SAMPLING THE SOLAR SYSTEM

Edward C. Stone

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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. 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? An interesting aspect of the puzzle is the absence of tributaries. On Earth, creeks, streams, and rivers form extensive water collection systems. On Mars there seems to be no similar water collection system. High resolution images from Mars Global Surveyor, orbiting since 1997, has provided 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. There is a great asymmetry between the southern hemisphere of Mars, which is three kilometers higher than the average, and the northern hemisphere, which is three kilometers lower than average. (The relief on Mars is approximately thirty kilometers from highest to lowest point.) There are ancient streambeds in the southern hemisphere, carved by water that at one time flowed northward into this great low-lying basin.

Several years ago it was inferred from Viking data that an ancient shoreline might exist around this northern plain. Two possible shorelines were identified 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 1,500 meters. There is debate, however, about whether there ever was a standing ocean in this region. In the few spots along the 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. The landing site was purposely selected 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

atmosphere 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.

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. There is 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 this older Martian surface, but not everywhere; there is none, for example, where there are very large impact basins (one of these, Hellas, is nine kilometers 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 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 400 km/s ionized wind from the sun can sweep in and slowly carry away the atmosphere. 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 sublimes into carbon dioxide gas during the summer, what is left is 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 1,000 meters, and peak thickness is about 3,000

meters. 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, in December 1999, we were trying to land the Mars Polar Lander to search for water. We were aiming for a spot at a height of about 1,000 meters 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 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 $1^1/2$ 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 $4^1/2$ 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. Jupiter is so massive that its moons, as they orbit Jupiter, have a large tide in their crust. It is estimated that as Io orbits Jupiter every 1.8 days, its crust flexes up and down by about 30 meters. 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 ten, 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 volcanoes on Io melts the ice beneath Europa's icy crust.

Voyager flew within 200,000 kilometers of Europa. Galileo, in orbit around Jupiter, can fly by at a distance of only hundreds of kilometers 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. There are areas where the highly patterned, regular surface, appears to have broken apart into ice floes and floated apart 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 happening? 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, like Earth, has an immense magnetic field, generated inside the planet. And like Earth's, Jupiter's magnetic field is not aligned with the rotation axis but is tilted, so that the magnetic field wobbles as Jupiter rotates. 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 (such as a salty ocean). Since the Jovian magnetic field at Europa wobbles from one direction to the other every $5^{1}/2$ hours, the induced Europan magnetic field should also reverse direction with the same period. This is exactly what Galileo measured—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 is unlikely to be sunlight. Perhaps there are volcanic vents beneath the ocean. It has been suggested that 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 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 200 kilometers above its surface. We can then use a laser altimeter to measure exactly how much that surface is flexing. If it flexes 30 meters, we'll know it's a very thin crust; if it flexes only one meter, 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 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. 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. Chemical models suggest that some of the organic material created in that atmosphere should be liquid, resulting in rain and lakes of liquid hydrocarbon.

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, that 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 vaporize, creating an

extended tail. Twenty years ago, it was expected that comets, composed of water ice, would have icy surfaces, but we now know they're covered with a charcoal-black material.

When the European Giotto spacecraft flew 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 500 kilogram copper projectile into comet Tempel 1 as it flies by. The resulting crater, more than 25 meters deep and 100 meters 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 6 km/s. If we use a sheet of ordinary material to collect the comet dust particles, they will evaporate on impact. We will use aerogel, a substance made of silica but with very low density. The aerogel blocks on Stardust are about six times denser than air, but rigid enough to be embedded in a holder. With its aerogel blocks extended, the spacecraft 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.