

IN THE OUTER SOLAR SYSTEM

The habitable-zone story is quite different for the outer solar system. There the warmth needed to provide regions of liquid water depends less on the Sun's energy and more on the frictional heating of planetary interiors by gravitational forces and the decay of radioactive elements. Liquid water may well be present inside some icy satellites of the Jovian planets, where tidal forces stretch and distort the crust, causing frictional heating above the melting point.

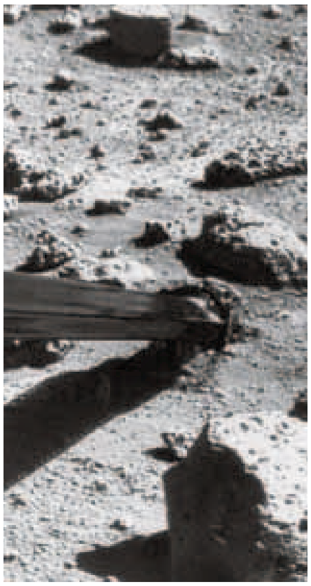
Perhaps the most visible manifestation of this tidal phenomenon is the Galilean satellite Io, which is unquestionably the most volcanically active object in our solar system. Its interior constantly erupts

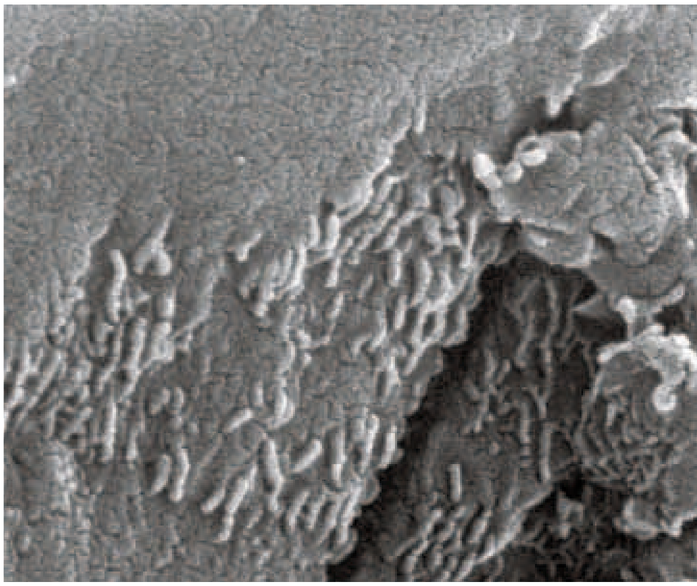
smokers," found on the ocean floor.

Such habitats support diverse microbial communities that have no need for sunlight to support photosynthesis but thrive by synthesizing organic compounds from the inorganic materials provided by springs. Could simple chemotrophic (chemical-eating) communities have also developed in association with hydrothermal systems elsewhere in the solar system?

On Mars, potential internal heat sources for maintaining hydrothermal systems were primarily the energy of impact and the decay of radioactive elements. Systems of hot circulating water were probably also widespread early in Mars's history, particularly in association with the flanks of large impact craters and volcanoes, or the floors of giant rift valleys.

To explore for ancient Martian life we first need to pinpoint the locations of deposits that have the greatest potential for preserving a fossil record. A first step is to map the mineralogy and chemistry of the surface. During the next few years, Mars-orbiting spacecraft will provide high-resolution maps to guide landers to the rocks most likely to hold organic signatures. We would like to locate any aqueous sedimentary deposits within the ancient, heav-





Above: **Channels on Mars's surface are clear signs that water once flowed there. The planet was likely much warmer then because of a denser atmosphere and a resulting greenhouse effect. If water still remains on Mars, it is locked deep underground. This 160-km-wide scene shows Reull Valles, near the Hellas basin. Courtesy U.S. Geological Survey.** ***Right:*** **Each of the Viking landers had a mechanical arm to scoop up soil samples. Onboard experiments tested for signs of life but found none. Courtesy NASA/JPL.** ***Far right:*** **Life on Mars could have existed well below the surface (and may still). Meteorite ALH 84001 is known to have originated on Mars. Analysis revealed that the rock contains complex, carbon-rich molecules and intriguing elongated structures that have been interpreted as microfossils but could be inorganically formed. Courtesy NASA/JSC.**

molten sulfur as the gravitational attraction of Jupiter and its other moons tugs and flexes it. Io can hardly be considered a clement place for life, but its ice-covered neighbors Europa and Ganymede may have more propitious conditions.

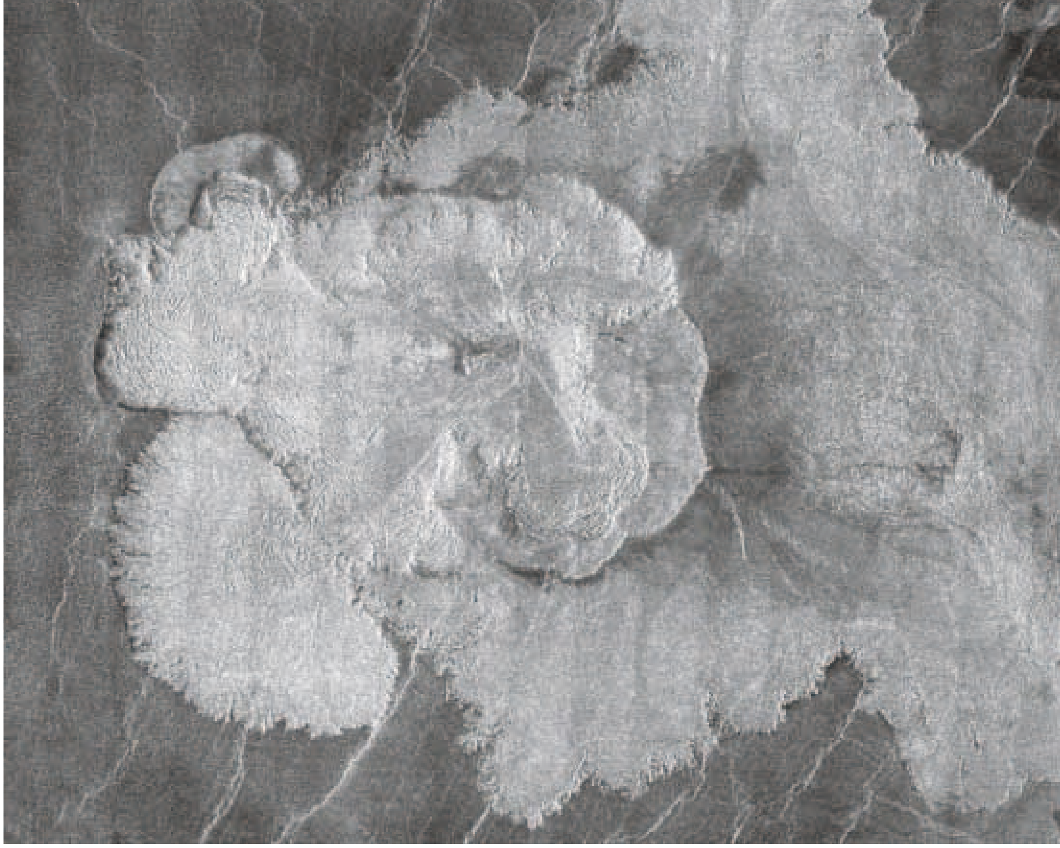
The surface of Europa is smooth and virtually free of impact craters, suggesting it is constantly renewed by active interior processes. Spectacular images recently obtained by the Galileo spacecraft reveal complex crustal fractures edged by darker material (June issue, page 14). The pictures show fractures of differing ages crisscrossing one another, large regions of the crust broken up into blocks, and places where ridges have been offset along faults or rotated. Some blocks appear to be "floating" like icebergs in terrain of smoother ice. There are even signs of younger ice flows spilling out from below, obscuring the older surface features.

While scientists debate how these features formed, one exciting proposition is that dark organic or mineral-rich ice results when liquid water from a subterranean ocean — sustained by the tide-induced heating of the interior — wells up between diverging plates of ice. There are still many unanswered questions, but this opens the intriguing possibility that an organic-rich ocean lies below.

Where there is liquid water and the right mix of organic molecules, there may be life. Some researchers even suggest that hydrothermal vents may also exist on the floor of a Europan ocean. We know that on Earth, such places teem with microbial life and are able to sustain communities of many complex higher forms. Perhaps the same will prove true for Europa! If not, we may someday find that the ice contains evidence of prebiotic chemistry or even fossilized life from long ago.

Ganymede is almost half water by mass. Similar to Europa, it is covered by an icy crust that has been cracked and mobile. Rifted mountain ranges cross the surface of Ganymede for hundreds of kilometers, testimony to a past history of tectonic activity. Could Ganymede also harbor interior zones of liquid water where chemical evolution may have led to some form of life? Similar questions can be asked of Enceladus, one of Saturn's moons, and Neptune's moon Triton, which also shows signs of an active interior.

The outer planets and their moons may also provide important natural laboratories for understanding the chemical evolution that led to life on Earth.



Even if life became established on Venus, any traces of it are extremely unlikely to exist today. Geologic processes have recycled much of the planet's surface during the past several hundred million years. In just one example, the volcano at the center of this radar image taken by the Magellan spacecraft spread lava over a 100-kilometer-wide area. Courtesy NASA/JPL.

Titan, Saturn's largest moon, is of particular interest. Its atmosphere — about 50 percent denser than the Earth's — interacts with solar-wind particles trapped by Saturn's magnetic field. This bombardment fuels chain reactions in the atmosphere that split molecules of nitrogen (N_2) and methane (CH_4), which then recombine to produce complex organic molecules. (Similar processes have been envisioned for the synthesis of molecules in the atmosphere of the primitive Earth.) The atmospheric reactions can create molecular chains heavy enough to rain out on Titan's surface.

At –179° C, the surface is certainly too cold for life to exist today. But some have speculated that billions of years from now, when our Sun expends its supply of hydrogen fuel and expands to engulf the orbits of the inner planets, the surface of Titan will become a veritable oasis. The warmer Titan will be a new habitable zone within the solar system, complete with a ready mix of complex prebiotic chemicals and water — ready to originate life anew!

The discovery of other planets, and the intriguing possibilities for habitable zones within our own solar system, open opportunities for the probing eyes of new large telescopes glimpsing first light. They also provide a sound rationale for NASA's current focus on astrobiology and the search for extraterrestrial biology. Finding life elsewhere — or for that matter, even the precursor chemistry that could lead to it — would help us understand life's origin on Earth. It is quite possible that life will be shown to be a natural consequence of planetary evolution and "a cosmic imperative" anywhere that habitable zones of liquid water are maintained for even short periods of geologic time.

As eloquently stated by Norman R. Pace (University of California, Berkeley), "The question may not be the probability of the origin of life but rather the probability that life, having arisen, survives and comes to dominate a planet." As members of the dominant species on planet Earth, reaching out to the cosmos for answers about our origin, we can only hope that our chances for survival will continue to improve as we grow to better understand, value, and take care of the unique habitable zone that nurtures the only life we have yet discovered.

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