

The family of planets (in order outward from the sun, starting at the top, plus Earth's moon and minus Pluto) has been imaged for this montage by a succession of spacecraft including Mariner 10, the Viking orbiters, Voyagers 1 and 2, and Magellan. The next step in getting to know our neighbors will be to sample their atmospheres, land on them, and eventually pick up some pieces. Prime targets are Mars and the moons of Jupiter and Saturn.



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Sampling the Solar System

by Edward C. Stone

During the first four decades of the space age, missions of exploration have revolutionized our view of the solar system. The Mariners, Pioneers, Voyagers, and Magellan gave us a global view of these diverse bodies. In the last five years, exploration has begun to shift from global to close-up views as we begin to sample these other worlds—first in place, and then returning samples to Earth. The analysis of such samples is critical to our understanding of the geological, atmospheric, and climatological processes that have shaped our neighboring planets and their moons, and of what role those processes may have played in the origin of life.

The first samples returned to Earth were brought back from the moon in the late '60s and early '70s by the Apollo missions. The first missions to sample the surface of another planet were the two Viking landers that touched down on the surface of Mars in 1976 to search for both extant and extinct life. They didn't find any. Because of high levels of ultraviolet radiation and a lack of protective ozone, the surface of Mars is quite sterile, and a highly oxidizing material in the soil destroys any organic substances, including those deposited by meteorite impacts.

The Viking missions asked specific questions: Is there life? Was there life? The disappointing answer was clearly no. But, at about the same time, our view of life on Earth was beginning to change. The underlying assumption was that the sun was the source of energy for life and that photosynthesis was at the bottom of the food chain. But in 1977, one year after Viking landed on Mars, oceanographers exploring boiling water vents on the floor of the Pacific discovered that life was thriving on the chemical energy coming from inside the Earth.

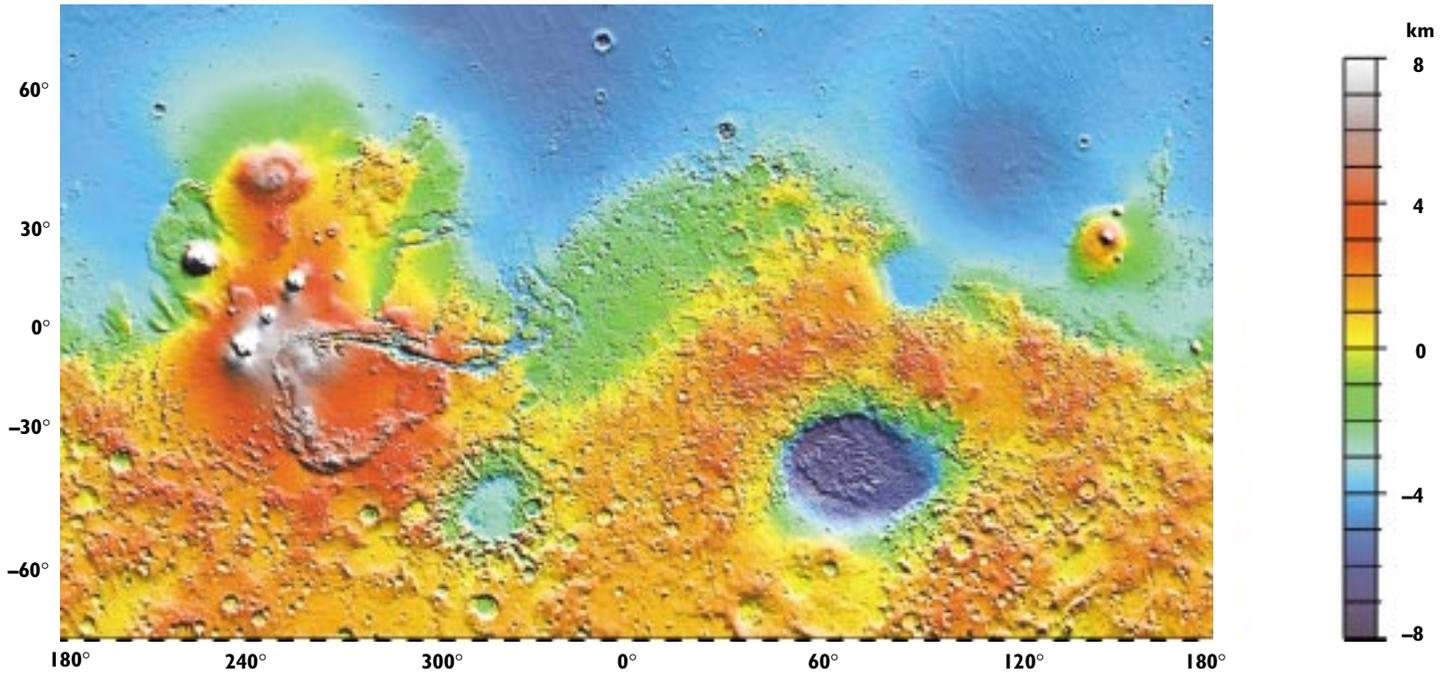
In Antarctica there are algae that are quite viable at near-freezing temperatures. Drill one or two miles into the Earth's crust, bring up the rock, and if there's water in the rock, there's life. (see

E&S, 1999, No. 1-2, "The Search for Extra-terrestrial Life," by Kenneth Nealson.) The Rio Tinto in Spain has a pH of 2, a very acidic river, yet there's life there too. It turns out that where there is water here on Earth, there is life—microbial life. This has renewed interest in exploring the possibility of life elsewhere by asking not whether there is life or was life, but rather: Where was the water, and perhaps where *is* the water? Understanding the geological, atmospheric, and climatological processes that control the presence or absence of water on other bodies in the solar system will help us discover the answer.

Mars is again a focus of our search. The planet is similar to Earth in that there is water in the atmosphere in the form of clouds and haze, but there is no liquid water on the surface. Billions of years ago, however, there was a lot of water, and massive floods carved huge canyons. What might the water cycle have been like when there was liquid water on the surface of Mars? The Viking image below of one of these canyons illustrates an interesting aspect of the puzzle. There are no tributaries. On Earth, creeks flow into streams that flow into ever-larger rivers in massive water-



Viking Orbiter I showed massive dry riverbeds on Mars, where water must have flowed billions of years ago. But there are no tributaries. Where did the water come from?



Mars Global Surveyor captured this higher-resolution image of a stretch of Nirgal Vallis shown on the previous page (outlined by the white box). The little side canyons jutting out of the main canyon wall on the upper side indicate an underground source of the flood waters that created it. (Malin Space Science Systems)

collection systems. On Mars there seems to be no similar water-collection system. Mars Global Surveyor, orbiting since 1997 (Michael C. Malin, PhD '76, is the principal investigator for the Mars Orbiter Camera, and Arden Albee, professor of geology and planetary science, is the project scientist), has provided a high-resolution picture of this area (left) and clues as to what might have happened. It appears as though the water burst out of the canyon walls from underground, creating massive floods carrying rock and debris downstream into the basin. Presumably the water erupted where there was sufficient heat from volcanic activity to have kept it liquid, rather than frozen, beneath the surface.

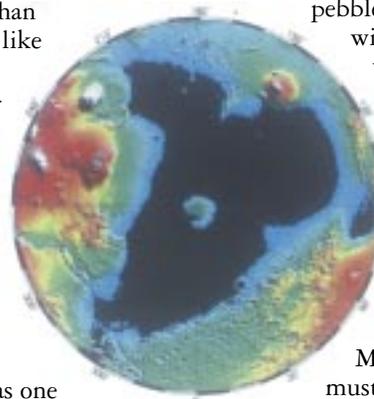
To understand this different water cycle, we must look at where there might have been ocean basins on Mars. The laser altimeter on Mars Global Surveyor measures the height of the surface of Mars very accurately. The topographic map above illustrates the great asymmetry between the southern hemisphere of Mars, which is several miles higher than the average, and the northern hemisphere, which is several miles lower than average. (The relief on Mars is something like 20 miles from highest to lowest point.) There are ancient streambeds in the southern hemisphere, carved by water that one time flowed northward into this great low-lying basin.

Several years ago Timothy J. Parker at JPL inferred from Viking data that an ancient shoreline might exist around this northern plain. He and his colleagues identified two possible shorelines. Their analysis was based on the observation that inside the inner contour it's very smooth, as one

might expect for the bottom of an ancient ocean. Between the first and second contours, it's somewhat rougher, and above the second contour the terrain rougher still.

With Mars Global Surveyor's accurate height measurements, we can conjecture what that ocean might have looked like if the basin had been filled to a depth of about 5,000 feet (see below). There is debate, however, about whether there ever was a standing ocean in this region. In the few spots along this potential shoreline examined in high-resolution Global Surveyor images, there's no evidence of a shoreline. Perhaps the water flowed in and immediately froze, forming a layer of permafrost.

On July 4, 1997, Mars Pathfinder landed near the mouth of one of the massive canyon systems flowing into this basin. Matthew Golombek, the Pathfinder project scientist, and his team purposely picked a spot far enough downstream from the mouth of the canyon so that the slowing flow could have carried only smaller rocks to the site. Sojourner examined conglomerate rocks, dust,



pebbles, and sand, all consistent with a Mars that was once warm and wet, since flowing water tumbles material to make pebbles, sand, and dust. The dust itself proved to be magnetic, an indication that iron may have been leached out of the crust. How long ago might water have flowed on Mars? To answer that, we must ask first when the atmo-

Left: Mars Global Surveyor's laser altimeter yielded this precise global relief map of Mars in Mercator projection. The red areas are about four kilometers above the average surface height, and the blue of the northern hemisphere, about four kilometers below. Note the great difference between the northern and southern hemispheres. Seen in a pole-to-equator view (below, left), the northern hemisphere topography suggests where an ocean might have been. The laser altimeter uses its own coordinate system, in which longitude increases as you go eastward—the opposite of the standard system. (Head et al.)

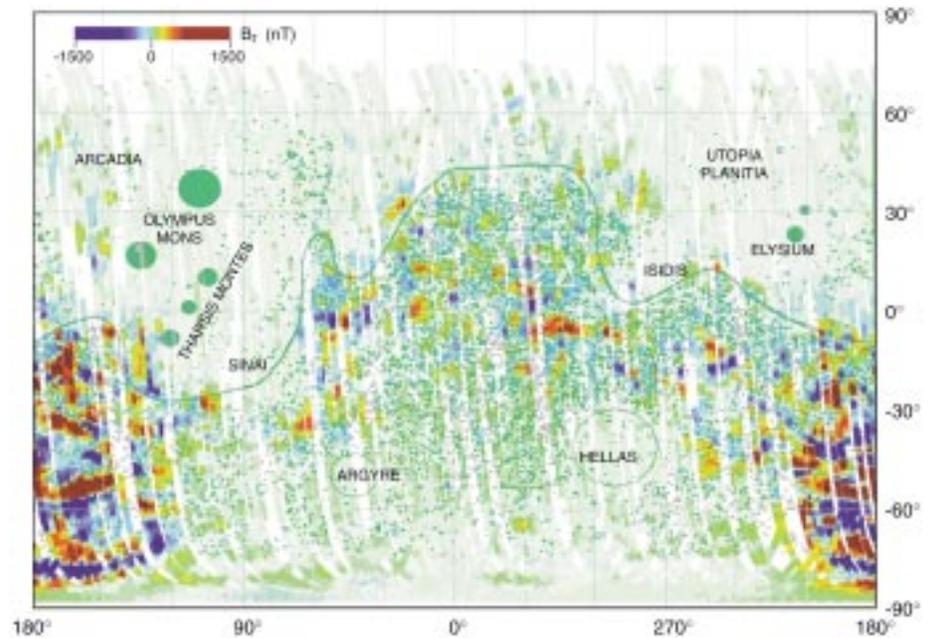
sphere became so thin that water could not exist in liquid form. (Today it's less than one percent of the pressure on Earth; under such low pressure, liquid water will vaporize.) Various processes contribute to atmospheric loss, including weathering, erosion by meteoritic impact, and sputtering from ions in the solar wind colliding with the upper atmosphere. A global magnetic field will shield the atmosphere from sputtering by deflecting the ions away from the planet.

Earth has a global magnetic field like a bar magnet, with a north pole and a south pole, but Mars does not. Instead, the magnetic field exists only in local regions on the surface, in a bar code pattern of alternating north and south polarities. (The magnetic field is positive if it's red, negative if it's blue in the illustration below.)

This surprising finding means that the magnetic field is "frozen" into the rock. In other words, there was a global magnetic field at the time the rock cooled, and the rock preserved the direction of the magnetic field at the time it cooled. This is observed on Earth where seafloor spreading at the bottom of the oceans is fed by magma oozing from the interior. Earth's magnetic polarity regularly reverses, so that as new seafloor cools, it freezes in the direction of the magnetic field at that epoch, creating an orderly magnetic pattern.

Given such a model, the locations of the frozen remnant magnetic fields are quite striking. Notice that there's no remnant magnetic field in the north, where the surface is younger than 3.9 billion years, as indicated by the relative paucity of impact craters. The southern hemisphere, however, is heavily cratered, indicating that its surface dates from the period of heavy bombardment that ended 3.9 billion years ago. There are remnant magnetic fields in the older part of Mars, but not everywhere; there's none, for example, where there are very large impact basins (one of these, Hellas, is six miles deep). A major impact would have heated and demagnetized whatever was there. Had there still been a global magnetic field as the impacted material cooled, it would have been remagnetized. Since that did not happen, the impact must have occurred at a time when there was no longer a planetary magnetic field. This tells us that there was a global magnetic field on

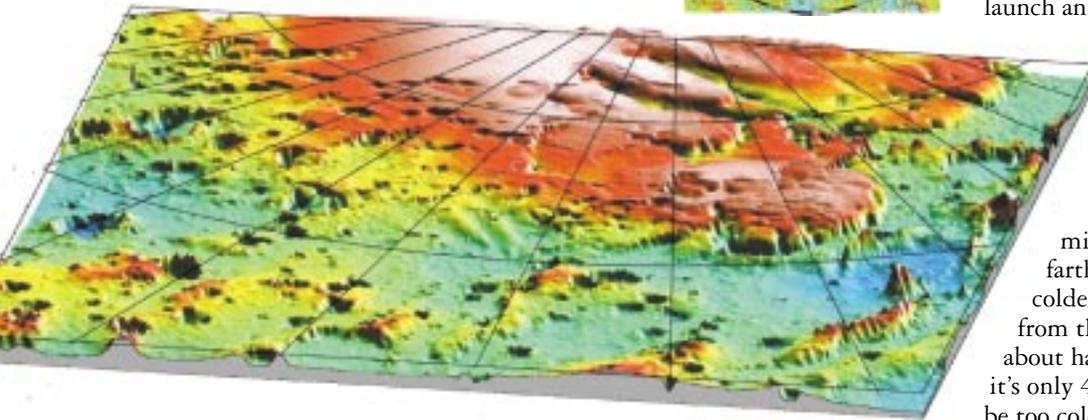
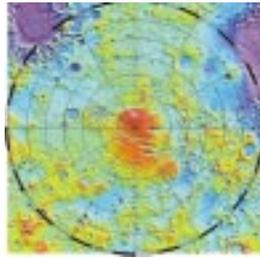
Below: Mars's spotty bands of magnetic field (red is positive, blue is negative) are located only in the older, heavily cratered southern hemisphere, indicating that, when the impacts stopped after the first 500 million years or so, there was no magnetic field left—only these remnants "frozen" into the rock. Without a magnetic field, the solar wind would have swept away the atmosphere. Hellas and Argyre are two deep impact craters, also visible in the relief map on the opposite page. (Acuña et al.)



Mars for only the first few hundred million years, before the heavy bombardment stopped. By then, the planet's churning interior, which creates the field, had evidently cooled enough that the churning stopped and the magnetic field decayed away.

Without a planetary magnetic field to shield the atmosphere, the million-miles-per-hour ionized wind from the sun can sweep in and carry away the atmosphere, little by little, year by year. This is what likely happened on Mars, until today there's very little atmosphere left, making liquid water on the surface of Mars no longer possible.

There is still some water on Mars besides that in the atmosphere—frozen in the polar caps. The north polar cap is composed of both water ice and dry ice (solid carbon dioxide), forming a very intricate pattern. In the winter dry ice covers most of the surface, but as it sublimates into carbon dioxide gas during the summer, what is left is



Top: The south pole of Mars, seen here by the Mars Global Surveyor's laser altimeter, rises to a height of 4,000–5,000 meters (red). The small polar cap, made of dry ice, sits atop a terrain that scientists think may be water ice, dry ice, and dust built up over billions of years. The layers of this terrain, where the ill-fated Mars Polar Lander was aimed to search for water, can be seen in the edge-on view at bottom.

mainly water ice. In order to determine how much water ice is there, we need to know how thick it is, and Mars Global Surveyor, with its laser altimeter, has been able to tell us that. The typical thickness is about 3,300 feet, and peak thickness is about 10,000 feet. So we now know how much water is on Mars in the north polar cap: about half as much as is on Greenland or about a tenth as much water as we believe must have been on Mars to create the massive canyons.

The visible south polar cap is smaller, and it's all dry ice. But if we measure the topography, we find that there's a much larger accumulation of material there than just the small white polar cap. The polar cap is sitting on top of a large deposit called the "layered terrain." We believe that this might be a buildup of water ice, dry ice, and dust, accumulated over billions of years. This south polar region is where, last December, we were trying to land the Mars Polar Lander to search for water. We were aiming for a spot at a height of about 3,000 feet above the surrounding plain, believing that we might be landing on an ancient icy polar cap. Unfortunately, the landing was not successful, and no data were returned from the surface.

But we have an opportunity to go to Mars every 26 months, when Earth and Mars are positioned in their orbits so that a spacecraft can "hop" from one to the other. The next opportunity will be in March and April of 2001, and we're currently looking at exactly what the sequence of missions should be. We want to sample the surface of Mars in interesting places, perhaps where there once may have been thermal activity similar to Yellowstone National Park. We can identify such locations by using orbiting spacecraft with different

sets of instruments to help determine where it may have been wet at one time. Landers with instruments that allow us to measure and to sample in situ will eventually lead, perhaps by the end of this decade, to landers with rovers to acquire samples for launch into Mars orbit and return to Earth. In addition to the NASA program, the European Space Agency is planning to launch an orbiting mission called Mars Express, to arrive in 2003. It will have a radar system, which JPL will provide, to look for water underground. The Japanese spacecraft Nozomi will also arrive in late 2003 to study the Martian atmosphere.

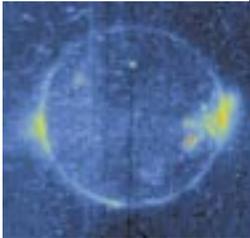
Mars is not the only place where we might look for water. Jupiter is five times farther from the sun than Earth, and much colder than Mars (which is 1½ times as far from the sun as Earth). At Mars, the sun is about half as bright as we see it, but at Jupiter, it's only 4 percent as bright, so it would seem to be too cold for there to be an ocean.

Jupiter is a giant gaseous planet with no solid surface, but it has several interesting moons, in particular Io and Europa. Although they're distinctly different from each other today, they were probably much alike 4½ billion years ago. But they don't look the same today because of great differences in geological activity. When Voyager flew by in 1979, it found Io to be the most volcanically active body in the solar system. The Galileo spacecraft returned to Jupiter in December 1995 and has been orbiting the planet since then. Every couple of months it can fly close by a moon and provide hundred-times-better images than Voyager could.

Io is just a small moon, but it has eight active volcanoes and more than a hundred hot spots—active volcanic areas glowing with lava flows, a hundred times more than here on Earth. How can such a small moon so far from the sun be so active? The answer is tidal heating. We're familiar with the tides that cause our ocean surfaces to bob up and down about every 12 hours as Earth rotates under the moon. Jupiter is so massive that its moons, as they orbit Jupiter, have a tide in their crust. We estimate, as Io orbits Jupiter every 1.8 days, that its crust is flexed up and down by about 100 feet. This tidal flexing produces enough energy to drive the remarkable volcanic activity on Io.

Io is six Jupiter-radii away from the planet's center. Europa is 10, so the same flexing occurs on Europa, but not as strongly. In 1979 Voyager found what looked like streaks drawn on Europa's surface. From spectroscopy, we know Europa is covered with water ice. Since the surface of Europa is the smoothest in the solar system, with no mountains or valleys, the idea soon emerged that perhaps it is a layer of ice on a liquid-water ocean. The same tidal heating that drives the

Right: Two of Jupiter's moons, Io (left) and Europa, caught here by Voyager 1 in 1979, might harbor conditions conducive to life. Io, shown below by Galileo in the eclipse of Jupiter's shadow, bristles with volcanic activity. Hotspots, increasing in brightness from yellow to red, indicate the volcanoes and their oceans of lava.



Right: Jupiter's tilted, wobbling magnetic field generates a continually reversing magnetic field in Europa—exactly what was predicted if an electrical conductor, a salty ocean, say, were hidden under its crust.

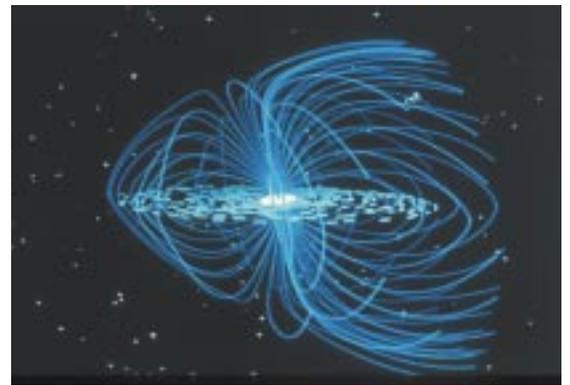
Below: The cracks and ridges seen by Galileo in Europa's icy crust also suggest that it's being flexed as it orbits Jupiter.

(U. of Arizona/DLR)

volcanoes on Io melts the ice beneath Europa's icy crust.

Voyager flew within 130,000 miles of Europa. Galileo, in orbit around Jupiter, can fly by at a distance of only a few hundred miles once every several months. These close-up views have revealed cracks and ridges and places where the surface has been broken, as if from a warm upwelling of a substance with the reddish-brown color characteristic of magnesium sulfate—Epsom salts—an indication of salty material seeping from below. The cover image on this magazine suggests a highly patterned, regular surface, but with pieces that have broken apart, as ice floes do in spring in the Arctic, and floated away before the material in between refroze.

Mobility on the surface suggests some sort of fluid beneath. But how long ago did this happen? Is it possible that it's still going on? Is there evidence that suggests that there might be liquid below the surface and not just soft ice? Again, the magnetic field is giving us a clear answer to these questions. Jupiter has an immense magnetic field, generated inside the planet just like Earth's. And like Earth's, Jupiter's magnetic field is not lined up with the rotation axis but is tilted a bit, so that



the magnetic field wobbles as Jupiter rotates. Dave Stevenson, the Van Osdol Professor of Planetary Science, has suggested that as this wobbling magnetic field sweeps past Europa, its changing directions will generate a magnetic field in Europa, provided there is an electrical conductor beneath its surface (a salty ocean will do nicely). Since the Jovian magnetic field at Europa wobbles from one direction to the other every 5¹/₂ hours, the induced European magnetic field should also reverse direction with the same period. This is exactly what Galileo measured—very strong evidence that beneath the icy crust there's a conducting liquid, most likely a salty ocean.

For life, though, you also need a source of energy. On Europa it certainly can't be sunlight. Perhaps there are volcanic vents beneath the ocean. Perhaps the radiation environment of Jupiter creates a complex set of organic and oxidizing materials on Europa's surface that are cycled back into the ocean in upwellings between the cracks; that might be a source of energy on which microorganisms could exist. To answer the question of whether there's energy, and life, we need to sample both the surface and—if



Below: An artist's rendering of the Huygens probe, carried by the Cassini spacecraft, landing on Saturn's moon Titan, which it is scheduled to do in 2004; the top arrow in the bottom image indicates the landing site. This image was made of Titan's surface (here in Mercator projection) by the Hubble Space Telescope's Wide-Field and Planetary Camera 2, which was able to peer in the infrared through Titan's thick, orange haze for the first time. Scientists believe that the dark areas may be hydrocarbon lakes and the bright ones higher terrains. The lower arrow points to what may be a continent-type feature the size of Australia.



we can find a place where it's thin, broken up, or cracked—below the surface.

The next step is to send an orbiting spacecraft to Europa, so that we can map the entire surface rather than just the few small areas that we have from Galileo. We're currently developing a technology that will allow us to return to Europa in the next 10 years, placing a spacecraft into orbit at a distance of about 125 miles above its surface. We can then use a laser altimeter to measure exactly how much that surface is flexing. If it flexes 100 feet, we'll know it's a very thin crust; if it flexes only three feet, it's frozen solid—although that would be unlikely, given the magnetic field data that we already have. Perhaps a radar system could measure the thin spots in the ice, and a high-resolution imaging system should reveal the most promising spots for a future mission to land and sample the surface on this world.

Today, there are no other places in the solar system where we think there may be liquid water. But there are other places that may help us understand the chemical circumstances associated with the origin of life. One of these is Saturn, 10 times as far from the sun as Earth, with only 1 percent of the sunlight. Saturn is a giant planet, like Jupiter, and one of its moons, Titan, is about the size of the planet Mercury. Unlike Mercury, however, Titan has a very dense atmosphere, with a surface pressure about 60 percent greater than on Earth. The atmosphere is mainly nitrogen, like Earth's, but there's no oxygen, which on Earth was produced by microbial life. Titan does, however, have a trace of methane (natural gas, CH_4), and solar and particle radiation converts that methane into complex organic molecules. Some of the molecules become polymerized, forming particles large enough to block visible light and obscure Titan's surface: it looks fuzzy because of all the organic haze in its atmosphere. The organic chemistry that's occurring today in Titan's atmosphere may in some important ways resemble the chemistry that occurred in the early Earth's atmosphere before life evolved.

Fortunately, the Hubble Space Telescope can

peer through Titan's haze. Using the infrared rather than visible light, Hubble can image Titan's surface and discriminate between lighter and darker regions. Jonathan Lunine (PhD '85), Professor of Planetary Science Yuk Yung, and Dave Stevenson calculated that some of the organic material created in that atmosphere should be liquid, resulting in rain and lakes of liquid hydrocarbon. Those lakes would be very dark, so perhaps these darker spots are the low regions and the brighter ones are higher.

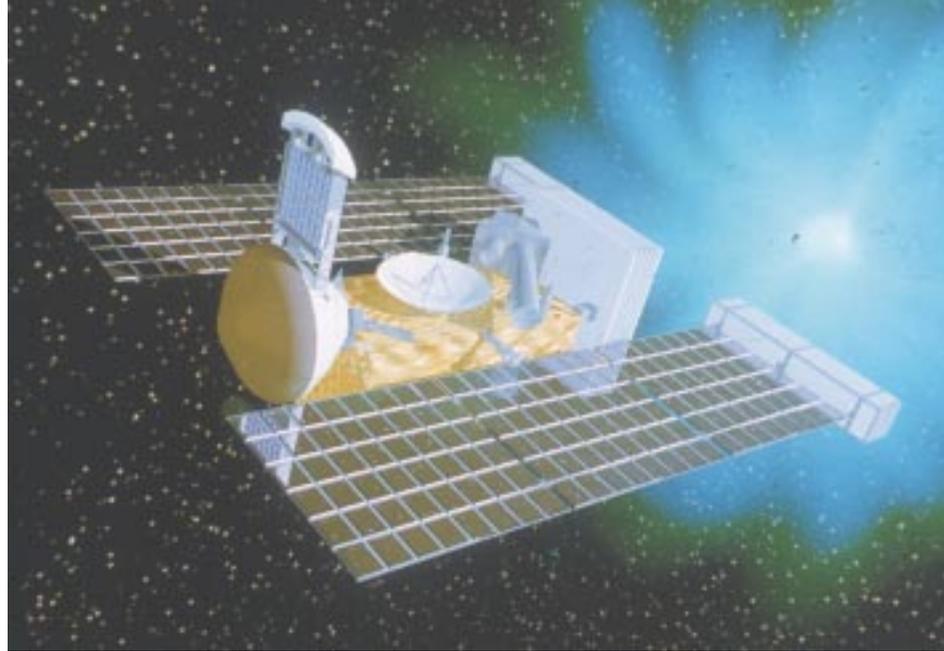
In December 2004, we will sample Titan's atmospheric chemistry and map the surface. Cassini, launched in 1997, will begin orbiting Saturn in July 2004, carrying an imaging radar system, built jointly with Italy, that will map the surface through the haze. Cassini also carries the Huygens probe, built by the European Space Agency, which will plunge into Titan's atmosphere with instruments specially designed to analyze the organic molecules present. A camera will return images of the surface during descent. We have no idea whether Huygens will splash down into a liquid or crash onto a solid surface—that's part of the process of discovery. Eventually we may want to return to Titan to sample the surface with experiments designed to identify the materials that have been deposited there over the last millions of years, a frozen record that might tell us about the chemistry that occurred on Earth before life evolved.

Still more clues about the early solar system might come from comets, the ice and rock left over from when the solar system formed. Many comets ended up inside Jupiter, Saturn, Uranus, and Neptune, but these giant planets also scattered many comets out into the Oort cloud that surrounds the solar system. Occasionally, a comet is nudged into a journey back near the sun, where the heat causes the ices to sublime, creating a beautiful tail. Twenty years ago, it was expected that comets, composed of water ice, would have bright surfaces, but we now know they're covered with a charcoal-black material.

When the European Giotto spacecraft flew



Far right: The Stardust mission will visit comet Wild 2 in 2004 and return to Earth with bits of comet dust captured in the apparatus projecting above the conical return capsule. Embedded in that holder, shown at lower right, is an airy silica substance called aerogel. When the particles encounter the aerogel at 14,000 miles per hour (right), they slow down and are trapped.

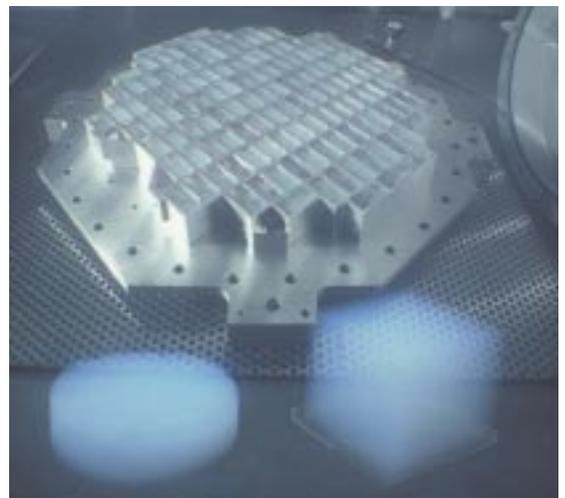


through the coma of Halley's comet in 1986, it found that the material coming off the comet contained atoms of carbon, hydrogen, oxygen, and nitrogen—the atoms basic to organic molecules. The fact that it's black certainly suggests carbon-bearing material. What is this material? Where did it come from? And what role might it have played in the origin of life here on Earth and possibly elsewhere in the solar system? All the planets, as they were forming, were bombarded by these comets and their black material. We can't answer any of these questions until we know what that material is. We need a sample.

We have two approaches under way. Deep Impact, which will be launched in January 2004, will fire a 1,000-pound copper projectile into comet Tempel 1 as it flies by. The resulting crater, about 70 feet deep and 300 feet across, will allow us to look below the surface. At the same time, material splashed out by the blast will be analyzed by spacecraft instruments during flyby. All these fireworks will help celebrate July 4, 2005.

We also want to bring a comet sample back, a task assigned to the Stardust mission. The challenge is to collect the comet dust as we fly through the coma at 14,000 miles an hour. If we use a sheet of ordinary material to collect the comet dust particles, they will crash into it at 14,000 miles an hour and evaporate. So Peter Tsou at JPL developed aerogel, a substance made of silica that's mostly nothing. The best analogy is cotton candy—sugar spun up so there's not much there. Aerogel's silica blocks are about six times the density of air, but rigid enough to be embedded in a holder. Stardust, with its aerogel blocks extended, will fly by comet Wild 2 in January 2004 and return the sample to Earth in January 2006, landing in Utah. We will have thousands, if not millions, of tiny bits of comet dust that can be analyzed for the first time.

Just as the first decades of planetary exploration revolutionized our view of the solar system, there



is every reason to believe that sampling the solar system in the decades ahead will greatly expand our understanding of the diverse worlds around us and of the conditions essential to the origin and evolution of life, not just here on Earth, but elsewhere. □

Ed Stone has been director of Caltech's Jet Propulsion Laboratory since 1991, but his connection to space goes back to his first cosmic-ray experiments on Discoverer satellites in 1961. Since then, he has been principal investigator on nine NASA spacecraft missions and co-investigator on five more, as well as project scientist for the spectacular Voyager missions. Stone, who came to Caltech as a research fellow in 1964 after earning his PhD from the University of Chicago, was named professor of physics in 1976 and served as chair of the Division of Physics, Mathematics and Astronomy from 1983 to 1988. He is now a vice president of the Institute and the Morrisroe Professor of Physics. This article was adapted from Stone's February Watson lecture; his series of Watson lectures on Voyager's planetary flybys appeared in E&S from 1979 through 1990.

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