

Searching for Life in Our Solar System

If life evolved independently on our neighboring planets or moons, then where are the most likely places to look for evidence of extraterrestrial organisms?

by Bruce M. Jakosky



Since antiquity, human beings have imagined life spread far and wide in the universe. Only recently has science caught up, as we have come to understand the nature of life on Earth and the possibility that life exists elsewhere. Recent discoveries of planets orbiting other stars and of possible fossil evidence in Martian meteorites have gained considerable public acclaim. And the scientific case for life elsewhere has grown stronger during the past decade. There is now a sense that we are verging on the discovery of life on other planets.

To search for life in our solar system, we need to start at home. Because Earth is our only example of a planet endowed with life, we can use it to understand the conditions needed

to spawn life elsewhere. As we define these conditions, though, we need to consider whether they are specific to life on Earth or general enough to apply anywhere.

Our geologic record tells us that life on Earth started shortly after life's existence became possible—only after protoplanets (small, planetlike objects) stopped bombarding our planet near the end of its formation. The last “Earth-sterilizing” giant impact probably occurred between 4.4 and 4.0 billion years ago. Fossil microscopic cells and carbon isotopic evidence suggest that life had grown widespread some 3.5 billion years ago and may have existed before 3.85 billion years ago.

Once it became safe for life to exist, no more than half a billion years—and perhaps as little as 100 million to 200 mil-



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DENDRITIC VALLEYS ON MARS

resemble river drainage systems on Earth, spanning roughly one kilometer across and several hundred meters deep. Occurring primarily on ancient, cratered terrain, the valleys may have formed from atmospheric precipitation or from underground water that flowed onto the surface. Compared with Earth's drainage systems, the Martian valleys show a lower channel density (number of channels per square kilometer), suggesting that on early Mars water was less abundant than it is on Earth.

above 400 degrees Celsius (720 degrees Fahrenheit). When that superhot water returns to the ocean, it can chemically reduce agents, facilitating the formation of organic molecules. This reducing environment also provides an energy source to help organic molecules combine into larger structures and to foster primitive metabolic reactions.

Where Did Life Originate?

The significance of hydrothermal systems in life's history appears in the "tree of life," constructed recently from genetic sequences in RNA molecules, which carry forward genetic information. This tree arises from differences in RNA sequences common to all of Earth's living organisms. Organisms evolving little since their separation from their last common ancestor have similar RNA base sequences. Those organisms closest to the "root"—or last common ancestor of all living organisms—are hyperthermophiles, which live in hot water, possibly as high as 115 degrees C. This relationship indicates either that terrestrial life "passed through" hydrothermal systems at some early time or that life's origin took place within such systems. Either way, the earliest history of life reveals an intimate connection to hydrothermal systems.

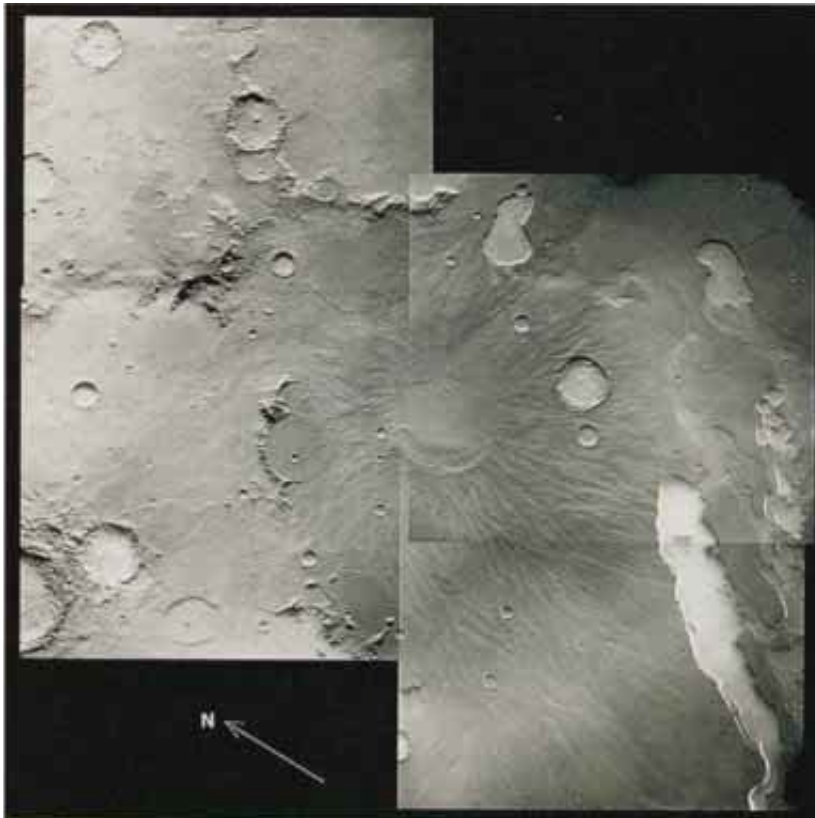
As we consider possible occurrences of life elsewhere in the solar system, we can generalize environmental conditions required for life to emerge and flourish. We assume that liquid water is necessary—a medium through which primitive organisms can gain nutrients and disperse waste. Although other liquids, such

as methane or ammonia, could serve the same function, water is likely to have been much more abundant, as well as chemically better for precipitating reactions necessary to spark biological activity.

To create the building blocks from which life can assemble itself, one needs access to biogenic elements. On Earth, these elements include carbon, hydrogen, oxygen, nitrogen, sulfur and phosphorus, among the two dozen or so others playing a pivotal role in life. Although life elsewhere might not use exactly the same elements, we would expect it to use many of them. Life on Earth utilizes carbon (over silicon, for example) because of its versatility in forming chemical bonds, rather than strictly its abundance. Carbon also exists readily as

lion years—passed before life rooted itself firmly on Earth. This short time span indicates that life's origin followed a relatively straightforward process, the natural consequence of chemical reactions in a geologically active environment. Equally important, this observation tells us that life may originate along similar lines in any place with chemical and environmental conditions akin to those of Earth.

The standard wisdom of the past 40 years holds that prebiological organic molecules formed in a so-called reducing atmosphere, with energy sources such as lightning triggering chemical reactions to combine gaseous molecules. A more recent theory offers a tantalizing alternative. As water circulates through ocean-floor volcanic systems, it heats to temperatures



CATASTROPHIC OUTFLOW CHANNEL on Mars—Dao Vallis—is on the flanks of the volcano Hadriaca Patera. Scientists believe the volcano's heat may have caused groundwater to well up, or erupt, onto Mars's surface at this location. The possible combination of volcanic energy and water makes this an intriguing place to search for life.

although we do not observe such signs today.

In addition, ancient impact craters larger than about 15 kilometers (nine miles) in diameter have degraded heavily, showing no signs of ejecta blankets, the raised rims or central peaks typically present on fresh craters. Some partly eroded craters display gullies on their walls, which look water-carved. Craters smaller than about 15 kilometers have eroded away entirely. The simplest explanation holds that surface water eroded the craters.

Although the history of Mars's atmosphere is obscure, the atmosphere may have been denser during the earliest epochs, 3.5 to 4.0 billion years ago. Correspondingly, a denser atmosphere could have yielded a strong greenhouse effect, which would have warmed the planet enough to permit liquid water to remain stable. Subsequent to 3.5 billion years ago, evidence tells us that the planet's crust did contain much water. Evidently, catastrophic floods, bursting from below the planet's

surface, carved out great flood channels. These floods occurred periodically over geologic time. Based on this evidence, liquid water should exist several kilometers underground, where geothermal heating would raise temperatures to the melting point of ice.

Mars also has had rich energy sources throughout time. Volcanism has supplied heat from the earliest epochs to the recent past, as have impact events. Additional energy to sustain life can come from the weathering of volcanic rocks. Oxidation of iron within basalt, for example, releases energy that organisms can use.

The plentiful availability of biogenic elements on Mars's surface completes life's requirements. Given the presence of water and energy, Mars may well have independently originated life. Moreover, even if life did not originate on Mars, life still could be present there. Just as high-velocity impacts have jettisoned Martian surface rocks into space—only to fall on Earth as Martian meteorites—rocks from Earth could similarly have landed on the red planet. Should they contain organisms that survive the journey and should they land in suitable Martian habitats, the bacteria could survive. Or, for all we know, life could have originated on Mars and been transplanted subsequently to Earth.

An inventory of energy available on Mars suggests that enough is present to support life. Whether photosynthesis evolved, and thereby allowed life to move into other ecological niches, remains uncertain. Certainly, data returned from the Viking spacecraft during the 1970s presented no evidence that life is widespread on Mars. Yet it is possible that some Martian life currently exists, cloistered in isolated, energy-rich and water-laden niches—perhaps in volcanically heated, subsurface hydrothermal systems or merely underground, drawing energy from chemical interactions of liquid water and rock.

carbon dioxide, available as a gas or dissolved in water. Silicon dioxide, on the other hand, exists plentifully in neither form and would be much less accessible. Given the ubiquity of carbon-containing organic molecules throughout the universe, we would expect carbon to play a role in life anywhere.

Of course, an energy source must drive chemical disequilibrium, which fosters the reactions necessary to spawn living systems. On Earth today, nearly all of life's energy comes from the sun, through photosynthesis. Yet chemical energy sources suffice—and would be more readily available for early life. These sources would include geochemical energy from hydrothermal systems near volcanoes or chemical energy from the weathering of minerals at or near a planet's surface.

Possibilities for Life on Mars

Looking beyond Earth, two planets show strong evidence for having had environmental conditions suitable to originate life at some time in their history—Mars and Europa. (For this purpose, we will consider Europa, a moon of Jupiter, to be a planetary body.)

Mars today is not very hospitable. Daily average temperatures rarely rise much above 220 kelvins, some 53 kelvins below water's freezing point. Despite this drawback, abundant evidence suggests that liquid water has existed on Mars's surface in the past and probably is present within its crust today.

Networks of dendritic valleys on the oldest Martian surfaces look like those on Earth formed by running water. The water may have come from atmospheric precipitation or "sapping," released from a crustal aquifer. Regardless of where it came from, liquid water undoubtedly played a role. The valleys' dendritic structure indicates that they formed gradually, meaning that water once may have flowed on Mars's surface,

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Recent analysis of Martian meteorites found on Earth has led many scientists to conclude that life may have once thrived on Mars—based on fossil remnants seen within the rock [see box below]. Yet this evidence does not definitively indicate biological activity; indeed, it may result from natural geochemical processes. Even if scientists determine that these rocks contain no evidence of Martian life, life on the red planet might still be possible—but in locations not yet searched. To draw a definitive conclusion, we must study those places where life (or evidence of past life) will most likely appear.

Europa

Europa, on the other hand, presents a different possible scenario for life's origin. At first glance, Europa seems an unlikely place for life. The largest of Jupiter's satellites, Europa is a little bit smaller than our moon, and its surface is covered with nearly pure ice. Yet Europa's interior may be less frigid, warmed by a combination of radioactive decay and tidal heating, which could raise the temperature above the melting point of ice at relatively shallow depths. Because the layer of surface ice stands 150 to 300 kilometers thick, a global, ice-covered ocean of liquid water may exist underneath.

Recent images of Europa's surface from the Galileo spacecraft reveal the possible presence of at least transient pockets of liquid water. Globally, the surface appears covered with long grooves or cracks. On a smaller scale, these quasilinear

features show detailed structures indicating local ice-related tectonic activity and infilling from below. On the smallest scale, blocks of ice are present. By tracing the crisscrossing grooves, the blocks clearly have moved with respect to the larger mass. They appear similar to sea ice on Earth—as if large ice blocks had broken off the main mass, floated a small distance away and then frozen in place. Unfortunately, we cannot yet determine if the ice blocks floated through liquid water or slid on relatively warm, soft ice. The dearth of impact craters on the ice indicates that fresh ice continually resurfaces Europa. It is also likely that liquid water is present at least on an intermittent basis.

If Europa has liquid water at all, then that water probably exists at the interface between the ice and underlying rocky interior. Europa's rocky center probably has had volcanic activity—perhaps at a level similar to that of Earth's moon, which rumbled with volcanism until about 3.0 billion years ago. The volcanism within its core would create an energy source for possible life, as would the weathering of minerals reacting with water. Thus, Europa has all the ingredients from which to spark life. Of course, less chemical energy is likely to exist on Europa than Mars, so we should not expect to see an abundance of life, if any. Although the Galileo space probe has detected organic molecules and frozen water on Callisto and Ganymede, two of Jupiter's four Galilean satellites, these moons lack the energy sources that life would require to take hold. Only Io, also a Galilean satellite, has volcanic heat—yet

Microbial Remnants from Mars?

In 1984, surveying the Far Western Icefield of the Allan Hills Region of Antarctica, geologist Roberta Score plucked from a plain of wind-blasted, bluish, 10,000-year-old ice an unusual greenish-gray rock. Back at the National Aeronautics and Space Administration Johnson Space Center and at Stanford University, researchers confirmed that the 1.9-kilogram (four-pound), potato-size rock—designated ALH84001—was a meteorite from Mars, one with a remarkable history.

Crystallizing 4.5 billion years ago, shortly after Mars's formation, the rock was ejected from the red planet by a powerful impact, which sent it hurtling through space for 16 million years until it landed in Antarctica 13,000 years ago. Geochemists concluded that the rock's distribution of oxygen isotopes, minerals and structural features was consistent with those of five other meteorites identified as coming from Mars.

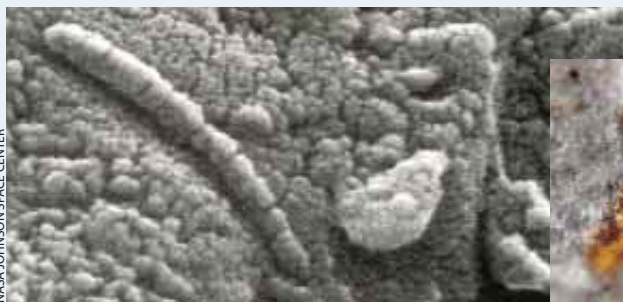
Lining the walls of fractures within the meteorite are carbonate globules, each a flattened sphere measuring 20 to 250 microns (millionths of meters). The globules appear to have formed in a carbon-dioxide-saturated fluid, possibly water, between 1.3 and 3.6 billion years ago.

Within those globules, provocative features vaguely resemble fossilized remnants of ancient Martian microbes.

Tiny iron oxide and iron sulfide grains, resembling ones produced by bacteria on Earth, appear in the globules, as do particular polycyclic aromatic hydrocarbons, often found alongside decaying microbes. Other ovoid and tubular structures resemble fossilized terrestrial bacteria themselves. Although the structures range from 30 to 700 nanometers (billionths of meters) in length, some of the most intriguing tubes measure roughly 380 nanometers long—a size nearing the low end of that for ter-

restrial bacteria, which are typically one to 10 microns long. The tubes' size and shape indicate they may be fossilized pieces of bacteria, or tinier "nanobacteria," which on Earth measure 20 to 400 nanometers long.

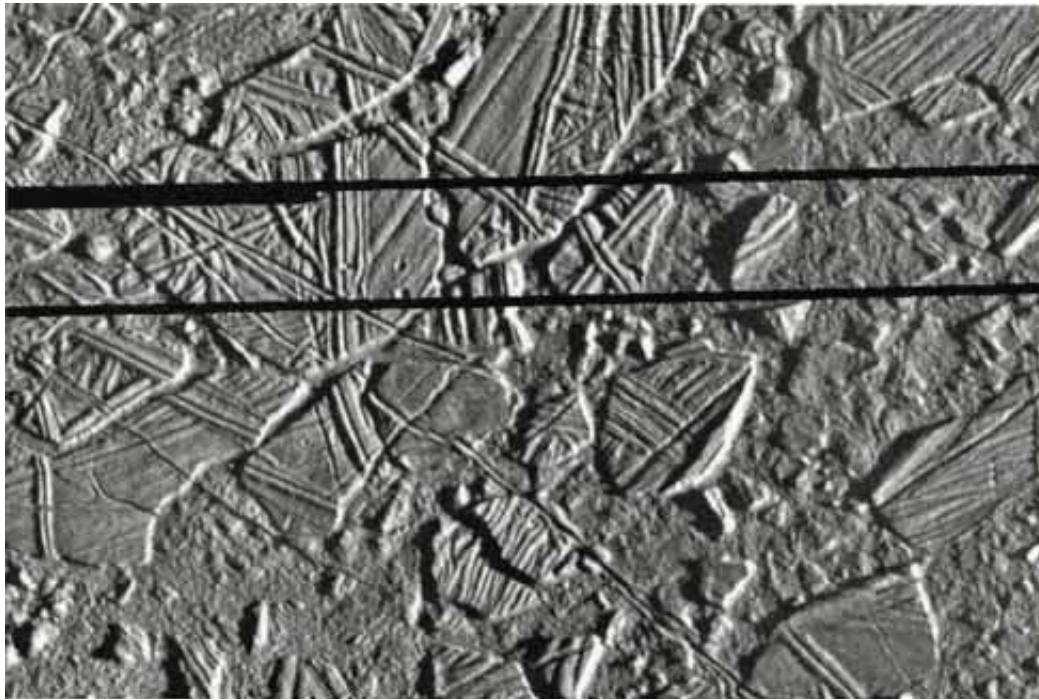
These findings collectively led NASA scientists Everett K. Gibson, David S. McKay and their colleagues to announce in August 1996 that microbes might once have flourished on the red planet. Recent chemical analyses reveal, however, that ALH84001 is heavily contaminated with amino acids from Antarctic ice, a result that weakens the case for microfossils from Mars. —Richard Lipkin



CARBONATE GLOBULE (right), about 200 microns long, seemingly formed in the Martian meteorite ALH84001. In the globule, a segmented object (left), some 380 nanometers long, vaguely resembles fossilized bacteria from Earth.

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EUROPA'S SURFACE is lined with features that suggest "ice tectonics." Blocks of ice appear to have broken up and shifted, perhaps sliding on slush or possibly even floating on liquid water. Either way, spectral analysis of reflected light indicates nearly pure water ice on Europa's surface. The horizontal black bars through the image designate data lost during interplanetary transmission.

JPL/NASA

it has no liquid water, necessary to sustain life as we know it.

Mars and Europa stand today as the only places in our solar system that we can identify as having (or having had) all ingredients necessary to spawn life. Yet they are not the only planetary bodies in our solar system relevant to exobiology. In particular, we can look at Venus and at Titan, Saturn's largest moon. Venus currently remains too hot to sustain life, with scorching surface temperatures around 750 kelvins, sustained by greenhouse warming from carbon dioxide and sulfur dioxide gases. Any liquid water has long since disappeared into space.

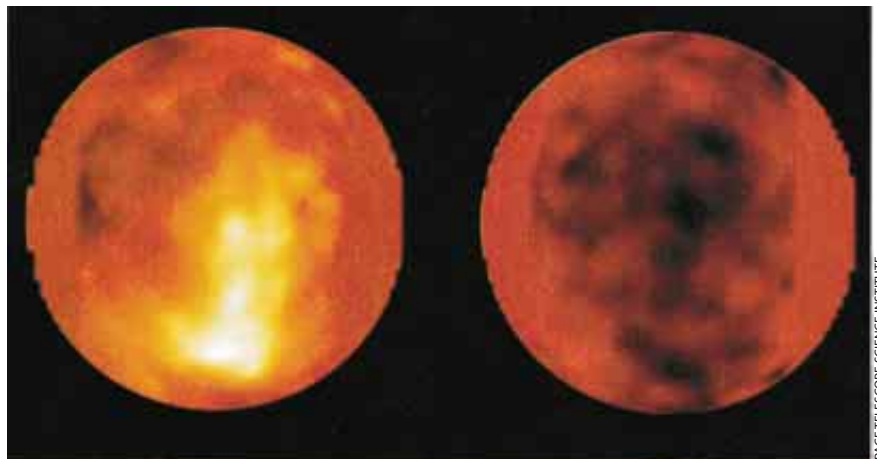
Venus and Titan

Why are Venus and Earth so different? If Earth orbited the sun at the same distance that Venus does, then Earth, too, would blister with heat—causing more water vapor to fill the atmosphere and augmenting the greenhouse effect. Positive feedback would spur this cycle, with more water, greater greenhouse warming and so on saturating the atmosphere and sending temperatures soaring. Because temperature plays such a strong role in determining the atmosphere's water content, both Earth and Venus have a temperature threshold, above which the positive feedback of

an increasing greenhouse effect takes off. This feedback loop would load Venus's atmosphere with water, which in turn would catapult its temperatures to very high values. Below this threshold, its climate would have been more like that of Earth.

Venus, though, may not always have been so inhospitable. Four billion years ago the sun emitted about 30 percent less energy than it does today. With less sunlight, the boundary between clement and runaway climates may have been inside Venus's orbit, and Venus may have had surface temperatures only 100 degrees C above Earth's current temperature. Life could survive quite readily at those temperatures—as we observe with certain bacteria and bioorganisms living near hot springs and undersea vents. As the sun became hotter, Venus would have warmed gradually until it would have undergone a catastrophic transition to a thick, hot atmosphere. It is possible that Venus originated life several billion years ago but that high temperatures and geologic activity have since obliterated all evidence of a biosphere. As the sun continues to heat up, Earth may undergo a similar catastrophic transition only a couple of billion years from now.

TITAN'S BLOTCHED SURFACE suggests that it is not uniformly coated with an ocean of methane and ethane, as scientists once thought. Instead a patchwork of lakes and solid regions may cover its surface. Enveloping the moon are thick clouds, rich in organic aerosols caused by atmospheric reactions. Scientists often compare Titan to the early Earth, before life began.



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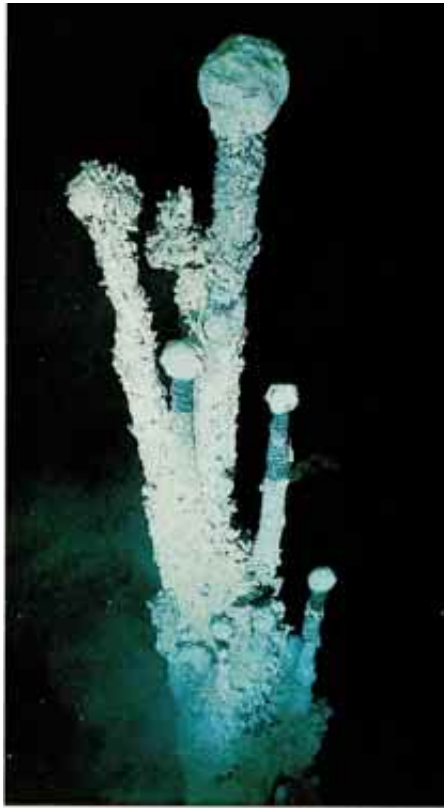
Titan intrigues us because of abundant evidence of organic chemical activity in its atmosphere, similar to what might have occurred on the early Earth if its atmosphere had potent abilities to reduce chemical agents. Titan is about as big as Mercury, with an atmosphere thicker than Earth's, consisting predominantly of nitrogen, methane and ethane. Methane must be continually resupplied from the surface or subsurface, because photochemical reactions in the atmosphere drive off hydrogen (which is lost to space) and convert the methane to longer chains of organic molecules. These longer-chain hydrocarbons are thought to provide the dense haze that obscures Titan's surface at visible wavelengths.

Surface temperatures on Titan stand around 94 kelvins, too cold to sustain either liquid water or nonphotochemical reactions that could produce biological activity—although Titan apparently had some liquid water during its early history. Impacts during its formation would have deposited enough heat (from the kinetic energy of the object) to melt frozen water locally. Deposits of liquid water might have persisted for thousands of years before freezing. Every part of Titan's surface probably has melted at least once. The degree to which biochemical reactions may have proceeded during such a short time interval is uncertain, however.

Exploratory Missions

Clearly, the key ingredients needed for life have been present in our solar system for a long time and may be present today outside of Earth. At one time or another, four planetary bodies may have contained the necessary conditions to generate life.

We can determine life's actual existence elsewhere only empirically, and the search for life has taken center stage in the National Aeronautics and Space Administration's ongoing



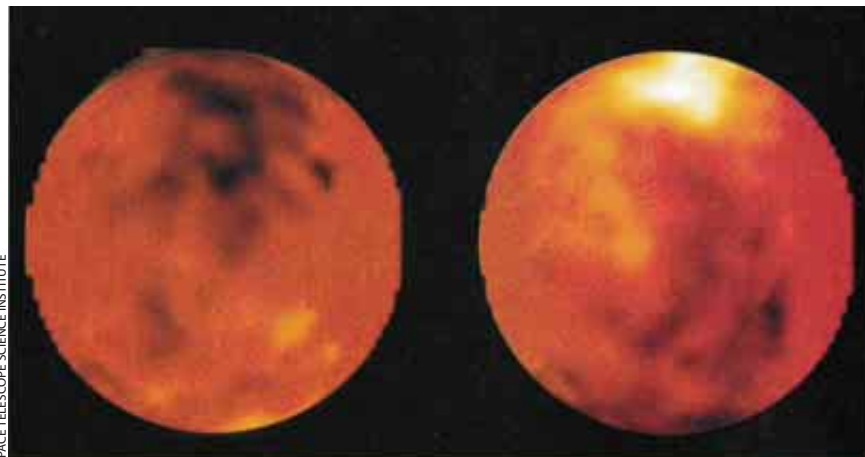
MINERAL CHIMNEY

near an undersea hydrothermal vent is located off Mexico's west coast at the East Pacific Rise of the Galápagos Rift. More than two kilometers below the sea surface along this midocean ridge, mineral-rich water, up to 757 degrees Celsius, spews from volcanically heated seafloor vents, which sprout mineral chimneys six to nine meters tall. Unusual life-forms, including tiny, white alvinellid worms and heat-tolerant bacteria, thrive in this seemingly hostile environment. Some scientists believe such hydrothermal vents fostered the origin of life on Earth.

science missions. The Mars Surveyor series of missions, scheduled to take place during the coming decade, aims to determine if Mars ever had life. This series will culminate in a mission currently scheduled for launch in 2005, to collect Martian rocks from regions of possible biological relevance and return them to Earth for detailed analysis. The Cassini spacecraft currently is en route to Saturn. There the Huygens probe will enter Titan's atmosphere, its goal to decipher Titan's composition and chemistry. A radar instrument, too, will map Titan's surface, looking both for geologic clues to its history and evidence of exposed lakes or oceans of methane and ethane.

Moreover, the Galileo orbiter of Jupiter is focusing its extended mission on studying the surface and interior of Europa. Plans are under way to launch a spacecraft mission dedicated to Europa, to discern its geologic and geochemical history and to determine if a global ocean lies underneath its icy shell.

Of course, it is possible that, as we plumb the depths of our own solar system, no evidence of life will turn up. If life assembles itself from basic building blocks as easily as we believe it does, then life should turn up elsewhere. Indeed, life's absence would lead us to question our understanding of life's origin here on Earth. Whether or not we find life, we will gain a tremendous insight into our own history and whether life is rare or widespread in our galaxy. **SA**



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