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Martian Chronicles

Killer Microbes from Outer Space

On September 28, 2015, the Washington, D.C., NASA conference room was packed. Under bright lights, the leaders of the Mars Reconnaissance Orbiter team squeezed behind a conference table as television cameras whirred and digital cameras flashed. The team announced it had found evidence of water on the red planet. Not eons ago, but today, dark, briny water was running in the mountain ridges around Hale Crater in subfreezing temperatures. In Nantes, France, the Nepalese student from the University of Arizona who first spot ed the dark gullies answered questions via satellite. Perchlorate salts, like those found in earth's polar regions, or in rocket fuel, kept the water liquid. Pure water froze at Mars temperatures, roughly between 70 above and 100 degrees below zero Fahrenheit, but heavily salted water could stay liquid. "Water, albeit briny," announced John Grunsfeld, associate director of the mission, "is flowing today on the surface of Mars."

Calls poured into Nantes as the now–graduate student, Lujendra Ojha, headed from bar to bar to get a bet er cell signal. At each he had to drink a beer, "so by the time I talked to reporters from Argentina," he recalled, "and Bolivia, China, Hong Kong, India, and my native Nepal, my answers progressively worsened."

That scene came nine months after a similar gathering in San Francisco, when the NASA Mars Curiosity team announced that it had detected several emissions of methane, a signature gas created by microbes like Archaea, on the Gale Crater surface, lasting up to two months at a time. "It was an oh-my-gosh moment," the Curiosity researcher Chris Webster said. Then, late in 2016, the Mars Reconnaissance Orbiter detected an ice field the size of Lake Superior beneath the region called Utopia Planitia.

The announcements set off a search for microbes on the red planet and what they might mean to life in the universe. Liquid water, methane, life that could live off of sulfur and hydrogen, all seemingly telltale signs of potential microbial activity, helped to reignite interest in Mars in movies, nightly comedy, and social media. Millions followed NASA's twit er feeds. Mainstays like *Scientific American* and National Public Radio, buzz feeds, and web thought catalogs all commented. The number of hits on Curiosity's and NASA's Facebook pages soared, as did the number of its followers on Twit er. The NASA app called Be a Martian shared Curiosity's images within hours after they were received. Postdocs and graduate students tweeted at astrobiology conferences from Chicago to Nagasaki as real-time images poured in. I eagerly followed most of them.

The idea was that in its early years Mars offered a bet er prospect for life than Earth. When methane emissions were detected in two two-month bursts inside of Gale Crater, all the old arguments about Mars microbes returned. Some researchers still claimed that NASA's first lander, Viking, had detected Mars life in 1976. Early Mars had a wet-dry cycle that the early Earth lacked, and many thought that made it a likelier candidate for life's origin than Earth. The facts that the planet was smaller and that its lower gravity allowed rocks to burst into space when hit by comets, along with the fact that the closest large body was Earth, meant that pieces of Mars often landed here, bolstering the idea that our microbes may have originated as Martians.

As the Curiosity rover, a nuclear-powered Mini Cooper–sized vehicle, climbed Mount Sharp, the Russian Space Agency, with the European Space Agency, worked feverishly to finalize their ExoMars probe preparation for takeoff in 2016. The European Space Agency closely watched its Schiaparelli probe hurtling toward the fourth planet. A NASA probe catapulted toward Pluto while the expiring Cassini was purposely driven into a plume of water jet ing off the surface of Jupiter's moon Europa. Around the solar system, a golden age of probes made the conditions of life look more possible in space.

How would you look for as microbial life on another planet? Hints came from Earth's most extreme and dangerous caves, its volcanic pools, and its coldest briny lakes. At the same time, new interpretations of microbe-human relationships took hold as new books appeared and commentators talked about the microbial cloud we carry around us. The business potential of microbial symbiosis brought us compost to clean wastewater and generate electricity. Microbes were projected to be a multibillion-dollar global business. From Jupiter's moon Europa to Saturn's volcanic satellite Enceladus, interest in the biosphere heated up.

Then Old Dominion University's Nora Noffke took a second look at Mars Curiosity's older photos and threw down a challenge. For three years, Noffke said, the NASA team had been staring at evidence of past microbial life on Mars, exactly the same structures she had found in Australia's desert or in the tidal marshes of Chesapeake Bay. The trouble was, they had missed it. It all began in 1976.

Panning for life

At midnight in a sweltering room in Pasadena in July 1976, Viking Mars team members sat hunched around a bulky monotone computer monitor, tensely awaiting the first data from the world's first successful Mars probe lander, the only Mars lander ever specifically designed to detect life. Over the next three hours each of Viking's first life-detection experiments came back with a striking signature. As the data fed in an agonizingly slow trickle into the Space Operations Facility, it was clear that carbon dioxide was released when organic compounds were added to Martian soil, though not when the mixture was superheated. This was a life signature, and exactly what had happened with the experiment on Earth. When water was added to the soil, oxygen was released, just as on Earth. The remote probe, panning for life, had found its signature in its first two experiments. The third experiment heated the soil, like warming food in the oven, and those results were mixed.

Arguments intensified, however, over the next several nights, as the fourth experiment's conflicting data came in. To claim life on Mars would be unprecedented. If they were wrong, no team member would live it down. Anything was bet er than striking out with a pompous grin on your face. Unbeknownst to most in the world watching, however, three of the four experiments on the primitive Viking lander could have been interpreted as testing positive for microbes, giving the same results as when they had been checked thousands of times on Earth. The researcher Patricia Straat told the director of the mission, Gil Levin, "That's life!"

However, the fourth experiment, employing a gas chromatograph of the kind employed by James Lovelock, and a mass spectrometer, a delicate instrument for measuring the size of molecules, showed no life—and not only that, but absolutely no organics—on Mars. That was a stunning result: organics exist all over space—on asteroids, comets, and meteors, and in interstellar dust. Not only that, but the experiment suggested that Mars's surface was poisonous or self-sterilizing. Mission scientists had a heated argument, and NASA eventually decided to err on the side of caution. The surface must be self-sterilizing, they concluded, owing to the planet soil's powerful oxidizing agents, which also helped to give it its red color. Viking had found a barren, windblown red planet, pockmarked by craters, cold and dead as the moon.

A few mission scientists disagreed, maintaining that the fourth experiment simply failed—as it had often in Earth tests. A group of activists, including Levin, wrote and spoke, goading NASA to release the full Viking data. On NASA's 2016 celebration of the mission's fiftieth anniversary, he repeated his call. He predicted Curiosity would find complex organics, which it did. When he saw the detection of methane bursts by Curiosity, he told me, he saw that the disappearance of the methane had happened too rapidly to have been caused by ultraviolet radiation: "This disappearance could have been caused by methanotrophs, which use methane and makes for a perfect lit le eco-cycle."

Other Mars probes gave conflicting results. NASA's Opportunity and Spirit rovers in the 1990s, whose daily reports thrilled millions of fans around the world, including me, were designed and constructed by geologists and engineers, not by biologists. Evidence of water came from the 2008 Phoenix lander, whose camera pictured clear droplets on its cold steel legs. Simulations suggested that either water condensed around windblown grains of calcium perchlorate, the salt-type mineral whose properties enable it to scavenge water from the atmosphere, or that the landing had stirred up dirty ice beneath the surface and drops had formed and melted on the legs. The point was, said the University of Michigan's mission scientist Nilton Renno, "On Earth, everywhere there's liquid water, there is microbial life." Such saline water on Earth housed microbes, in fact.

One of the best places to look for promising bits of Mars, paradoxically, was Earth.

Mars microbes on Earth

Walk along the frozen white expanse of the Antarctic and you will see bits of Mars, in the unmistakable form of small red stones. In fact, about ten pounds' worth of rock from Mars falls on Earth every year. If a large meteorite strikes Mars, it flings bits of rock into space beyond the small planet's gravity. As that planet's closest neighbor, our own, larger planet will find that its gravity traps some of the rocks, which fall to Earth's surface and are most easily found in barren, ice-covered regions such as the Antarctic. Their authenticity is determined by chemical analysis of their shock glass, the melted glassy substance original to the rock. If a stone's shock glass contains the exactly the same mix of gases as Mars's atmosphere, identified in the many Martian probes, it is from Mars.

Tiny squiggles on a famous Martian meteorite found in Antarctica, ALH 84001, in 1996 led the NASA researcher Dave McKay and his team to claim that they had discovered fossils of microbes. Today most regard that as unlikely. But eons ago abundant water had certainly flowed in Mars's oceans and rivers, the liquid's mineralized remnants clearly visible across the planet—floodplains, alluvial basins, even oxbow curves in long-dried great rivers. The original name given in 1887 by the astronomer Luigi Schiaparelli to the great rift valleys seen through early telescopes was *canali*, Italian for "channels" (though English-speaking researchers translated it incorrectly as "canals"). At the turn of the century, in Arizona, Percival Lowell thought he glimpsed active Mars rivers featuring seasonal changes in vegetation. In fact, numerous probes have imaged morning haze in Martian canyons. Seizing on Lowell's claim, Edgar Rice Burroughs, the author of the *Tarzan* books, wrote a wacky series of 1920s and '30s *Princess of Mars* science-fiction novels that sent generations of young Americans off to adventure. What Lowell saw was flaws in his mirrors. What Burroughs saw, as he divorced his wife for a Hollywood actress, was a gold mine of public gullibility.

Later NASA probes produced confounding results. The Mariner probe in the 1960s strongly suggested that the Mars's thin, cold atmosphere permit ed no possibility of pure liquid water, though the final orbiter clearly pictured the beds of ancient streams and oceans.

In 2010 a University of Arizona undergraduate studying the Mars orbiter images spot ed intermit ent dark streaks running in parallel at mountain ridgetops, then disappearing, as if in seasonal flow. What the Nepalese-born guitarist Lujendra Ojha noticed in the puzzling phenomena came from the high resolution imaging science experiment (HiRISE). The seeping dark streamlets appeared at dozens of sites. Excited, Ojha paired HiRISE observations with mineral maps of Mars. The spectrometer observations showed hydrated salts at several locations, but only when the dark features appeared and widened. Using the orbiter's compact reconnaissance imaging spectrometers, Ojha and the team then analyzed light reflecting off the streaks, detecting in it traces of either sodium perchlorate or magnesium perchlorate. Mars water contained a natural briny antifreeze.

Picture a cool planet with intermit ent water and dryness and the largest volcano in the solar system. Giant lakes contain the same volume of water as that in the Arctic Ocean, fed by rushing rivers that deposit tons of alluvial sediment in their deltas. That was early Mars. Now picture a brimstone-smelling, acidic, ocean-covered planet with a toxic atmosphere and hot greenhouse gases, with neither oxygen nor radiation-sheltering ozone, that was pummeled by comets, then rammed by a Mars-sized planet, ejecting enough rock to form a gigantic moon that wrenched the planet's surface into skyscraper-high tides. Welcome to early Earth.

For that and other reasons, the NASA investigator Steven Benner and others suggested that life originated on Mars and was carried to Earth by ejecta. Poring over the old Viking transcripts in the Houston NASA library, Benner found precious clues in the forty-year-old transcript to what they had seen in the hot nights as the data unfolded. What he found was "mass confusion," he told me. Studying the DNA of ancient microbes and resurrecting their genes and proteins, Benner sought to connect the origin of life on Earth with the existence of life in the solar system. Mars, he pointed out in a series of papers that landed him in *Nature*, featured "warm temperatures and a wet dry cycle," he said, enabling amino acids to concentrate "for our kind of chemistry."

The trouble was that many past claims of Martian life or water had been so wrong. But many ancient microbes had thrived in similar icy, alkaline environments on Earth. For that reason researchers raced to sulfurous caves, hot springs in Kamchatka containing molybdenum and borate, Yellowstone National Park, and the brine lakes of the Antarctic. What they found was beguiling.

In the west

NASA's Chris McKay and Penelope Boston were two of the researchers searching remote, extreme outposts on Earth for signs of microbe metabolism and origins. A former New Mexico School Institute of Mining and Technology professor and the daughter of two circus trainers, Boston started off studying microbes in the Arctic and then switched to searching in deep caves. California's Alison Murray sought extreme microbes in the Antarctic. Suddenly, after Curiosity, everyone was interested in what could live in an ice-covered lake or plain, or in a remote cave or mine miles below the planet's surface. The likelihood of microbial life on Mars, which Boston had placed at 30 percent, was now, in her view, increasing. If tiny forms of life exist in hostile lake, cave, or mine environments, Boston reasoned, microbial life could eke out an existence on the subsurfaces of Mars.

Starting as director of the Cave and Karst Studies program at the Institute and cofounder of New Mexico's National Cave and Karst Research Institute, Boston made the case for Mars, helping to create the Mars Underground and put ing together a series of discussions in which she won over the skeptics at NASA for life on Mars as a significant possibility. She was so successful that in 2016 the space agency named her the new director of its Astrobiology Institute in Moffet

Field, California, giving her the exciting opportunity to "help guide the science I love at a very high level," she told me.

From Nevada, the Desert Research Institute biochemist Alison Murray joined Louisiana State University geophysicist Peter Doran to study the microbes and ancient climates of the briny, ice-covered lakes of the Arctic and Antarctic, together finding a wide variety of Archaea and bacteria rising and falling with the seasons and times of day. "They don't do much—they hibernate most of the time," said Murray, who dipped ice cores down to the Antarctic Lake Vida's bottom, "but they're there." It was warmer further down below the brine, but the core tubes brought up ice from the deep sink.

That insight took researchers back to the American west, where the Berkeley biologist Jill Banfield studied the Colorado River and the water of an abandoned California mine at Iron Mountain. Banfield discovered dozens of new phyla of bacteria in a single toxic mine-waste site. The key was that these strange, previously unknown microbes depended on communities of other organisms to survive. This helped explain why so few could be grown in the lab. Working in the abandoned mine, Banfield's team applied a new technique to finding organisms and discovered several new phyla of bacteria, practically revolutionizing the tree of life. The Banfield team divided the 789 organisms into thirty-five phyla, twenty-eight of which were newly discovered, within the domain bacteria. They based the sorting on the organisms' evolutionary history and on similarities in their 16S rRNA genes; those that had at least 75 percent of their code in common went into the same phylum. The team found vastly different symbiotic species at each level and in each season.

In the fall of 2016 the Banfield team found new bacterial groups from a single Colorado aquifer, doubling the number of the planet's known bacterial groups, a massive underground find that again revised the tree of life. Banfield also studied the microbial colonization of gut of infants, taking her into neonatal intensive care units. Her work, and that of others in Yellowstone, in Chile's Atacama Desert, in Colorado's and California's abandoned mines, and even the inside of a dolphin's mouth, led to a new tree of life published in *Nature Microbiology*; about a thousand previously unknown species had been added over the past fifteen years. A second surprise in Banfield's discoveries was that almost half of the new bacterial diversity came from one group thought to live only in symbiosis.

Then Nora Noffke ignited the Mars search for life.

Hiding in plain sight

Through the hot coastal Virginia summer, Old Dominion University's Nora Noffke was studying the Curiosity rover photos from Gale Crater. The diminutive Noffke was a leading authority on microbially induced sedimentary structures (MISS), a term she coined for the stone pat erns left by tidal microbial mats in briny tidal shallows. Many people were familiar with stromatolites, the sediment mounds deposited by ancient microbes, but few understood the significance of the flat tidal mats. Over a thirty-year career Noffke had traveled to five continents studying and categorizing a dozen typical mat shapes, from roll-ups to diamonds to waves and shelves. The moundlike stromatolites made tourist destinations in the shallows off Australia and Hawaii, and in the Caribbean. Noffke found her MISS in the extreme outback of Australia. Virtually no one else had seen them, and they so far ranked as one the oldest pieces of evidence of life on our planet.

NASA invited Noffke to speak at a meeting to choose the landing site for its 2020 Explorer. If early Earth and Mars were similar, Noffke said to the group, perhaps there were microbially induced sediments preserved on the planet. In the audience, the Caltech geochemist Ken Farley sat up in his chair. His team had just published a paper on the polygonal structures seen by Curiosity in the ancient mud of Mars's Sheepshead Formation, a coastal plain on the route as it traveled twenty-two kilometers to Mount Sharp. After the meeting Farley sent Noffke the image and asked her what she thought. She studied the photos taken on Sol 126, the Mars day that Curiosity was in Sheepshead. Her heart leapt.

The images looked familiar. She spent hours making a drawing and sent it to Farley, saying, "This could be microbial. Should I analyze them further?" He said yes.

Noffke started her study in May, then, after teaching ended, resumed in July and August. All through the summer piles of papers stacked up higher and higher in her home office. She knew the dangerous tendency to see microbial structures everywhere. She studied her own personal huge archive of MISS photos from Earth. In the afternoon, when the sun lowered, she walked along the tidal flats of Chesapeake Bay, thinking about the ancient ocean beds on Mars, with its tinier sun, similar day length, and warmer temperatures. She was a Mars beginner. "I'll submit a hypothesis paper and see what people say," she thought.

When, in January 2015, she published "Signs of Microbial Life on Mars," the Curiosity team reacted strongly. Noffke was seeing the equivalent of "clouds in the sky," said one scientist. The team created a website to refute Noffke's claims.

But when Curiosity's research found perchlorate salts in briny water below the Martian surface, Michael Meyer, the lead scientist for NASA's Mars Exploration Program at the agency's headquarters in Washington, gave a boost to the search for life: "The more we study Mars, the more we learn how life could be supported and where there are resources to support life in the future." Then came the news of the methane burst. Yes, the methane bursts could have been contamination from the Curiosity. Then came the briny water.

The rancor grew. The Curiosity team said she had the geology wrong. Noffke responded. "It's now an eroded hillside but it has been a former lake, in a completely different paleoenvironment. They say it's a braided river. That's simply not true. It's a hillside left from a meandering river system. That's exactly where you would have microbial mats on Earth, in places like that!"

The only way to set le the question was to put people on Mars. The big problem was carrying enough fuel for liftoff from the Martian surface so that they could return to Earth. For that reason, a first step would likely be humans in orbit around Mars, as proposed by the U.S. Planetary Society, presided over by Bill Nye. Looking further, NASA was planning to send humans to Mars as early as the 2030s, while the European and Russian ExoMars mission, scheduled to land in 2018, was to select a lake bed for its site.

Further evidence of ancient microbial activity in the Gale Crater basin came from the University of Oregon, where the geologist Greg Retallack noted the soil's high level of sulfate, which could only be produced in an anoxic environment by anaerobic bacteria. Some of the "vesicular structures," or bubbles, in the Curiosity photos resembled those produced by microbes on earth after a rain, Retallack wrote in *Geology*. For her part, Noffke felt bruised by her experience with big-ticket science and the public fascination with extraterrestrial life. Her paper was merely a hypothesis, not a full-blown argument or claim, and the hostility of the Curiosity response took her aback. The Curiosity team did, however, shape a new itinerary for returning to the site of the methane burst, at exactly the same season as the first was detected. Perhaps it showed, more than anything else, how important the research was becoming to a popular base that included Twit er and Instagram followers like me.

For that reason, researchers and fans eagerly followed the European Space Agency probe Schiaparelli as it winged into orbit around Mars in the fall of 2016 and prepared for its test rover's descent. Monitored by its orbiting parent unit, the Schiaparelli test lander descended into the Meridiani Planum region on October 19, 2016. The parachute deployed twelve kilometers up, and the heat shield was released at 7.8 kilometers, as planned. Then a mistake happened with its inertial measurement, which ran one second too long as it became saturated with data and generated an estimated altitude that was below ground level. The one-second error triggered the second parachute to fire too soon, as did its braking thrusters, causing the dummy lander to crash hard and disintegrate. The debris could be seen from its orbiter and from NASA's Mars Explorer Rover.

The test was a bit er disappointment, but Schiapparelli's real rover landing was not scheduled until 2018. By then many will be looking beyond Mars, with its intense solar radiation and sterilizing soil. How would you recognize life on a solar system body if you saw it? What exactly would you look for, and how? There was no reason to suppose that either Earth or Mars was the only, or even the most ideal, model for life. Many thought that good places to look might include the moons of Jupiter. And Saturn.

Red rain

"But what exceeds all wonders, I have discovered four new planets and observed their proper and particular motions, different among themselves and from the motions of all the other stars; and these new planets move about another very large star, Jupiter," Galileo wrote to the Tuscan court in 1579, shortly before his treatise *Sidereus Nuncius* (Starry Messenger) gave the world his full report on a sun-centered system of the heavens. Galileo accurately mapped Jupiter's four moons and charted their orbital periods, size, and day lengths. Every amateur grade-school astronomer ever since, equipped with a good telescope and thirty nights of viewing, could do the same. The revolution that followed put humanity in a more accurate and humble relation to the universe.

To modern microbe hunters, those moons of Jupiter and Saturn held special allure. Two—Saturn's Enceladus and Jupiter's Europa—stood out from the rest, for different reasons. Enceladus had volcanoes, organics, water, ice, and showers of volatile hydrocarbons pouring down as red rain. Europa offered hints of a vast ocean.

It was not just any ocean, it was potentially liquid, heated by the squeezing of the moon by Jupiter's massive gravity, like a tennis ball, so much so that it cracked the thin ice of the surface. A tumultuous NASA mission, aptly named Galileo, launched in 1989. The vessel spun into the giant planet's orbit from 1996 to 2003 and soon began sending back amazing images of planet and its moons. What struck team scientists were the fissures in its waterlogged moon, Europa, showing that its ice was not so impermeable as they had thought. Rather, it was thin, and water may seethe underneath, presumably heated by a molten core, even though the surface temperatures range around 130 degrees below zero Fahrenheit.

Most likely Europa and Enceladus had volcanic magma heating their liquid water. They probably featured exactly the kind of hydrothermal vents that so excited Earth researchers as a source for Earth life. Then it was seen that Europa featured sulfate salts, much like the lakes in Antarctica. The significance was that life on either of those places would be proof of a second genesis, independent of the Mars-Earth axis.

Even more stunning, the Galileo probe seemed to show water gushing from Europa's surface into outer space. When arguments erupted on the Galileo team, a younger member decided to turn down the exposure on the black-and-white images. Suddenly water plumes could be distinctly seen shooting out from the ice, hundreds of miles into space. Subsequent Hubble images seemed to confirm the plumes. Europa's icy surface was riddled with undulating cracks and wriggling fissures. Beneath its frozen exterior distant, icy Europa appeared to feature a liquid ocean.

Then came Saturn's Enceladus, which had the same geysers as Europa, but also a torrential pouring of particulates that made the rock-and-roll musician Peter Gabriel's song "Red Rain" almost visible. Enceladus was so enticing as a target for life that, in the last months of 2015, NASA's Saturn Cassini team planned a daring maneuver with its dying probe. They drove Cassini through an Enceladus plume as it was ejecting into space and analyzed the content—the first time an alien ocean had ever been sampled. What they found was very similar to samples taken from Earth oceans: present were hydrogen, carbon dioxide, methane, and tiny silicate grains possibly produced at alkaline hydrothermal vents.

Add in Saturn's moon Titan, where Cassini uncovered chemical signatures suggesting conditions suitable to a primitive, exotic precursor to methane-based life. Hydrogen molecules flowed down through Titan's atmosphere and disappeared at the surface. A paper in the *Journal of Geophysical Research* mapped hydrocarbons on Titan's surface and found no acetylene. This absence was important because that chemical would likely be the best energy source for methane-based life, said Chris McKay, at NASA's Ames Research Center. One interpretation of the acetylene data is that the hydrocarbon is being consumed as food. But McKay said the flow of hydrogen was even more critical. "Hydrogen's the obvious gas for life to consume on Titan, similar to the way we consume oxygen on Earth," McKay said.

After the European Space Agency Roset a orbiter landed on the comet Churyumov-Gerasimenko, and after a nine-year-old NASA probe to Pluto showed it to be covered with water ice and erupting mountains, the solar system became a more interesting place. The Japanese space agency, JAXA, approached NASA about a joint mission to bring back a sample of water from Enceladus. Amazingly, the NASA probe discovered that an ocean of liquid water might lie beneath Pluto's frigid ice surface. Then came the discovery of seven Earthlike planets orbiting a nearby red dwarf star, which are three times more numerous in the universe than sunlike stars, and the search for signs of extraterrestrial life was reinvigorated.

Taken together, the islands of our own solar system were soggier, potentially warmer, and richer in minerals than expected. But what kind of life might they have? To answer that, a whole new system of interpretation was called for. It may come from one of the iciest lakes of the Antarctic.

Second genesis

It was unseasonably warm in the Lake Vida valley when they built their camp. The laconic Alison Murray was there with Peter Doran, who had made the same trip to the Antarctic many times before. They had eleven hours to get their camp up before the helicopter had to leave. The wind howled and the temperature plummeted in the harsh light of the vast, dry valley.

They planned to drive cores to the depths of Lake Vida, in the southernmost McMurdo Dry Valley, a frozen lake isolated under year-round ice cover, with water that was saltier than seawater. They had brought Lake Vida to the public's at ention a few years earlier when they discovered that a primitive form of cyanobacteria, frozen in its ice cover for more than 2,800 years, could be thawed and reanimated. Anything else that lived down there had been sealed off by ice for millennia. A nearby plain they found, by contrast, to be completely devoid of life—the only such region on Earth. The wind whipped up, and Murray tightened her gloves.

Raised in California, she had surprised herself out here in the frozen wasteland. First, she found it beautiful. Second, she loved the intense cold, light all day in summer, only shadowed for a couple hours at 3 A.M. by the mountains, and dark all day in winter. Here, "with life signals so weak we could barely detect them," she told me, she could truly understand microbes in an integrated system with chemistry, geology, and climatology, a strange icy world she came to know more intimately than her own. She had come back now to dig deeper.

They thought the briny lake might give clues to the types of microbes that could exist on Europa or Enceladus, or even Titan. Then they saw that the water contained perchlorate salts, made famous on Mars, in the heaviest concentrations seen on Earth. They drilled down deeper and deeper, to a depth of twenty-seven meters, and later radar analysis showed the brine could go as deep as fifty meters. It was strange that the surface was frozen solid but the depths were warm enough to support liquid water.

The team pitched their small, bright-orange sleeping tents in neat rows, set ing up a clean room on top of the hole, wearing the type of white suit used in germ labs to keep conditions sterile. When one microbe they discovered became of medical interest, Murray was contacted by an immunologist seeking promising compounds in its metabolism. Now they set to work. In this frozen time capsule for ancient DNA, they wanted no mistakes.

The first Antarctic season proved to be unseasonably warm, and meltwater was flooding down by the time they were half-finished at the lake; they raced back to the tents at full speed to move them to higher ground. The wind sheared their faces, and the core samples tugged down the sleds. They needed to finish as fast as possible.

For three weeks they sampled, storing the samples to go for further analysis to McMurdo and labs in North America and Australia. They were in contact with McKay in California. Murray had studied at the University of California and worked with one of the pioneering researchers of Archaea. McKay had grown up in Florida, learning physics by tearing around the dirt back roads on his motorcycle. The Viking images had changed his life. He thought hard about a second genesis of microbes on Enceladus. Life might not have RNA and protein and DNA. McKay also asked if life had to be water based. Oceans of hydrocarbons could be much more efficient energy producers than were water oceans. It was McKay who had advised that they bring a bet er drill than the one they had planned to use.

The microbe inhabitants of Lake Vida, Doran and Murray found, lived in total darkness in temperatures well below freezing, yet the lake teemed with unbelievable diversity, the more so the deeper you went. "Actually, the water temperatures rise the deeper you go," Murray told me, of the depths that shade a lit le closer to Earth's molten core. "The conditions are much like we think could be true of Enceladus or Europa." Then the warm temperatures created a dense fog that set led in. With only Murray and one team member left, the rescue helicopter they were desperately awaiting could not take off from McMurdo.

They were gradually running out of food. They sat and waited as the wind howled and traded stories until they were bored and bargained for chocolates.

At the end of his career Stanley Miller, escorted to conferences in a wheelchair, became convinced that life's building blocks might have been most effectively concentrated in ice. Early Earth might well have been quite cold in regions for long periods of the year, since the early sun generated some 30 percent less energy than it does today. Miller and his students took the same vials of chemicals he had worked with during his entire career. They had been frozen for years, yet, when thawed, the building blocks of nucleotides formed much more rapidly than at room temperature, owing to the molecular properties of water ice.

More intriguing, said McKay, the key to icy Enceladus, Titan, and Europa was that if life was there, it had to start there as a separate genesis from those of Mars and Earth. Some similar evidence had piled up from the forbidding Barberton Mountains in South Africa. It seemed as if life could indeed have started in ice. Deep inside the icy water, Murray extracted samples of genetic material and found a thriving world of life, moving very slowly, almost imperceptibly, but fashioning its miracle of RNA, proteins, and lipids from the energy sources of hydrogen, sulfur, nitrogen, iron, methane, and carbon.

Finally the helicopter landed and they raced to load. After numerous trips to the Antarctic, Murray was hired on to the new NASA team contemplating a Europa landing.

The potential revolution in these cold-world studies was that Earth's microbial life was much more diverse and opportunistic than we had imagined, and that life elsewhere could be more so. It seemed as though life could do anything. If that was true, then microbes could be engineered to make new energy, clean up the plastics choking our ocean, or perhaps deliver our medicine in such a way that pathogens could not resist. A vast effort in understanding and even making synthetic microbes was gaining steam. One place it took off was in the mountains north of Silicon Valley.

Something to talk about

Towering above San Francisco Bay, the Lawrence Berkeley National Laboratory was a hotbed of metabolic engineering as interest grew in symbiosis as a new paradigm for life. Metabolic engineering, predicted by the lab's director, Jay Keasling, could provide alternative medicines and fuels. Berkeley's John Coates studied microbial metabolism of industrial and military perchlorate to pioneer bet er waste treatment. Then it turned out some of that same perchlorate filled the soils of Mars.

Some of the research, said the University of California, Santa Barbara's Irene Chen and others, could increase interest in the work on phage therapy, a different model for controlling infection by using the age-old viral scourges of bacteria. "The problem of antibiotic resistance is becoming personal to me," said Chen—she was expecting her first child. In 2016 she won a $2.1 million National Institutes of Health New Innovator Award to sequence the phage viruses from a nearby medical facility. At her California campus she was excited to see that Jeffrey Bada, once a postdoc with Stanley Miller, had kept the famous, original origin-of-life Miller-Urey apparatus intact. "We marveled that it was still on," she recalled. "Jeff was boiling coffee in it!"

The Berkeley researchers led by Keasling discovered they could engineer the common yeast *Saccharomyces cerevisiae* to make high-energy, fat y acid–derived fuels they envisaged could be scaled up for industrial production. In American agriculture, the giants Bayer, DuPont, and Monsanto were investing a combined total of $1 billion in natural microbial pesticides called biologicals to increase yield and control pests.

One of the initial successes included a bacterium, discovered by researchers at the Kyoto Institute of Technology and Keio University, that could completely degrade plastics in the ocean. Previously only fungi were thought to be able to do so, but Shosuke Yoshida and his colleagues found a bacterium called *Ideonella sakaensis* that produced two plastic-degrading enzymes. The process was slow—it took up to six weeks to degrade a small film—but the team hoped to mass-produce the enzymes directly. Another team at University of California, Santa Barbara discovered that human anaerobic gut fungi that could degrade plant waste.

In 2016 the Venter Institute reported making the simplest living cell ever seen, with only 473 genes, nicknamed Synthia 3; still, they were unclear what one-third of its genes did. "We don't know a third of the basic knowledge of life," Venter told the *Atlantic*. They raced to uncover those functions, but in the meantime, the same technology "could be used to construct new cells with desired properties," commented the University of Valencia's Rosario Gil, "an unprecedented step."

One of the greatest of microbial inventions was photosynthesis, extracting fuel from sunlight and water—a feat very difficult to accomplish by any artificial means researchers raced to devise. By November 2016, however, a University of Illinois and Berkeley team led by Krishna Niyogi and Stephen Long had engineered 20 percent more efficient photosynthesis in tobacco plants by reducing a cooling mechanism of chloroplasts that protects them from harsh sun. "Making plants that yield more," a Munich-based molecular biologist told *Science*. "That is something that everyone should be happy about."

Business interest in symbiosis as a new paradigm in life science became more widespread. The number of companies selling targeted probiotics or synthetic microbes, such as Emefcy and Syngensis, was soaring. The number of researchers studying microbes in waste remediation was growing, as was investment. Microbes, it was seen, can survive in the stratosphere and in space. They might have survived in the pockets of comets, as Canadian researchers found. They might lie at the sites of asteroid impacts on Mars.

A prospect for bet er space probes was raised by the eminent physicist Freeman Dyson, commenting on the increase in privately funded cheap spaceships and space tourism. Future planetary probes could use the best new information technology at a fraction of the cost of NASA probes, Dyson wrote, and would be launched in quick succession, so that one failure need not set back the search for life for such a long time.

By 2016 a host of researchers had penned a global call for an international human biome effort, including Nicole Dubilier and Margaret McFall-Ngai. Noting that half of the world's oxygen is produced by microbes at sea, that we had a huge collection of their genes but only knew what half of them coded for, and that microbes did not observe national borders, they proposed combining the efforts in Japan, Europe, the United States, and Canada to create a global effort. "The revolution in understanding," they wrote, "must be seized."

As at ention increased, researchers turned to the recesses of the human body, to insect bodies, and to remote mountaintops and saline lakes, seeking more clues. What no one expected was that the discoveries on Mars and in the solar system would give new life to longtime research on life in similar environments on Earth. As the interest increased, so too did the controversies.

"I have writ en the wonders I have seen," concluded Galileo, shortly before he was placed under house arrest, "and of these discoveries more news will follow."