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IN THIS ISSUE

Commemorating 50 Years of Caltech and JPL's Partnership in Space Exploration

JPL's Cassini spacecraft delivered this stunning view of small, battered Epimetheus and smog-shrouded Titan, with Saturn's A and F rings stretching across the scene.

From the Editor:

Welcome to this special issue of *Engineering & Science* magazine, commemorating 50 years of a Caltech-JPL-NASA partnership exploring our home planet, the solar system, and the universe beyond. The Jet Propulsion Laboratory, an offshoot of Caltech's aeronautics department, is unique among NASA centers in being managed by a university—and a private one at that. JPL is a part of Caltech, just like the Division of Physics, Mathematics and Astronomy or the Division of the Humanities and Social Sciences, albeit—with some 5,700 employees —rather larger.

Caltech faculty, staff, and alumni have played and are playing critical roles in many JPL missions; a few of their stories are told in these pages. Many more of them have been chronicled in *Engineering & Science* over the years; a complete list is clearly impractical, but you'd be hard pressed to find an issue from the last couple of decades that doesn't have at least one JPL story in it. From short updates on the Mars rovers or the latest find from Cassini, to in-depth features on spacecraft navigation or global monitoring of climate change and profiles of specific missions, we have been proud to participate in this grand adventure in space by bringing you, our readers, along for the ride.

—Douglas L. Smith

ENGINEERING AND SCIENCE

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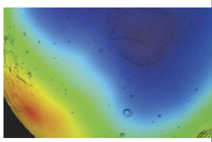

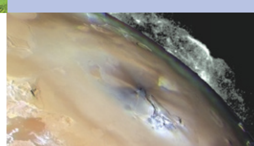

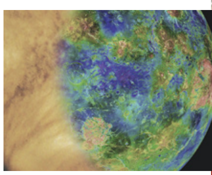

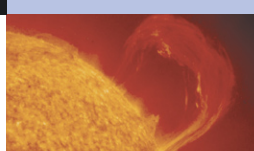

On the cover: On January 31, 1958, the U.S. launched Explorer I as an answer to the Soviet Union's Sputnik. At 2:00 a.m. the next morning, William Pickering (left), James Van Allen, and Wernher von Braun showed off a model of Explorer I at the press conference announcing their triumph. Built by JPL, the satellite catapulted the U.S. into the space age.

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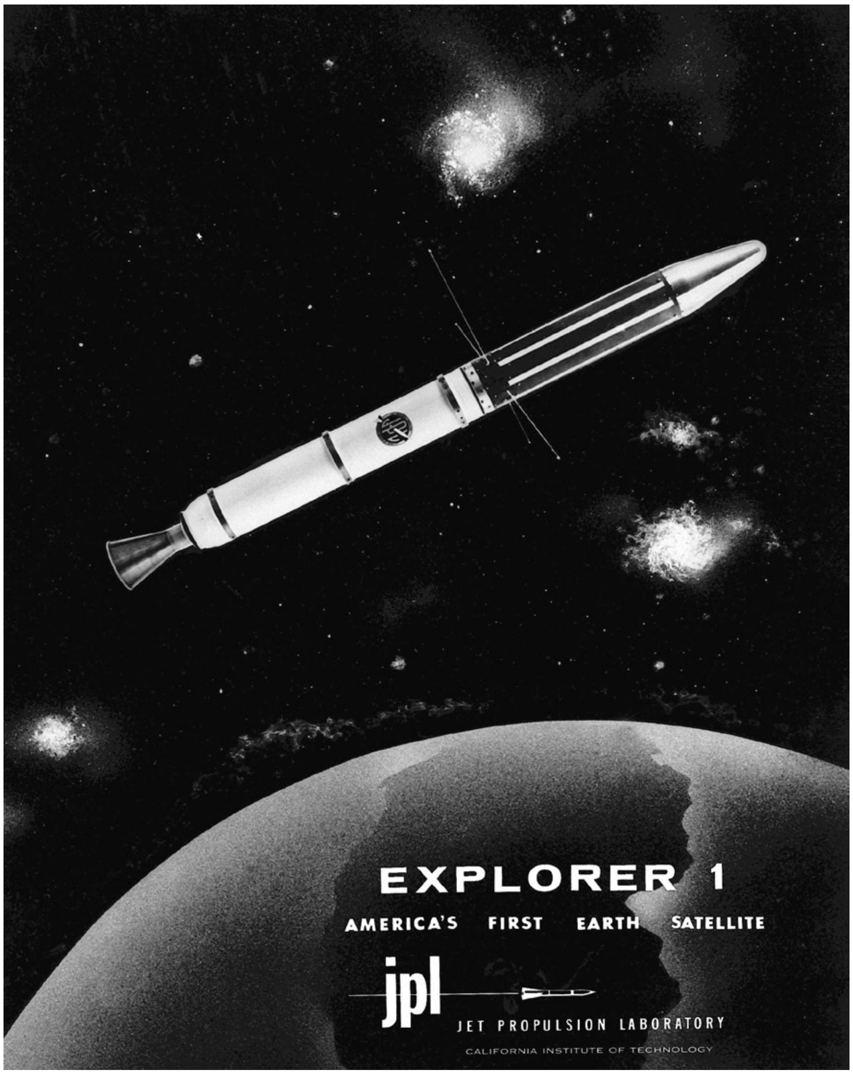
From Rockets to Spacecraft:

Making JPL a Place for Planetary Science

by Erik M. Conway



The cover of a brochure JPL created in 1958 to explain the Explorer mission to the American public.

Since the dawn of the space age, JPL spacecraft have visited the sun, the moon, and all eight planets, and some are even headed out of the solar system entirely. The agency that sent the Voyagers, Galileo, and Cassini to the outer planets, landed rovers on Mars, mapped Venus's cloud-shrouded surface, and paved the way for Neil Armstrong's "one small step" on the moon began as a military rocket research facility run by a pacifist who just wanted to explore the upper atmosphere. Caltech's Jet Propulsion Laboratory unofficially started life when Frank Malina [MS ME '35, MS AE '36, PhD '40], a graduate student of Professor of Aeronautics Theodore von Kármán, and some friends test fired a rocket engine in a dry wash in 1936. JPL has been out of the rocket business since 1958, a victim of its own success at developing the United States' first satellite—Explorer 1, launched in response to Sputnik, which in October 1957 staked the Soviet Union's claim to low Earth orbit. Following in the heels of the launch of the world's first intercontinental ballistic missile—a Russian one—in August 1957 and, passing overhead every 96 minutes, Sputnik reminded a jittery America that nuclear warheads could be put up there just as easily. This is the story of JPL's journey from weapons lab to planetary explorer.

Malina, von Kármán, and American Rocketry

Malina, the son of Czech immigrants, graduated from Texas A&M in 1934 and came west to the Guggenheim Aeronautical Laboratory at Caltech (GALCIT), in hopes of developing rockets capable of much higher speeds than piston-engined aircraft could achieve. He was encouraged by von Kármán, GALCIT's director, who gave him work at the drafting table in support of some of von Kármán's own research, and eventually got him a position in the GALCIT wind tunnel. In 1936 Malina paid a visit to rocket pioneer Robert Goddard's test agreed to build an instrumented, alcohol-burning test motor. Most of their rig was scrounged from junkyards, as Caltech was not funding this "spare time" project. They soon attracted Bollay and two other grad students, Apollo M. O. ("Amo") Smith [BS '36, MS ME '37, MS AE '38] and Hsue-Shen Tsien [PhD '39], who helped Malina with the theoretical work and sometimes with the test rig; and meteorology graduate student Milton W. "Weld" Arnold [MS '37], who unexpectedly provided the huge sum of $1,000—in small bills. Arnold never told the team where the money came from, and they didn't press him on the subject.

Below, left to right: Rudolph Schott, Apollo Milton Olin Smith, Frank Malina, Ed Forman, and Jack Parsons (right, foreground) take a break between rocket-engine tests on November 15, 1936.

Right: Another test firing on the 28th.

The first day of testing was Halloween 1936. Caltech had not welcomed potential fires and explosions on its campus, so Forman suggested a spot in the Arroyo Seco on the outskirts of Pasadena above Devil's Gate Dam, part of the regional flood-control system—a suitably remote area that was still easily accessible from campus. Even so, it took hours to ferry equipment up the Arroyo. On the first three tests, the powder fuse the group was using to light the motor blew out. No ignition. The fourth time, they taped the fuse into place, and the motor ignited . . . as did the oxygen line. "The oxygen hose for some reason ignited and swung around on the ground, 40 feet from us. We all tore out across the country wondering if our check valves would work," Malina would later write home. The valves did their jobs—there was no explosion, nobody injured, and little equipment was damaged, thanks to a sandbag wall. No data was collected from the thrust gauge, but they did learn that the powder-fuse idea was a bad one. Forman modified the motor to accommodate a spark-plug igniter instead, and the team lugged their gear back to the Arroyo on November 15 for four more attempts. The new electric starter worked reliably, and Malina got his first thrust data. More tests on November 28 and January 16 provided enough data to satisfy Malina, and the January tests were the last ones in the Arroyo for a while.

The tests pleased von Kármán enough to give them space on the third floor of Guggenheim, the building that also housed GALCIT's pride and joy—a 10-foot-diameter wind tunnel, the largest in the world. But a rocket-fuel leak that instantly rusted all the metal surfaces in the building, including the wind tunnel's delicate torsion gauges, evicted them. A few months later, the thrust balance they had installed on Guggenheim's outside wall exploded, damaging the building. This did not enhance their standing. They kept working on campus, however, until May 1938. By that time, the demands of "real life" had drawn them away from the rocket work, as several of the experimenters had taken on outside jobs in order to feed themselves.

The future JPL could have fizzled there, but the rocketeers were rescued in January 1939 by a $1,000 grant from the National Academy of Sciences. Henry "Hap" Arnold, chief of the Army Air

facility in Roswell, New Mexico, to seek a collaboration, but found Goddard uncooperative.

Rocketry was in the air, as it were, and a public lecture on recent German rocket-plane work by grad student William Bollay [MS '34, PhD '36] drew Pasadena residents John W. Parsons and Edward Forman, who were doing rocketry experiments of their own. Parsons was a self-taught explosives expert, while Forman was mechanically skilled. Bollay referred them to Malina, and the threesome formed the core of what would become known around Caltech as the Suicide Squad.

Theirs was not an easy relationship. Parsons and Forman just wanted to fire rockets into the sky, while von Kármán insisted, and Malina agreed, that collecting performance data and developing a theoretical understanding of how rocket engines worked was paramount. Eventually the group

Right: The GALCIT rocket group makes final plans for the first jet-assisted takeoff test flight. From left: Clark Millikan, Martin Summerfield (MS '37, PhD '41), Theodore von Kármán, Frank Malina, and pilot Homer Boushey. Far right: Shortly thereafter, the Ercoupe was flung skyward by 28 pounds of solid-fuel-fired thrust.

Photo courtesy of the Caltech Archives.

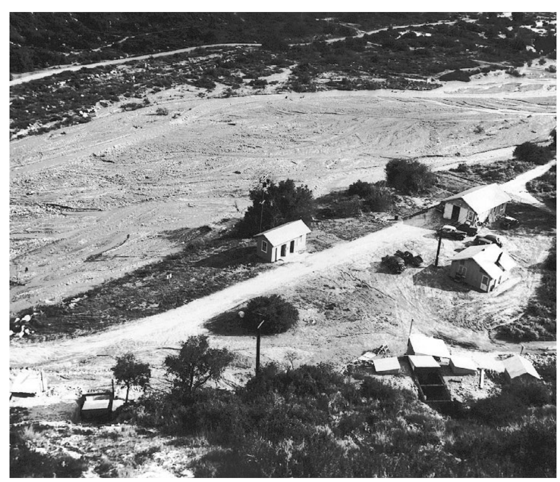
Corps, had visited GALCIT in spring 1938 and was intrigued enough to ask the academy's Committee on Air Corps Research to fund a project to develop rockets to help aircraft take off on short runways. The committee—whose members included both von Kármán and Caltech's de facto president, Robert A. Millikan—agreed. Malina reassembled his little group and they started working, in the Arroyo, on what would become known as Jet-Assisted Takeoff (JATO) rockets. In July, they were given another $10,000. After this, they were officially known as GALCIT Project Number One.

Arnold had financed the JATO work in the belief that the United States would soon be at war. Malina and von Kármán, a Hungarian immigrant, thought so too. They had both supported the Soviet Union's lonely effort to oppose Germany's proxy forces in the Spanish Civil War. In fact, Malina joined a Communist discussion group in 1937, although the magnitude of his involvement has never been clear. He denied ever having been a Communist party member, and the group dissolved after the shocking announcement of the Soviet Union's nonaggression pact with Germany in 1939. Malina was otherwise a pacifist, willing to work on rockets for the Army only because of their value in opposing Fascism.

The JATO tests eventually moved to March Field, near Riverside, California. After a series of firings with the airplane chained down, on August 12, 1941, Army lieutenant Homer Boushey made the first JATO flight in an Ercoupe—a fighter-sized civilian aircraft. The rockets cut the plane's takeoff distance in half. Impressed, the Army gave GALCIT more money to make larger JATOs, and in April 1942, those rockets muscled a 20,000-pound Douglas A-20 bomber into the sky. In those days, Caltech had no prohibition on faculty members running outside businesses, so von Kármán and Malina set up a company named Aerojet—now a major space and defense contractor—to manufacture them. This allowed Malina and Tsien to continue research, while Aerojet dealt with the challenges of large-scale production. Parsons and Forman went to Aerojet, while the rest of the original team left the rocket business entirely.

GALCIT Project Number One officially became the Jet Propulsion Laboratory in June 1944. It remained a Caltech organization, although not yet a full division of the Institute, with von Kármán as the chair of its executive board. With numerous Army research projects to work on, JPL grew rapidly. At the same time, the city of Pasadena was expanding northward, producing the odd sight of a large industrial facility adjoining a tony residential zone.

Malina drew on Caltech faculty as well as hiring from the outside. Aeronautics and meteorology



In February 1942, there were only a few small buildings and some rocket-motor test pits at JPL's present site in the Arroyo Seco.

professor Homer J. Stewart [PhD '40] headed the Lab's research and analysis branch, and electrical engineering professor William Pickering [BS '32, MS '33, PhD '36] set up the guidance and controls section. Aeronautics also contributed professor Louis Dunn, who became Malina's assistant director. Most of the work concentrated on improving the performance of solid- and liquid-fueled rocket engines—studies of combustion thermodynamics, means for cooling rocket engines, and ways to control solid-rocket burn rates. The Lab also developed three series of complete rockets, as opposed to rocket *engines*—a critical turn on JPL's path to the planets.

Fittingly for an Army contract, the Lab's first complete rocket was called the Private. It stood eight feet tall, had a range of about 10 miles, and was unguided except for its tail fins. In one of the Lab's earliest failures, Malina and Tsien thought they could double its range by enlarging some of the fins into wings. There they rediscovered what

The next three all failed, with the third being the most spectacular. Dubbed the "rabbit killer," it lifted far enough to clear the launch tower, tipped over, and scooted along the ground for a few hundred yards before exploding.

the Wright brothers had realized in 1902: winged flight is fundamentally a control problem, not a lift problem. The winged Privates all corkscrewed out of control after launch, crashing far short of the finned Privates' mark. But calling this a failure may be too strong, as it showed that the Lab would need to emphasize guidance and control technologies—another prerequisite for spaceflight—if the range of its rockets was to improve.

Next came the Corporal, JPL's first guided missile. The Lab started by developing a shorter-range rocket to test the Corporal's liquid-fueled engine, which ran on aniline and red fuming nitric acid. This unguided version was named the WAC Corporal, for "Without Attitude Control." The WAC Corporal debuted on October 11, 1945, at the Army's new test range in White Sands, New Mexico. It set an altitude record of 230,000 feet—more than twice what stratospheric balloons could reach. The first guided Corporal, the Corporal E, flew successfully in May 1947—a fluke, as it turned out. The next three all failed, with the third being the most spectacular. Dubbed the "rabbit killer," it lifted far enough to clear the launch tower, tipped over, and scooted along the ground for a few hundred yards before exploding. It took JPL a year and a half to fix Corporal's problems.

By then, Malina was gone. His late-'30s flirtation with Communism had started to haunt him by early 1946, when the FBI raided his house while he was away at a conference. The FBI had no evidence that he had remained active after 1939, but that meant little during the "Red Scare." Malina was also increasingly unhappy with weapons work. He knew that his rockets would shortly be married to atomic bombs, and he hated the idea. He had proposed offering the WAC Corporal to the larger scientific community, but in 1945 and again in 1946 Caltech's board of trustees turned him down. (In a vindication for Malina, Aerojet eventually adapted the WAC Corporal into the Aerobee sounding rocket—ironically, with Navy money. Aerobees were widely used for upper-atmosphere and cosmic-ray research until the mid-'60s.) So in July 1947, after receiving a job offer from biologist Julian Huxley, director of UNESCO, Malina moved to Paris and left rocketry forever.

Louis Dunn, a transplanted Afrikaner, succeeded Malina. After a series of successful Corporal flights in late 1949 and early 1950, the Army asked that the Corporal be turned into a deployable nuclear-weapon system. In May 1952, the Army ordered 200 missiles and requested a production rate of 20 missiles per month; this didn't come close to happening. There were reliability problems with the electronics, but the Corporal posed other problems as a field weapon. Because the nitric-acid fuel was so corrosive, it had to be carried in tanker trucks until launch. And then there was the radar and command gear. Each missile was supported by eight trucks, so each of the nine Corporal battalions deployed to Europe stretched for miles on the road, and required many hours to set up and fire.

This drawback triggered a return to solid-fuel rockets, which had been plagued by safety issues. A solid propellant core burns from its central axis outward, with the burning surface expanding as it does. More burning propellant equals more pressure, and explosions were commonplace. But in 1948, three JPL engineers found that a star-shaped central cutout allowed even a very large core to burn at a constant pressure. This technology became the basis for JPL's last Army missile, the Sergeant, authorized in 1954, and for all the

A Corporal missile on its launch truck.

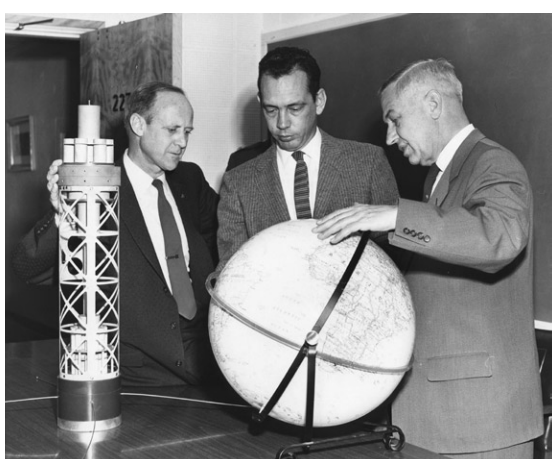
large solid-fuel rockets developed in the 1960s and 1970s: the submarine-launched Polaris and Poseidon ballistic missiles, and the solid-rocket boosters that have been strapped onto liquid-fueled rockets ever since.

Baby Steps Toward Space

The Sergeant contract came to JPL a few months before the ascent of its third director—William Pickering, previously head of the guidance and controls section. As a grad student under physicist Robert A. Millikan, Pickering had studied cosmic rays, flying sensitive instruments on high-altitude balloons. The data were sent back by telemetry, so Pickering worked at the cutting edge of instrument technology as well as science. He had a long-standing interest in adding the latter to JPL's activities, having joined Malina in the effort to get the WAC Corporal opened up for scientific research in 1946. (Dunn, by contrast, was perfectly happy making weapons—in fact, he resigned JPL's directorship to head the Ramo-Wooldridge Corporation's Atlas missile program.)

The time was ripe for a fundamental shift in JPL's mission. Neither Caltech president Lee DuBridge nor Pickering was content with JPL's Army role. Classified weapons development did not sit well with the Caltech faculty, because secrecy prevented any significant interaction between campus and JPL, and development was not *research*. JPL was not making fundamental discoveries, but was merely solving utilitarian problems. Pickering and DuBridge wanted JPL out of the weapons business.

Pickering was a member of an informal group known as the Upper Atmosphere Rocket Research Panel. Chaired by James Van Allen, a cosmic-ray specialist and head of the University of Iowa's physics department, and originally called the V-2 Upper Atmosphere Panel, this group selected and developed scientific instruments that flew on German V-2 rockets captured at the end of World War II.



From left: JPL director William Pickering, Explorer project manager Jack Froehlich (BS '47, MS '48, PhD '50), and Caltech president Lee DuBridge in February 1958. Pickering holds a mock-up of Explorer's instrument package.

When the V-2s ran out in early 1948, they changed their name and switched to several newly developed rockets, including Aerojet's Aerobee. The Army, meanwhile, had settled Wernher von Braun and his ex-Nazi rocketeers on the grounds of the Redstone Arsenal in Huntsville, Alabama, to create the Army Ballistic Missile Agency (ABMA).

The world's first successful two-stage rocket, the Bumper WAC, perched a WAC Corporal on a V-2. (The V-2 gave the Corporal a "bump" to higher altitudes.) This one was Cape Canaveral's inaugural launch on July 24, 1950.

In 1954, the rocket research panel got a scientific Earth-orbiting satellite project added to the program of the upcoming International Geophysical Year (IGY) of 1957–58. A worldwide program of coordinated experiments by scientists on both sides of the Iron Curtain, the IGY was intended to vastly increase our knowledge of our planet while showcasing the virtues of cooperation over confrontation. A committee chaired by Homer Stewart was given the responsibility of choosing IGY's satellite. ABMA and JPL proposed a five-pound uninstrumented sphere, to be tracked by radar, called Project Orbiter. The Naval Research Laboratory and the Glenn L. Martin Corporation proposed using the former's sounding rocket, the Viking, to launch a 25-pound package capable of carrying several small instruments and a transmitter. This was called Project Vanguard. In August 1955, the committee recommended that Project Vanguard be approved, because it offered a greater scientific return.

Stewart and one other member disagreed vehemently. "I remember staying up 'til three o'clock in the morning at home writing the most purple prose that I have probably ever written, trying to write the minority report as to why I thought that was the wrong way to go," Stewart remembered much later. He thought the Navy's proposal, which required a substantial scaling-up of Viking's first and second stages and the development of a new third stage, would need more work than there was time for, while the Army's Redstone launcher was much further along.

Having lost their bid for orbit, JPL and ABMA teamed up on a highly classified effort known as the Reentry Test Vehicle (RTV) program, part of the development of an intermediate-range ballistic missile named Jupiter. The Jupiter warhead would reach space and reenter Earth's atmosphere, which meant it would experience enormous temperatures. The Germans were aware of this hazard—during the war, some V-2s had vanished midflight en route to London, and von Braun's team eventually discovered that they were exploding from reentry heat. ABMA needed to demonstrate that it could prevent the Jupiter from experiencing this little problem, and the RTV program was designed to prove that an ablative heat shield—a fiberglass-based material in this case—would provide sufficient protection by simply burning away, carrying much of the heat with it.

ABMA provided the liquid-fueled booster, while JPL provided the solid-fueled upper stages and the guidance and control system. JPL also developed a tracking system, called Microlock, which enabled reception of milliwatt-strength signals from thousands of miles away. ABMA had decided to use transistors—brand new technology—for the RTV's transmitter, and they operated at extremely low power levels. Even so, Microlock allowed the missile to be tracked through its entire flight—vital because ABMA intended to retrieve the warhead from the ocean and inspect the heat shield. Not getting the warhead back amounted to a failed test. (This technology, of course, would also prove vital for communicating with far-flung spacecraft.)

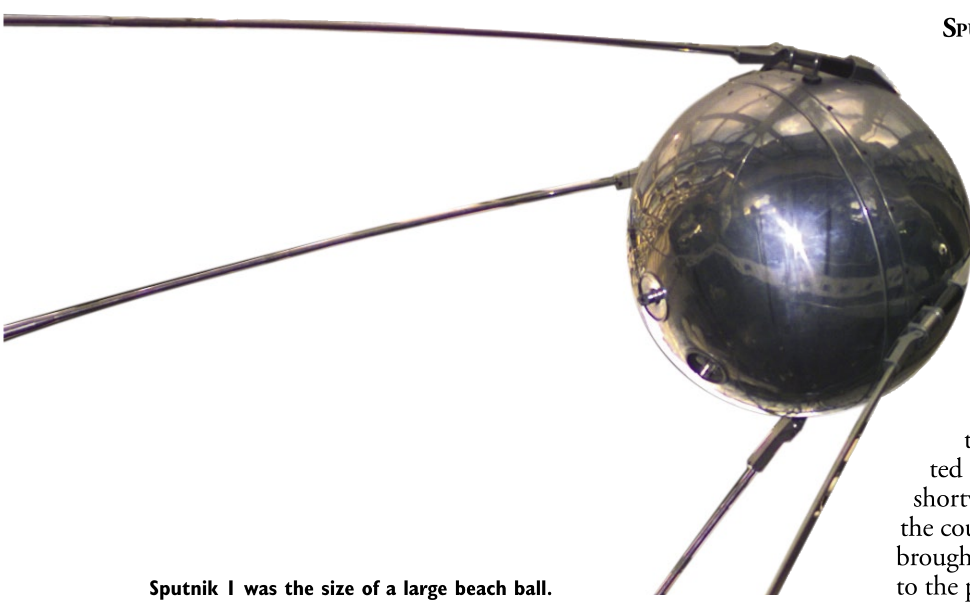
RTV flew three times. The first flight used Project Orbiter's configuration, complete with a dummy payload that ABMA's commander, General John Medaris, had filled with sand—on orders from his superiors—to give it enough extra weight to ensure that it didn't "accidentally" go into orbit. Flown as Missile 27 on September 20, 1956, this shot demonstrated the launch vehicle, tracking, and communications systems. Surviving correspondence suggests, but does not prove, that JPL and ABMA hoped this would overturn the decision to let the Navy's Vanguard go first. If so, it didn't work. Missile 27's backup, Missile 29, was put into storage.

Corporal missiles being assembled at JPL. This building was later used to build the Mariner and Ranger series of spacecraft.

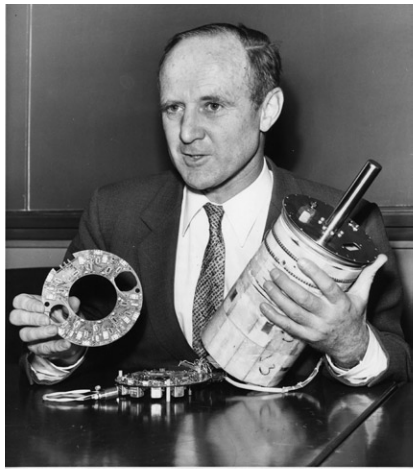
Missile 34, which had a dummy Jupiter warhead with a heat shield, was launched in May 1957. Its guidance system failed, but the warhead was tracked to splashdown. The warhead was never found, however, probably because the floats failed. But the next flight, Missile 40, was a complete success that September. The rescue ship *USS Escape* retrieved the warhead, which showed little damage—although one of the float bags had shark bites in it, leading to jokes that the previous attempt had been eaten. Medaris ended the program, and the remaining sets of RTV hardware joined Missile 29 in storage.

Sputnik Changes Everything

Pickering was at a reception at the Soviet embassy in Washington on the evening of October 4, when the news broke that the Russians had beaten Project Vanguard into orbit. Using a modified ICBM, the USSR had orbited an 84-kilogram sphere named Sputnik. Pickering made his way to the IGY offices nearby, and with some other JPL folks tried to calculate when it would fly overhead. He remembered later that "the Soviets were clever because they put a transmitter on there that transmitted on 20 megahertz. That was a frequency any shortwave receiver could pick up. People all over the country could listen to this thing. . . . It was brought home to everybody in the country." More to the point, Sputnik demonstrated that the Soviets



Sputnik 1 was the size of a large beach ball.



Pickering poses with a copy of Explorer's cosmic-ray detector and some of its circuit boards in December 1957.

were now capable of dropping nuclear warheads on the United States almost without warning. Fears of a "nuclear Pearl Harbor" were rampant among the American public, and the Dow plunged 10 percent in the next three weeks.

The night of Sputnik's launch, von Braun and Medaris happened to be in a meeting with Secretary of Defense Neil McElroy down in Huntsville. "Vanguard will never make it!" von Braun said. "For God's sake, turn us loose and let us do something! We can put up a satellite in sixty days, Mr. McElroy." But McElroy, mindful that the White House wanted the science-oriented Vanguard to fly first, returned to Washington unmoved. But a few weeks later, President Eisenhower did approve Medaris' recommendation to pull Missile 29, the Project Orbiter–configured backup RTV, out of storage . . . just in case. After the November 8 launch of Sputnik 2—which carried a dog, Laika, on a one-way trip into space, raising the stakes enormously in the game of international prestige—the White House also approved construction of a payload for Missile 29. But who would build it?

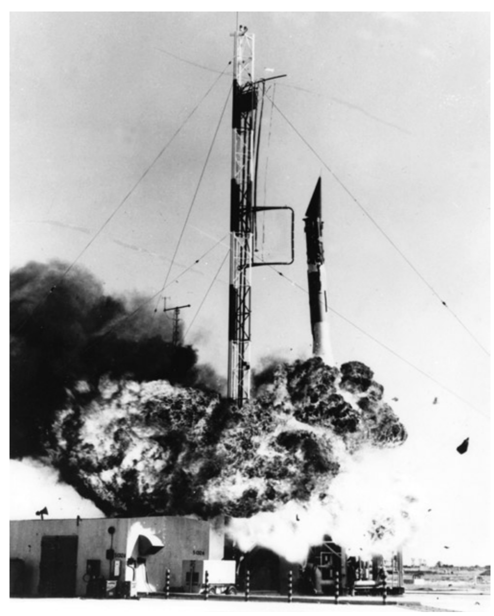
Wernher von Braun, space enthusiast that he was, wanted the job. But in a private meeting with Medaris, Pickering argued that JPL should "be responsible for the upper stages, the satellite itself, and the tracking of the satellite." When Medaris agreed, "the project was set up that way, so that the ABMA was responsible for . . . the Redstone rocket. And we built the rest of the system. At first, I think the group at ABMA were rather unhappy that they didn't have the entire responsibility but in point of fact, it worked out very well."

Initially, the effort was called Project Deal, a name derived from the all-night poker games that JPLers often played on the train down to the White Sands testing grounds. Project manager Jack Froehlich [BS '47, MS '48, PhD '50] reflected "when a big pot is won, the winner sits around and cracks bad jokes and the loser cries, 'Deal!'" Pickering asked his old friend Van Allen for a cosmic-ray detector to use as a science payload. Van Allen was down in Antarctica for the IGY, so he dispatched a grad student, George Ludwig, to JPL to build what was basically a Geiger counter. The payload would be a whopping 20 pounds.

Despite von Braun's boast, JPL and von Braun's group gave themselves 90 days to pull the launch vehicle out of storage, recondition and assemble it, and build the final stage, the satellite, the other instruments, and the radios. They also had to build a ground station at Pasadena and a more elaborate antenna array, capable of triangulating the spacecraft's exact position by interferometry, at Earthquake Valley, in the desert inland of San Diego. (The British IGY team agreed to build copies of JPL's Microlock tracking station and put them in Nigeria and Singapore, so that data could be captured from other parts of the prospective orbit.) In reality, the schedule meant that construction had to take less than 90 days, to allow for extensive testing. Nobody wanted to put up the first American satellite and then never hear from it again! As things turned out, the job was finished in only 84 days of frenzied, round-the-clock effort.

Meanwhile, the Navy's Vanguard launched on December 6. The rocket got about four feet off the pad, lost thrust, fell backwards, and exploded—all on live TV. The satellite fell free of the burning wreckage, transmitter still beeping. It now hangs in the National Air and Space Museum in Washington, D.C. Flopnik, as it was instantly dubbed in the press, was the Army and JPL's golden opportunity.

Eisenhower approved an end-of-January launch for Project Deal, now renamed Explorer. The upper stages and satellite were moved from Pasa-



Vanguard erupted in flames on the launch pad on December 6, 1957.

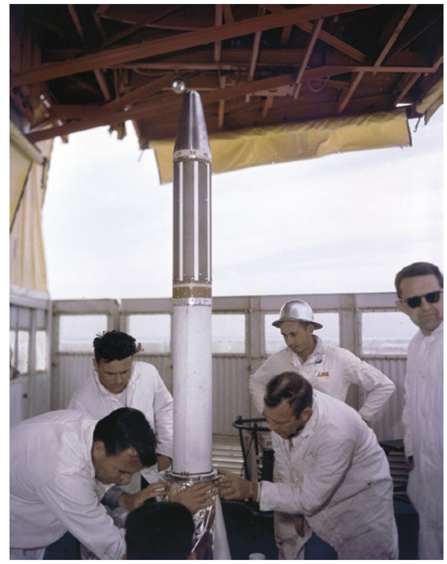
dena to Cape Canaveral in mid-January under very tight secrecy restrictions. Assembly was completed on January 29, and then bad weather intervened. In the late evening of January 31, problematic high winds abated and Medaris gave the go-ahead.

This is how the Associated Press reported it: "The Army's Jupiter-C missile blasted off Friday night, carrying a satellite into space. Army officials said it would not be known for about two hours whether the missile had succeeded in propelling the first American 'moon' into orbit around the Earth."

Explorer caused some nervous moments when it did not show up at JPL's California tracking station on time. JPLer Al Hibbs [BS '45, PhD '55], at the Cape and using data from the tracking station on the Caribbean island of Antigua, was certain that it had gone into orbit and had already told Medaris so (see *E&S* Number 2, 2003); Pickering, in Washington, wanted to hear from California before announcing it to the public. Explorer finally showed up eight minutes late—it had gotten extra velocity from winds in the upper atmosphere, and was in a higher orbit. JPL radio engineer Henry Richter, in charge of Explorer's electronics, recalls that the first detection was actually made by the San Gabriel Valley Amateur Radio Club. (The station at JPL itself turned out to be blinded by high-voltage power lines running through the mountains right behind the lab.) The Earthquake Valley station picked up the signal moments later.

At 2:00 a.m. on February 1, Pickering, von Braun, and Van Allen hoisted a model of Explorer's third stage and payload above their heads at a press conference at the National Academy of Sciences in Washington for a photo that ran under the next day's headlines in newspapers around the world. The Sputnik challenge had been answered.

Explorer 1's Geiger counter would fall silent for a few minutes each orbit. Since the instrument was sending data back to Earth in real time, some losses were to be expected, but Van Allen eventually realized that the detector was overloading, not failing. Explorer 3, launched March 26, carried a tape recorder to capture a full orbit of data, and



Explorer 1 being mated to the Jupiter-C rocket.

Van Allen determined that Earth was surrounded by belts of very high energy radiation. (Explorer 2, launched March 5, did not reach orbit when the fourth stage of its Jupiter-C rocket failed to ignite.) The Van Allen belts, as they are now known, are formed by charged particles trapped in Earth's magnetic field, and were the first scientific discovery of the new space age.

Pickering, Van Allen, and von Braun triumphantly display a model of Explorer at the press conference in Washington, D.C.

Making NASA

Eisenhower now had to decide who would control the nation's space capabilities. The Army had won, but it made little sense for them to own this technology. Eisenhower, a five-star general, could see that the Air Force, the CIA, and even the Navy had better claims to military uses of space. He also had to consider the public impact—a military program would be classified, unlikely to produce the public spectacles that the Cold War competition for "hearts and minds" seemed to require.

There were strong advocates for a civilian space agency. Scientists wanted an open, unclassified program. And then there was the old National Advisory Committee for Aeronautics (NACA), whose four research centers—Langley, Ames, Lewis (now the Glenn Research Center), and the High-Speed Flight Station (now the Dryden Flight Research Center)—had been the foundation of American aeronautical superiority. NACA's leadership, however, was deeply divided. Many of Langley's personnel thought very little of space, for example, seeing little work for an aerodynamicist to do up there. At a December 18, 1957, meeting now known as the "Young Turks" dinner, an open

In a ceremony on October 1, 1958, President Eisenhower commissions T. Keith Glennan (right) as NASA's first administrator and Hugh L. Dryden as deputy administrator.

The official seal of NASA's predecessor, the National Advisory Committee for Aeronautics (NACA), established in March 1915, depicts the Wright brothers' first flight.

fight broke out over the agency's direction. The space advocates were eventually shouted down, but the agency brass got the message and decided to promote NACA's conversion into a new, civilian space agency.

And so NACA became NASA, the National Aeronautics and Space Administration. But the National Aeronautics and Space Act of 1958, signed into law on July 29, did not change the status of JPL or the ABMA. They remained Army facilities. Pickering wanted JPL moved into NASA, as did NASA administrator T. Keith Glennan, who also coveted ABMA. But even though Pickering promised to finish up the Sergeant contract, the Army was not keen, for obvious reasons: losing ABMA and JPL meant losing the next military, and technological, frontier to the Air Force. Glennan prevailed, and JPL was formally transferred to NASA on December 3. ABMA would stay in the Army until July 1, 1960, when it became the Marshall Space Flight Center.

Claiming the Planets

It was not clear what the Lab's role would be in this brand-new agency. Should JPL try to take the lead in manned space flight, stick to satellites, or pursue the planets? At a brainstorming session, Pickering and his senior staff concluded that JPL should not stick to Earth-orbiting satellites, despite having just launched America's first one. Al Hibbs would later recall, "Finally, it was decided we will go after the moon and planets. . . . We'll get out of the satellite business, because we could see there were going to be communications satellites, there were going to be observations satellites, there were going to be military satellites . . . and the aerospace companies were going to be in this. It wasn't just going to be us any more." But JPL could go to the planets uncontested. NASA had no planetary plans at all, as reaching Venus and Mars was thought by headquarters to be far too audacious for the new technology's capabilities.

That's precisely what attracted JPL—the planets would be hard technologically, but hugely rewarding scientifically. Pickering recalled, "I think the principal thing as far as Caltech was concerned was the opportunity to move out of the field of classified military research into a field of space science which would have a much broader attraction to the faculty as a whole." And the rest, as they say, is history. □

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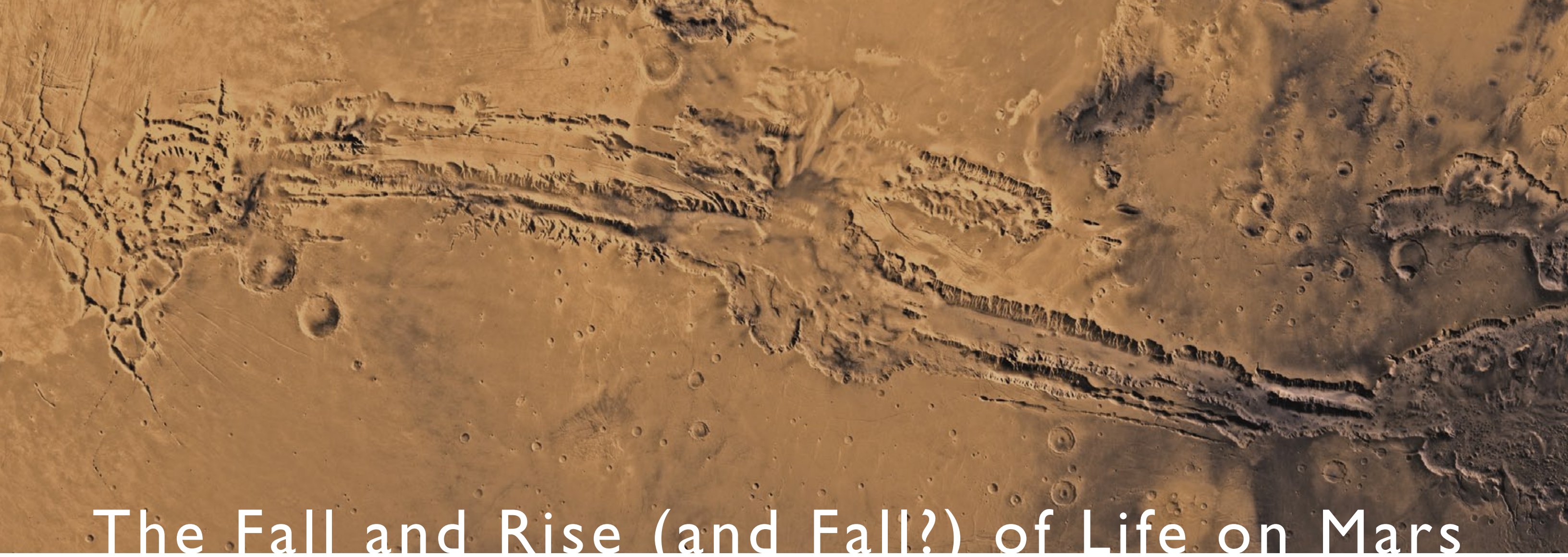


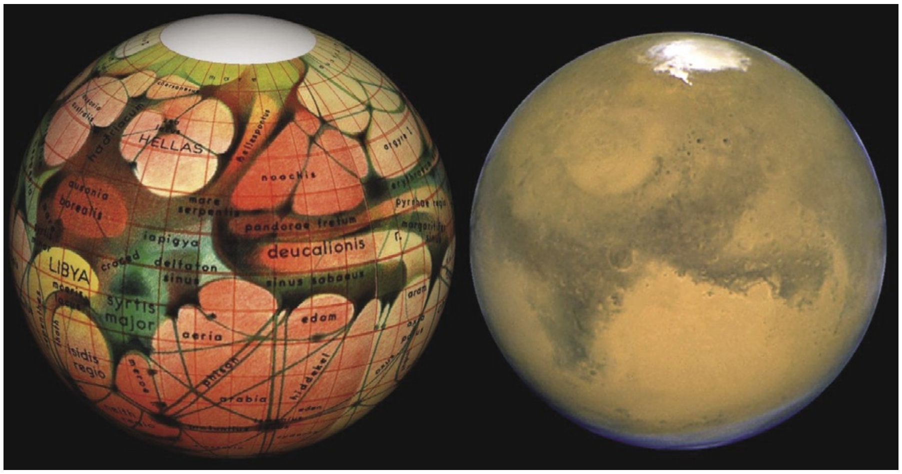
The Fall and Rise (and Fall?) of Life on Mars

by Douglas L. Smith

Top: A color composite of Valles Marineris, the "Grand Canyon of Mars," as seen by the Viking Orbiters. Above: On May 19, 2005, one of JPL's current Mars explorers, the Spirit rover, captured this stunning view as the sun sank below the rim of Gusev crater.

Is there life on Mars? If there is, it has so far eluded our best efforts to find it, but the quest for it has informed our missions to Mars since the early days of spaceflight. Meanwhile, our conception of that life has changed as our understanding of the planet has evolved—from little green men, to little green cells, to perhaps something unlike anything on Earth. The late professor of biology Norman Horowitz (PhD '39), who had been a consultant to NASA since 1960, recalled in his oral history, "Everything that was known about Mars at the time later turned out to be wrong, but everything suggested that there was a good possibility of life on Mars. At least it was plausible."

What was known before the space age had been deduced by squinting at Mars through telescopes. The Martian day is 37 minutes longer than ours, and the planet has a season-inducing tilt of 24 degrees, almost identical to Earth's. Mars has white polar caps, presumably made of water ice, that wax and wane with those seasons. Mars has weather, in the form of globe-girdling dust storms. Astronomers began mapping the planet in detail in the mid-1800s. Giovanni Schiaparelli, in particular, recorded arrow-straight, whisker-thin linear features that ran for hundreds of miles. He called them "channels" (*canali* in Italian) and there was much speculation that they might be artifacts of intelligent life. The notion of a planet-wide network of canals—the last gasp, or perhaps gulp, of an advanced civilization slowly dying of thirst—had met considerable scientific skepticism as early as the 1910s, but Martians remained alive and well, as the widespread panic sparked by Orson



http://antwrp.gsfc.nasa.gov

The map on the left was originally prepared by Eugene Antoniadi (1870–1944), and was redrawn by Lowell Hess for the 1956 book *Exploring Mars*, by Roy A. Gallant. (Image courtesy of Lowell Hess.) The Hubble Space Telescope image at right gives the same view. South is at the top in these images, which are shown inverted, the way they would appear through a terrestrial telescope.

Welles's Halloween 1938 broadcast of *The War of the Worlds*, where Earth was conquered live on the radio, would attest.

Mars's temperature had been taken spectroscopically, giving an equatorial summer high of a balmy 25 °C, although this would plummet by 100 degrees or more overnight. Very little was known about the atmosphere, but Gerard Kuiper had detected carbon dioxide, also spectroscopically, in 1947. How thick that air was was harder to determine. The planet's apparent brightness partially depends on the amount of light scattered our way by gas molecules and airborne dust particles, so by measuring brightness variations over many years and working backward through an elaborate chain of assumptions, the average pressure could be calculated. The accepted figure was 85 millibars, equivalent to about 16 kilometers above sea level on Earth. At this pressure droplets of water, the solvent of life, could exist . . . at least on Martian summer afternoons. Mars also has a seasonal wave of darkening (some observers went so far as to call it "greening") that begins near each pole in the spring and works its way toward the equator as the weather warms. Just what you would expect, in other words, on a living world whose water supply is locked up in an ice cap each winter.

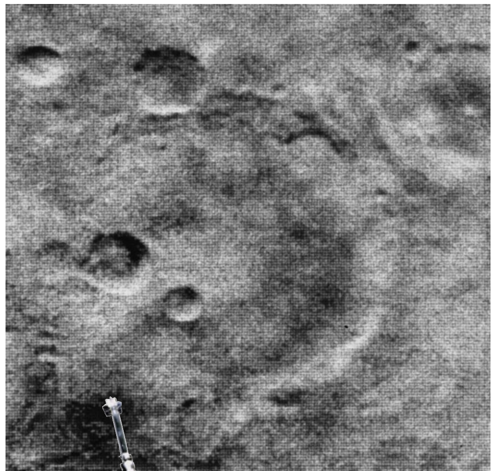
Absent any evidence to the contrary, Mars's atmosphere was assumed to be Earth-like, that is, mostly nitrogen. This was a key assumption, as Earthly life is built up of nitrogen-containing amino acids strung together to make protein molecules. So although no reputable scientists believed in death-ray wielding Martians, smaller, hardier creatures were perfectly plausible. In fact, Caltech professor of embryology Albert Tyler once suggested that the only life-detecting equipment a Mars lander really needed was a mousetrap and a camera.

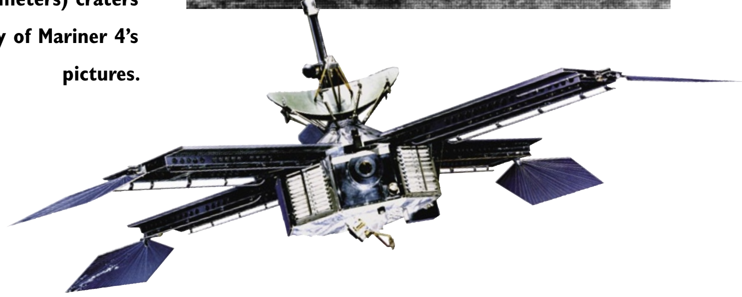
The Death of the Little Green Men

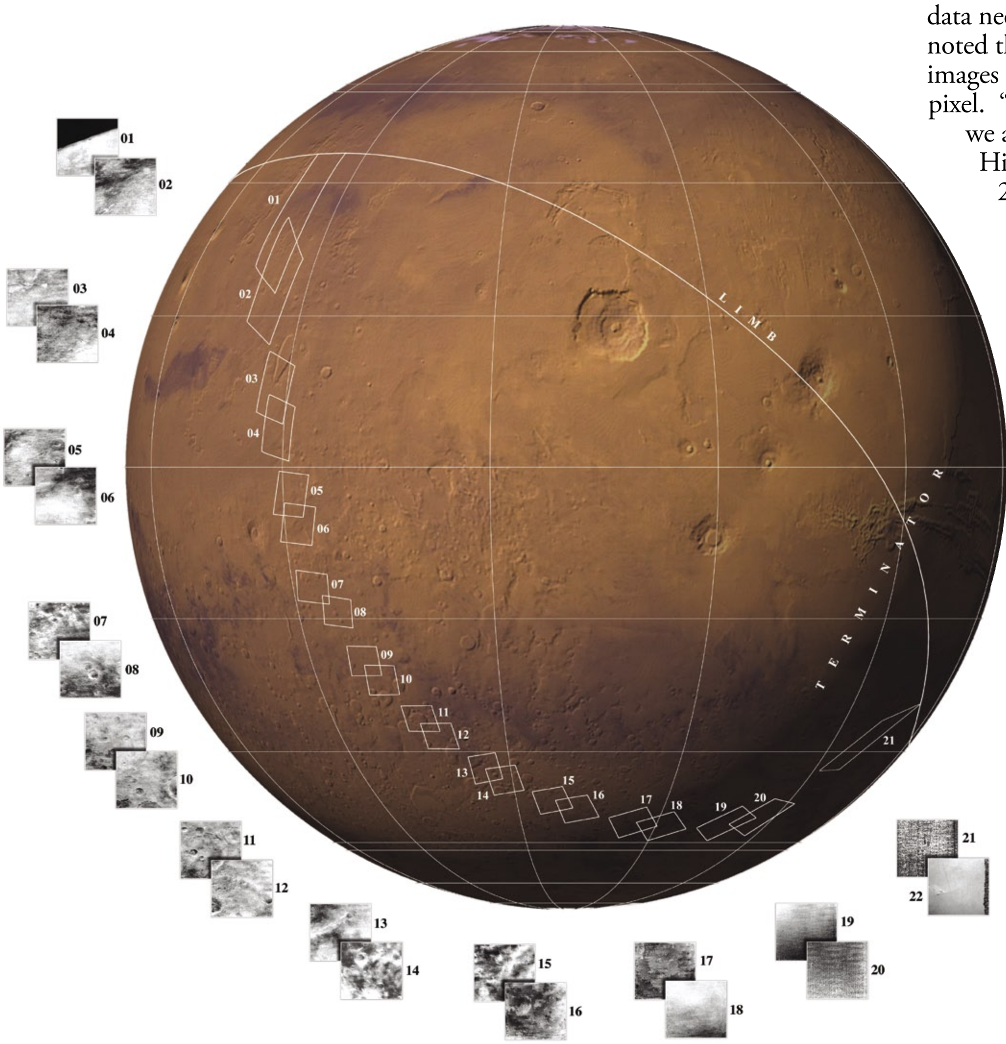
This view began to change in April 1963 because of an infrared spectrum taken at the Mount Wilson Observatory, just north of Pasadena. The water vapor in our atmosphere absorbs strongly in the infrared, so "it must have been a very dry night above Mount Wilson, a very calm night," said Horowitz. "They got this marvelous single plate, and it was interpreted by Lew Kaplan, who was at JPL, and Guido Münch, who was professor of astronomy here—he's now gone to Germany—and Hyron Spinrad." The spectrum's detailed absorption lines allowed Mars's atmospheric pressure to be calculated from first principles. The result was more like 25 millibars than 85, making the presence of liquid water an iffy proposition. "They also identified water vapor in the spectrum; that had never been seen before. They found very little water. And it was obvious that carbon dioxide was a big portion of the atmosphere and not a minor portion."

By this time a flight to Mars was already in the works. The Army still had ties to JPL, and a young first lieutenant named Gerry Neugebauer (PhD '60), doing his ROTC service after graduation, had been put in charge of evaluating science payloads for planetary missions. (Neugebauer, an infrared astronomer with an interest in instrumentation, joined the Caltech faculty as an assistant professor of physics in 1962.) Thus he became the project scientist for Mariner 2, the first spacecraft to fly by another planet—Venus—whose cloud-shrouded surface it found to be hot enough to melt lead. At the same time, Neugebauer was looking to Mars. He had worked with physics professor Robert Leighton (BS '41, MS '44, PhD '47), who would die in 1997. Leighton had been photographing Mars through Mount Wilson's 60-inch telescope, and, with an ingenious image-stabilization system, had created the first time-lapse "movie" of Mars rotating. Neugebauer encouraged Leighton to

Mariner 4 (below) revealed Mars's cratered, moon-like surface. The diagram shows where the pictures were taken. (Number 22 was a partial image.) Image 11 (right), called "one of the truly great scientific photographs of all time" by geologist Sharp, shows the largest (120 kilometers) and smallest (6 kilometers) craters seen in any of Mariner 4's pictures.







propose a photographic experiment—a miniature black-and-white TV camera (there were no color ones back then that were small enough for interplanetary flight)—for Mariners 3 and 4, a pair of spacecraft that weighed a mere 261 kilograms each. Leighton in turn recruited Robert Sharp (BS '34, MS '35) to interpret the images. Sharp, who died in 2004, was chair of the Division of Geological Sciences and an expert on landforms; he brought in postdoc Bruce Murray. (Murray would be on the Caltech faculty for his entire career, and served as director of JPL from 1976 to 1982.)

Recalled Leighton in his oral history, "That really was a landmark experiment. And by today's standards, the equipment we used was so rudimentary . . . to get any pictorial data at all was very difficult." In fact, a camera was not widely welcomed as a good idea. Some scientists (including a few at Caltech) didn't consider pictures to be "real data" as no actual measurements were returned. Furthermore, a camera would soak up a disproportionate amount of telemetry time. The bit rate from the spacecraft was low to begin with, because it would be sending data back over unprecedented distances. The pictures also had to share bandwidth with six other instruments, plus the engineering data needed to run the spacecraft itself. Leighton noted that he and Murray had to fight to get the images encoded at more than a couple of bits per pixel. "JPL was going to use about three bits. But we absolutely insisted upon there being eight." High-def digital this wasn't, but it did give 256 shades of gray—enough so that the team still had a fighting chance of making out some features if they had the bad luck to arrive during a dust storm. "The TV part of the mission would have been a real failure if they'd only used the eight shades of gray that are possible with three bits."

Mariner 3's protective shield failed to jettison once clear of Earth's atmosphere, and the added weight sent the spacecraft into a useless orbit around the sun. Five Soviet Mars missions also failed, but Mariner 4 whizzed by the red planet on July 14–15, 1965, at a respectful 9,846 kilometers. The TV pictures were stored on a tape recorder, to be played back later at a blistering eight bits per second. But first the spacecraft would fly behind Mars while broadcasting a radio signal, whose alteration on passage through Mars's rarefied air would allow its pressure to be measured, directly, from the fringes of space all the way down to the planet's surface. This was truly a do-or-die experiment. For a nail-biting hour and more, Mariner 4 was not only incommunicado behind the planet, but the sun sensor that kept the

Part of Mariner 4's TV team sweats out the arrival of their first pictures. From left: JPL's Robert Nathan (PhD '56), Murray, Sharp, and Leighton. They'd sweat plenty more before it was over—each frame took eight hours to downlink, and the team had to invent the first digital image-processing software in order to bring out any detail at all. The press camped outside JPL's gates during the days of round-the-clock work that ensued. Some reporters threatened to get Lyndon Johnson to intervene to force the images' release, Murray recalled in his book, *Journey into Space*. Presidential ire wasn't the only risk: "In those days, JPL had no food available at night. Our only source of nourishment was an ice cream machine, which led to a weight gain of about 10 pounds per Mars encounter."

solar panels properly oriented was in shadow—if the batteries or the gyroscopes failed, those stored pictures would never be seen.

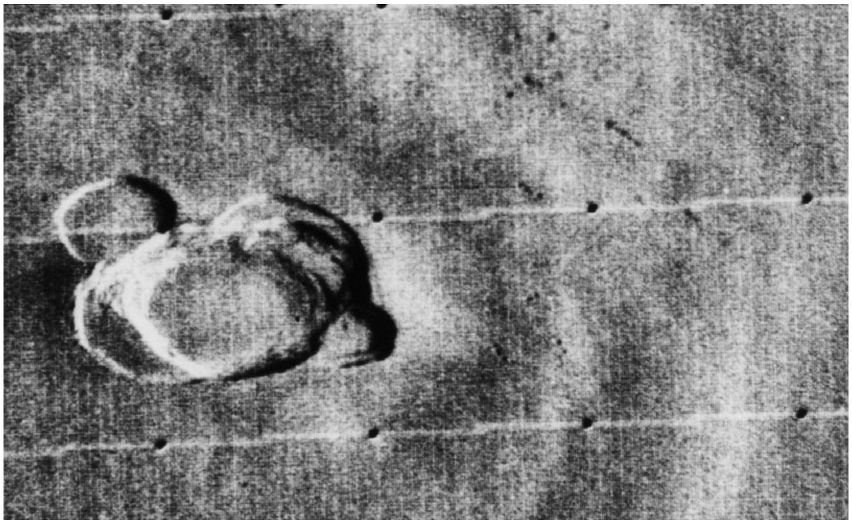
Mariner 4's 21 pictures covered about 1 percent of the planet in a swath along the flight path. They revealed a moonscape untouched by erosion for billions of years, as measured by the crater counts; worse, the radio-occultation experiment showed a surface atmospheric pressure of about five millibars, equivalent to an altitude of some 30 kilometers on Earth. That did it for water droplets. And the magnetic-field experiment, whose team included the late professor of theoretical physics Leverett Davis (MS '38, PhD '41), found no global field. This meant that charged particles from the solar wind, which a magnetic field would have trapped a safe distance away, would blast right through what passed for the Martian atmosphere and kill any creature foolish enough to wander around unprotected. Suddenly Mars had become a very hostile place indeed.

The Blind Men and the Elephant

Things didn't look any better after Mariners 6 and 7, which flew over the Martian equatorial zone and south polar region, respectively, in the summer of 1969. (Mariner 5 went to Venus.) Buzzing the planet at about one-third the distance of their predecessor and returning 200 TV pictures at 16,000 bits per second, the twin spacecraft confirmed the view of the planet as a cold, dry desert. Leighton and his co-authors described the Mariners' flight paths thus in *Science*: "The Mariner 6 picture track was chosen to cover a broad longitudinal range at low latitudes in order to bring into view a number of well-studied transitional zones between light and dark areas, two 'oases' (Juventae Fons and Oxia Palus), and a variable light region (Deucalionis Regio). The picture track of Mariner 7 was selected to . . . include the south polar cap and cap edge, to intersect the 'wave-of-darkening' feature Hellespontus, and to cross the classical bright circular desert Hellas." Mariner 6 discovered the so-called "chaotic terrain"—areas where the permafrost vanishing from a mix of permafrost, dust, and sand grains had caused the surface to slump in peculiar patterns. And Mariner 7 found that Hellas, an impact crater some 2,300 kilometers in diameter, had vast expanses so flat that Sharp coined the term "featureless terrain" to describe them. "There is nothing in the new data that encourages us in the hope that Mars is the abode of life," Horowitz, now a member of the expanded television team, said in the October 1969 issue of *E&S*. "However, there is nothing that excludes that possibility, either." The cameras also failed to see any seasonal surface darkening, which is now thought to be caused by winds blowing light-colored dust off of darker rocks.

These Mariners found traces of oxygen and carbon monoxide—both formed by the breakup of carbon dioxide molecules by ultraviolet light—but still no nitrogen. High doses of that UV light, the kind used to sterilize medical labs, reached the surface, unfiltered by the nonexistent ozone layer. The infrared radiometer experiment, directed by Neugebauer and Münch, showed that the south polar temperature was as low as –125 °C. This is cold enough to freeze carbon dioxide at Martian pressures, implying that the polar ice caps were actually dry ice, not water ice. Readings higher than –112 °C would have been needed for the caps to have been unambiguously water.

Each flyby had a close-up field of view limited to the ground directly beneath it. Recalled Leighton, "There's an area called Hellas that shows up very light-colored, whitish, on various occasions. Being a manifestation of something that seems to change on Mars, it was a good idea to take a look at that. And then there were the polar caps. . . . But the interesting thing is that each of these three spacecraft—going over terrain which all was selected ahead of time and was not selected on the basis of



Olympus Mons, the biggest volcano in the solar system, towers above a dissipating global dust storm in this Mariner 9 picture. Standing three times taller than Mount Everest, Olympus occupies an area nearly as big as the states of Washington and Oregon combined. The crater complex at the summit is almost 64 kilometers in diameter.

really very deep knowledge of anything—managed to uncover a particular type of terrain that had not been seen by any of the previous spacecraft. . . . If you could send three spacecraft past Mars in an essentially random manner, being certain only not to look at the same main area twice, and come back with something new each time, that must mean that the chance of seeing something new again was very great." And so it was.

The rocket carrying Mariner 8 lost pitch control and plunged into the Atlantic within minutes of liftoff on May 8, 1971. But an identical probe, Mariner 9, became the first spacecraft to orbit another planet. Much more sophisticated than, and four times the weight of, Mariner 4, Mariner 9 photographed Mars's entire orb in detail—in some areas, at 100-meter resolution—from its arrival on November 13, 1971, until October 27, 1972. Bruce Murray picked up the tale in *his* oral history:

Might there not, even now, be microbes lurking in the soil or under rocks, shielded from cosmic rays and the ultraviolet sun, waiting in suspended animation for the life-giving kiss of liquid water?

"We got there and there was a dust storm—very dramatic, if you want to think of it in retrospect. It didn't seem very dramatic at that time; it seemed like a very serious problem. All we could see was the outline of the south polar cap . . . and then there was a gradual clearing, like a stage scene, and three dark spots showed up. Couldn't imagine what those were. We finally photographed them, and there were these huge craters. . . . They were the tops of these huge peaks; they were standing high enough [that] the dust was not that thick over them. Then, of course, the dust storm cleared and there they were. The size of these volcanoes is just incredible."

Mariner 9 also revealed a rift system, called the Valles Marineris in the spacecraft's honor, 10 times the length of Earth's Grand Canyon—long enough, if it were laid across the United States, to stretch from San Francisco to Washington, D.C., with a branch reaching up to Canada. Mars thus had a lurid geologic past that might have resembled Earth's. Volcanism and crustal fractures implied a hot, churning interior, and a warmer surface to go with it. And if Mars had an iron core, as Earth does, the moving mass of metal would have generated a magnetic field to keep the solar wind at bay. But what really breathed new life into the question of life on Mars was unmistakable evidence of ancient water. There were features, said Murray, "formed, at least in part, by flooding at times. They are huge. There's nothing on Earth that parallels it. The closest thing . . . on Earth is what's called the Columbia River scablands, which is the area in Idaho and eastern Washington [where the glacial dam that formed] ancient Lake Bonneville broke at the end of the Pleistocene and flooded in one gigantic flood." There were also runoff channels, and things that looked like ancient river beds. Assuming that life had gotten a toehold on a more Earth-like Mars, could it have adapted as the planet slowly assumed its current barren state? Might there not, even now, be microbes lurking in the soil or under rocks, shielded from cosmic rays and the ultraviolet sun, waiting in suspended animation for the life-giving kiss of liquid water?

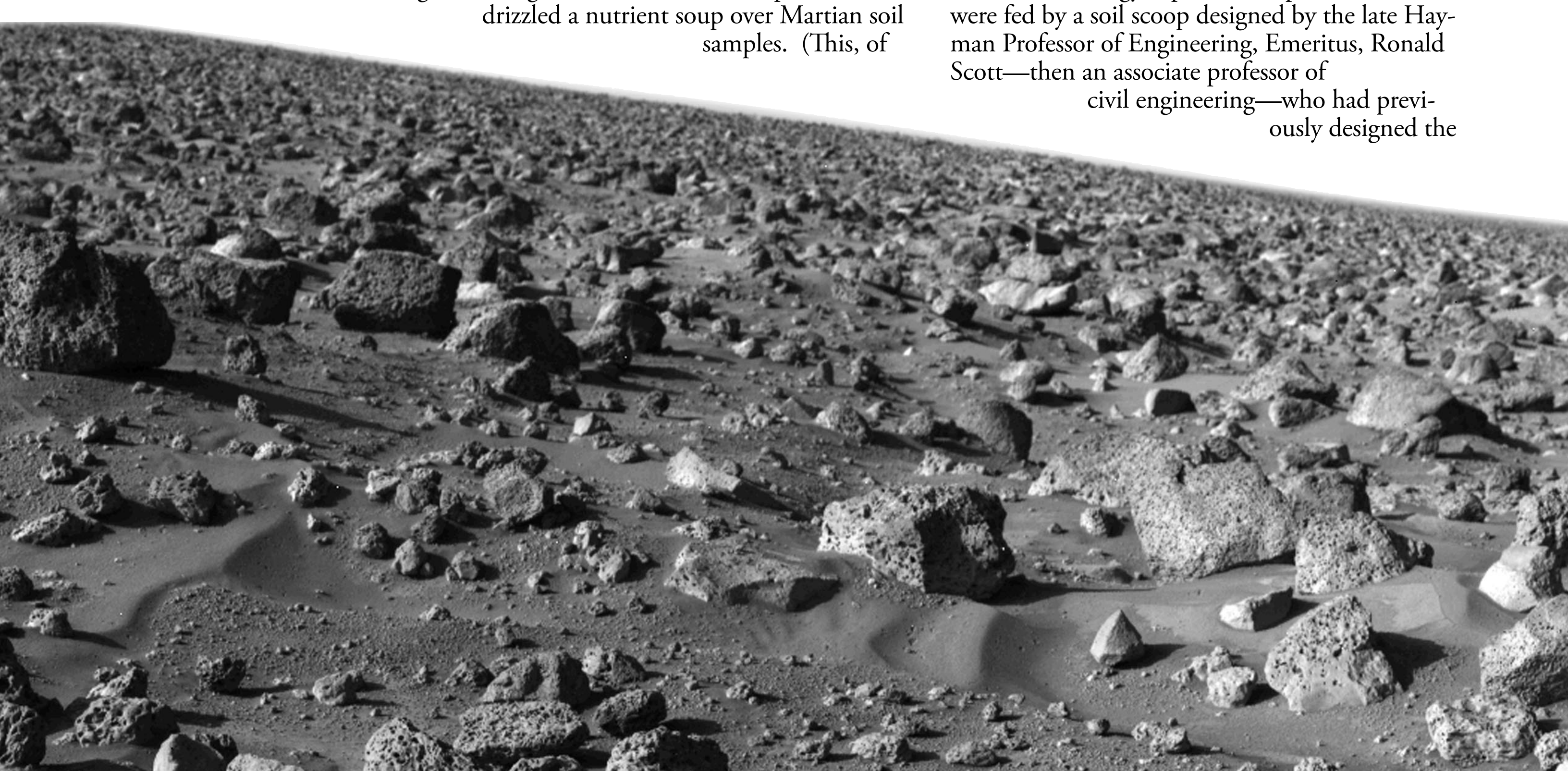
There was only one way to find out, and that was to actually land on Mars—the mission that became Viking. Looking for single-celled life meant turning to biologist Horowitz, an expert on a type of bread mold called *Neurospora*. He was tapped to head JPL's bioscience section, under an unusual arrangement where half his salary was paid by JPL and half by Caltech. He continued teaching one class and maintained his campus laboratory, but the half-time arrangement quickly got skewed, he remarked in his oral history. "I spent most of my time up there."

So how *do* you look for microbial life on an alien world? You cast as broad a net as possible, and Viking carried an extremely versatile instrument that could identify essentially any organic, which is to say carbon-based, compound. Horowitz called it "probably the most important single instrument on the lander." The gas chromatograph–mass spectrometer—or GCMS, as it's known in the trade—works by slowly heating the sample. As the component molecules evaporate or break down, they or their fragments are whisked by an inert carrier gas through a column—the gas chromatograph—packed with absorbent material. The small stuff wafts right through, while larger molecules (or pieces) get held up. The sample thus emerges sorted by particle size. These particles enter the mass spectrometer, where they pass through an electron beam that further breaks them down and gives the fragments a positive charge, and then sorts them by their charge-to-mass ratio. The GCMS was being built by Klaus Biemann at MIT and was already well along, so Horowitz's role was limited to "making sure that there was a lot of ground-based experience with it." The output is a sequence of mass numbers, and the amounts of the sample that have those masses, but the higher each number is, the more combinations of atoms can add up to it. So the operator has to tease out combinations that add up to a plausible breakdown sequence and try to work backward to the original compound. "There's not much general principle or general theory you can go on; you just have to have a library of results you can compare your actual results with."

The GCMS was not explicitly a biology instrument—the gas chromatograph also analyzed the atmosphere during the lander's descent—but there were three other experiments whose sole mission was to find life. All three of them occupied a mere cubic foot of space within the lander—a bacteriological laboratory in a shoebox. Two of them, the gas-exchange and labeled-release experiments, drizzled a nutrient soup over Martian soil samples. (This, of course, meant that the samples had to be kept at a temperaure and pressure where the broth wouldn't flash-freeze or sublime.) The idea was that if any Earth-like bugs were lying dormant, they'd wake up, slurp the soup, and betray their presence in one of two ways. The gas-exchange experiment, designed by Vance Oyama of NASA's Ames Research Center, looked for various metabolic gases with its own gas chromatograph. The labeled-release experiment, invented by a public-health engineer in Washington, D.C., named Gilbert Levin, spiced its consommé with radioactive carbon atoms. If any microorganisms were supping, some of this carbon would eventually show up on their breath, and a Geiger counter would register the emission of "hot" CO_2.

Horowitz thought this was a bad approach. "After the Mariner 4 flyby, it was obvious that the chance of liquid water on Mars was so remote that one had to plan for the contingency that there was no water—that if there was any life on Mars, it was living under conditions that were in no way terrestrial. So we designed an experiment that would work under Martian conditions and that involved no liquid water." In collaboration with University of Texas microbiologist George Hobby, whom Horowitz lured to JPL, and JPL's Jerry Hubbard (who left for Georgia Tech before Viking landed), Horowitz developed a pyrolytic release experiment, which exposed the soil to a sample of Mars's own air that had been spiked with a soupçon of radioactive carbon monoxide and carbon dioxide. The soil was then left to sit in simulated Martian sunlight at midsummer Martian pressures and temperatures. After 120 hours, the soil was heated under a stream of helium to 625 °C—hot enough to break down any organic material and turn it into carbon dioxide. The helium was checked for radioactivity. If any showed up, it must have been cooked out of some Martian microorganism.

All three biology experiments, plus the GCMS, were fed by a soil scoop designed by the late Hayman Professor of Engineering, Emeritus, Ronald Scott—then an associate professor of civil engineering—who had previously designed the



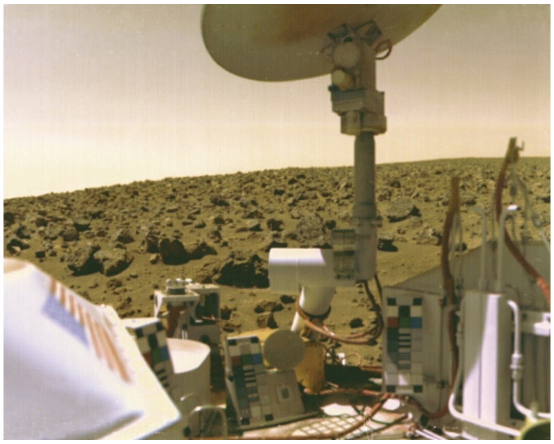
scoop for the lunar soil-mechanics experiment on JPL's Surveyors 3 through 7. The scoop's remote-controlled arm dropped the Martian dirt into a chamber from which it was dispensed, in half-cubic-centimeter lots, into experiment chambers on a rotating carousel as needed.

As part of the instruments' testing and checkout process, Horowitz dispatched JPL microbiologist Roy Cameron to the Antarctic where, just inland of McMurdo Sound, the soil is exposed year-round in ice-free "dry valleys." Their summer temperature tops out near 0 °C, and the year-round average is about 20 below. Any dustings of snow evaporate almost upon landing, due to the strong, dry winds sweeping down from the central Antarctic plateau. "These dry areas are as Mars-like as you can find on the earth," Horowitz explained. "I thought that Roy ought to be spending his time down there instead of in the Sahara and the Mojave and Atacama and so on." During the International Geophysical Year of July 1957–December 1958, a team of microbiologists had taken soil samples in the valleys that were absolutely sterile—unheard-of, since microbes eke out existences in the harshest of climates, which led some people to doubt the quality of the work. Cameron, his colleagues, and a bunch of Caltech grad students spent eight seasons down there, finding that "some 10 to 15 percent of the soil samples contained no bacteria, and the rest had very low bacterial counts." The valleys held saline lakes and ponds whose shores teemed with bacteria, yeasts, and molds, and the farther away the samples were taken from a water source, the fewer bacteria they contained. If there was life, even minimally, in this Mars on Earth, life on the real deal was certainly possible—it all depended on the water.

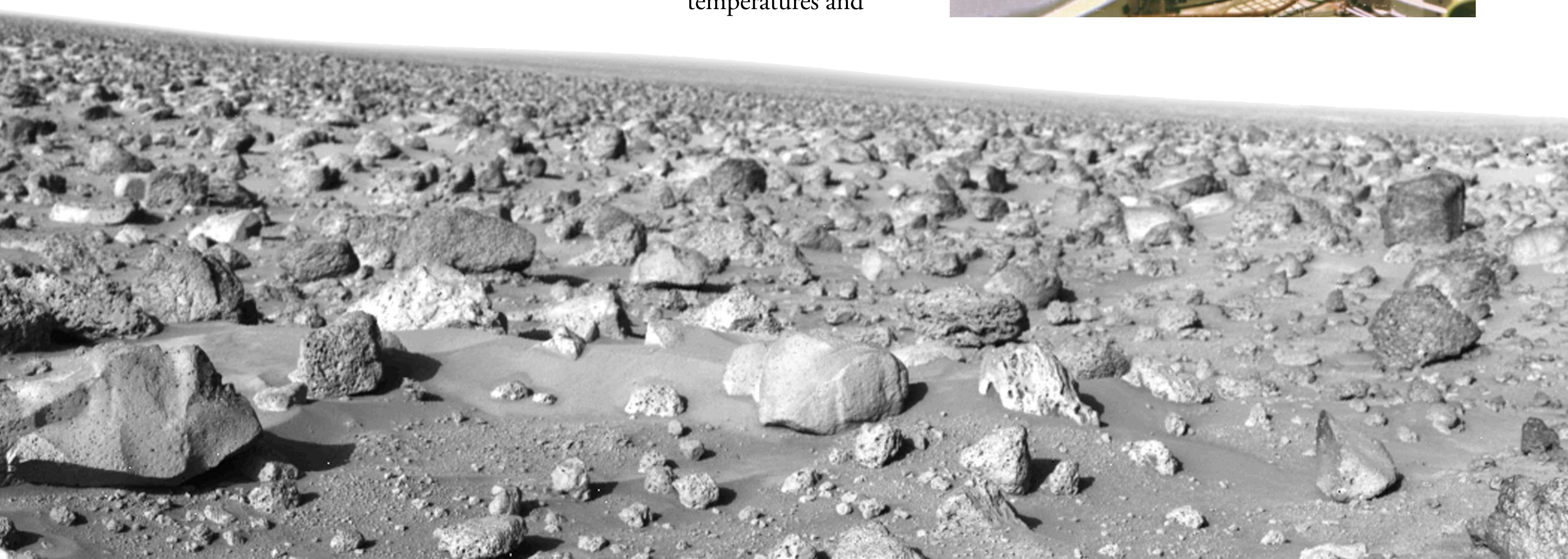
Viking Strikes Out

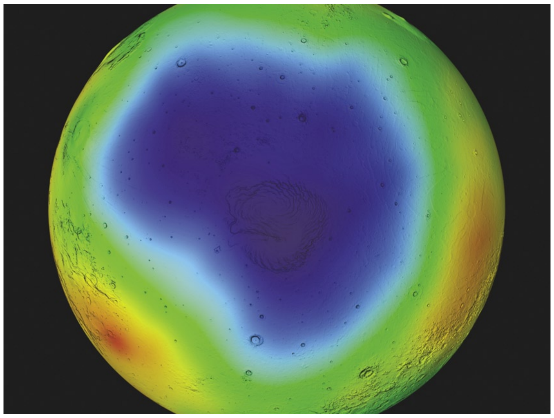
The most ambitious space mission the world had seen, the two Vikings each consisted of an orbiter, designed and built by JPL, and a Volkswagen-sized lander designed and built by Martin Marietta. Upon their arrival at Mars, the orbiters would scout the terrain with cameras and infrared sensors—the latter to look for higher-than-average temperatures and moisture levels. This close inspection proved prudent, as both the primary landing sites, which had been chosen in advance from Earth, turned out to be unsuitable. Safer sites were soon found, but no warm, moist oases, and on July 20, 1976, Viking 1 touched down. The landing had originally been slated for the Fourth of July as part of America's bicentennial celebration, but the delay caused Viking to mark a more apropos anniversary instead—Neil Armstrong's and Buzz Aldrin's first steps on the moon in 1969. Viking 2 followed on September 3. The two landers were placed on opposite sides of the planet, on the Chryse Planitia downstream of some ancient drainage channels (22° N, 48° W) and on Utopia Planitia (48° N, 226° W), respectively. It was summer in the northern hemisphere, the time when life—if any existed—should be flourishing. The nominal missions were 90 days, but all four spacecraft operated for two years, with Lander 1 surviving for more than six and Orbiter 2 for four.

Besides the GCMS and the shoebox lab, each lander carried a complete weather station, two cameras, and a seismometer. Designed and prototyped by Don Anderson (MS '58, PhD '62), then professor of geophysics and director of Caltech's seismo lab, the instruments were built with a latch the manufacturer added to protect the motion sensor in flight. Viking 1's seismometer failed to unlatch, but Viking 2's picked up wind-induced vibrations—terrestrial seismometers routinely record the rustle of the grass as the wind goes by. It



Below and right: This boulder-strewn field reaches to the horizon, which is nearly three kilometers from Viking 2's landing site on Utopia Planitia.





This summertime view of Mars's north polar region shows data from the Mars Odyssey's high-energy neutron detector. The purple and deep blues represent soil enriched by hydrogen, which is a proxy for water, presumably as ice—in some areas up to 90 percent by volume. In the winter, much of this region is covered by frozen carbon dioxide.

also recorded only one event that might have been a Marsquake, showing that the planet is now tectonically dead.

There was a very real concern that the lander itself could ruin the biology experiments. Mock news footage on a *Saturday Night Live* "Weekend Update" segment showed a lander squashing a crowd of Martians waving a banner of welcome. While JPL didn't expect a disaster on quite that scale, the landers' descent rockets were designed to minimize scouring and heating the Martian surface, and specially purified hydrazine (N_2H_4) fuel was used to avoid contaminating the landing site with organic chemicals. (Hydrazine combustion produces only nitrogen, hydrogen, and ammonia gases, plus a trace of water vapor.) And all four spacecraft were rigorously sterilized before launch to prevent any terrestrial microbes from colonizing a new world.

The landers' cameras revealed a sandy, wind-blown, rock-strewn, ocher landscape. No lichens or mosses were seen. (The camera had a close-up resolution of a few millimeters per pixel.) There were no signs of movement among the rocks from frame to frame, and no footprints or animal tracks. And certainly no Martian ever came up and tapped inquiringly on the lens.

Some meteorites contain organic material, so it was anticipated that carbon-based compounds would be found on Mars whether life existed or not. Each lander took two soil samples for GCMS analysis, including one from under a rock at Utopia Planitia. The instrument was sensitive to organic molecules at the parts per billion level, Horowitz wrote in his 1986 book, *To Utopia and Back*, but "the only organic materials found were traces of cleaning solvents left over from the manufacture of the instrument." Case closed. No carbon-based compounds, no life—at least not as we know it, Jim.

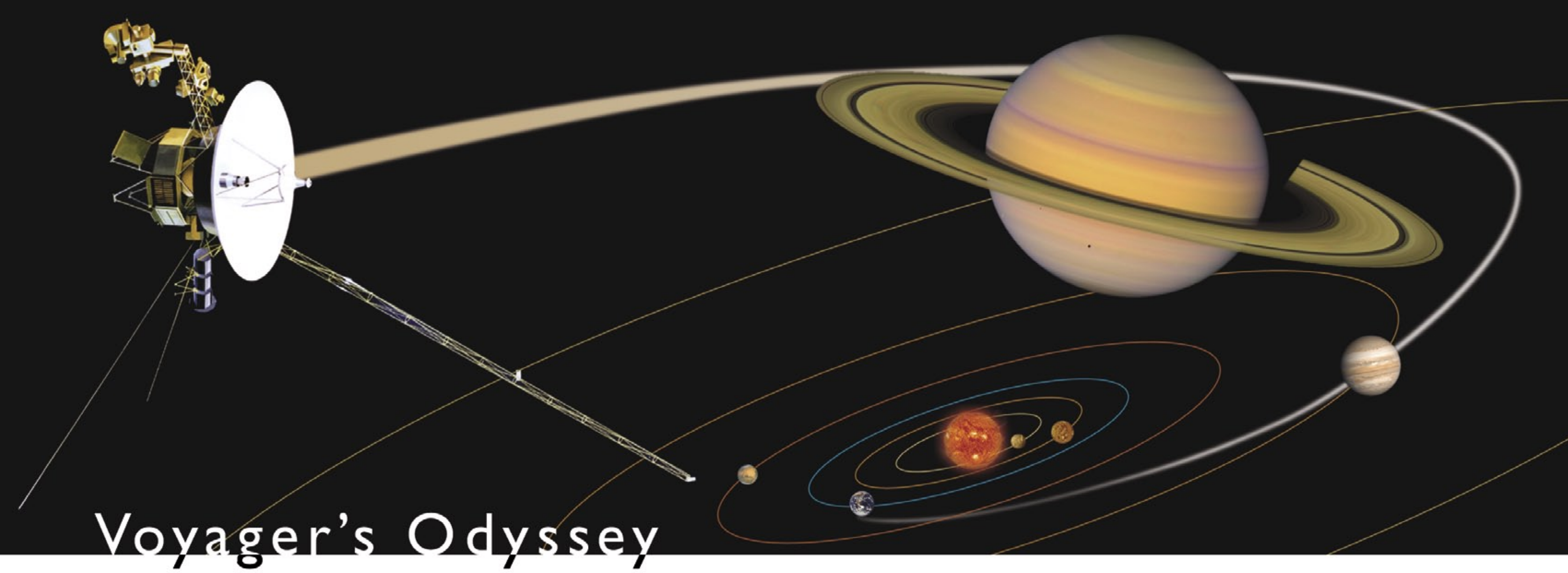
But first, the gas-exchange experiment got everybody's hopes up. When Martian soil was exposed to water vapor for a few days before being sprinkled with the nutrient rain, the parched ground released a flood of oxygen. This was unanticipated—methane was the gas people expected to see, based on the metabolism of anaerobic bacteria on Earth. The outgassing lasted for nearly a week, a phenomenon later attributed to highly oxidizing minerals in the soil reacting with the water molecules. Such compounds had been predicted, albeit not in such quantities, as a result of Mars's UV bath. These oxidants also explained the surprising lack of background organics—any prebiotic chemicals had been fried in short order like so many microscopic sliders on the grill. After the outgassing had ceased, the experiment proper began. The dirt was incubated for nearly seven months with no further result.

The labeled-release soil liberated a similar surge of gas upon initial moistening. The sample was then heated for several hours to sterilize it, and spritzed again. No further radioactive gas wafted out. Levin, the instrument's inventor, argued that this proved the initial release had been biological, and the heat had killed the bugs—as intended. Horowitz, citing the negative GCMS results, held that it was simply because all the oxidants in the soil had been used up. "The most likely source of this gas was formic acid [one of the nutrients], a one-carbon compound that is easily oxidized to CO_2 by peroxides," he wrote in *Utopia*.

Horowitz's own experiment gave "weakly positive" results. The very first one, by Viking 1 on Chryse Planitia, released an amount of carbon "small in comparison to that found when using terrestrial soil samples, but . . . far above the background level." However, this effect was not repeated in two later tests on fresh soil, which showed much weaker emissions. The Viking 2 tests at Utopia were even less encouraging. One gave low levels comparable to the latter two Chryse ones, but two more showed nothing above the preflight baseline. "Although the positive signals . . . are still not completely understood, the chance that their source was biological seems negligible," Horowitz concluded. He attributed them to a reaction between an iron-rich mineral, such as maghemite, and carbon monoxide.

Oyama, previously one of the strongest proponents of life on Mars, was convinced by the GCMS results that the planet was sterile, as was Horowitz and most of the scientific community. Levin, however, didn't buy the peroxide explanation, saying that his instrument had detected life in exactly the way it was designed to do—a view he maintains to this day. He is no longer alone. The discovery of possible bacterial fossils in a rock ejected from Mars that landed in Antarctica; photographs by JPL's Mars Global Surveyor of what appear to be fresh, water-carved gullies in the walls of craters; and indications from JPL's Mars Odyssey that permafrost lies within one meter of large parts of the planet's surface have again reopened the question. And Arthur Lafleur, a member of the original GCMS team, now says that millions of microorganisms would be needed for their aggregate organic material to register on the Viking instrument, whereas the labeled-release experiment was capable of detecting far fewer cells—as few as 10, he claims. So if the ultraviolet-induced self-sterilizing soil zone doesn't extend too deeply, Mars may once again turn everything we think we know about it on its head. Only a future lander will find out. □

PICTURE CREDITS: 13-17—NASA/JPL-Caltech; 11—JPL/USGS; 12—STScI; 18—NASA/JPL/GSFC/IKI



Voyager's Odyssey

by Marcus Woo

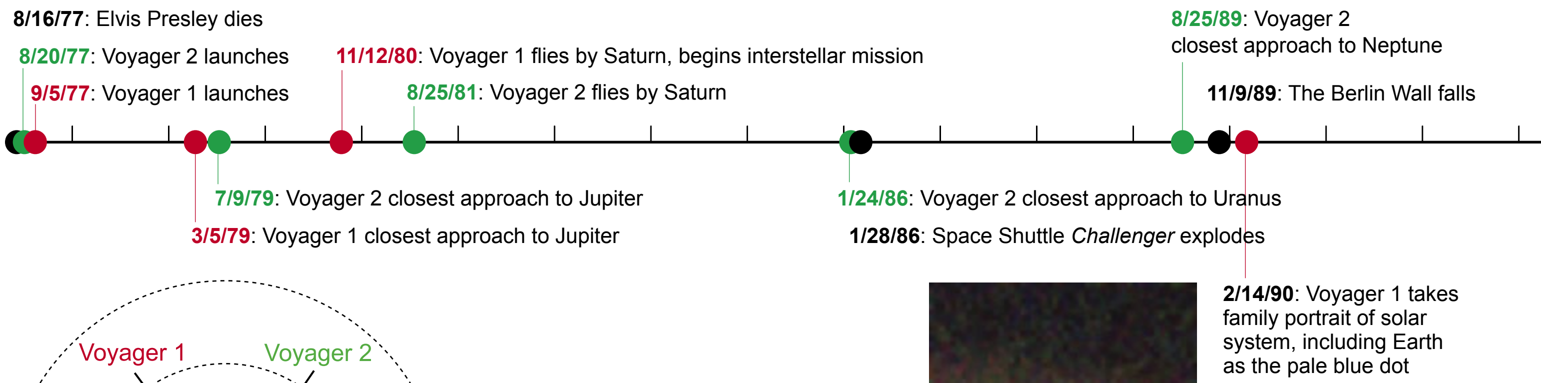
Right: Voyager 2 launches from the NASA Kennedy Space Center at Cape Canaveral in Florida. Far right: Saturn's moon Mimas.

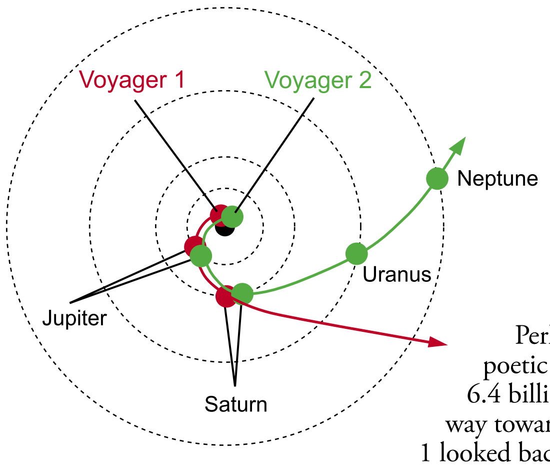
Four days after Elvis Presley died, a rocket blasted off into the blue skies above Cape Canaveral. While America was mourning the loss of a cultural icon, the Titan III-Centaur was propelling the first of two robotic craft toward their own iconic status—symbols of discovery, exploration, science, and the human spirit. Voyager 2 lifted off on the morning of August 20, 1977, and its sister ship would launch on September 5. They would explore alien worlds, capturing the imaginations of scientists and the public as they ventured on a quest as epic as any in history.

"Voyager is undoubtedly the ultimate mission of discovery," says Edward Stone, the Morrisroe Professor of Physics, vice provost for special projects, and Voyager project scientist. "There will never be another mission that will see so many new things for the first time."

For more than a decade, as the Voyagers hopped from planet to planet and moon to moon, they returned jaw-dropping images, showing the solar system to be a place more wild and wonderful than imagined. The mission would reveal, for instance, the violent, churning clouds of Jupiter and the winds of Neptune, which can blow at nearly 1,500 kilometers per hour. The Voyagers would discover rings on Jupiter and Neptune, and find even more than those previously known around Saturn and Uranus. They found volcanoes on Jupiter's pockmarked moon Io, with plumes bursting up hundreds of kilometers into space, and moons with bizarre surfaces that would make any geologist swoon. When the monitors at JPL's Von Karman auditorium displayed the first image of Saturn's moon Mimas, showing its enormous crater, somebody reportedly exclaimed, "My God, it's the Death Star!"

Voyager shook our view of Earth's place in the solar system. Our world was no longer the only body alive with earthquakes, volcanoes, and geysers. Our atmosphere with its storms, winds, and clouds was nothing compared with those of the outer planets. Most scientists, including Andrew Ingersoll, the Anthony Professor of Planetary Science and an atmospheric scientist on the Voyager team, hadn't anticipated such diversity. "I only had Earth to think about, and Earth didn't provide me with enough imagination to guess what we would see," Ingersoll says. "I couldn't imagine how rich it could be."





Top: A timeline of notable dates during the Voyager mission. Above: The Voyager spacecraft trajectories from Earth to the outer planets and beyond.

Perhaps the most profound and poetic image was of Earth from 6.4 billion kilometers away. On its way toward interstellar space, Voyager 1 looked back toward us and snapped a shot of a bright speck floating in space, filling just over a tenth of a pixel. It was humanity's humble home and, as Carl Sagan famously described it, nothing but a pale blue dot.

More than 30 years after launch, having made one astounding discovery after another, and having penetrated popular culture with appearances on *Star Trek: The Motion Picture* as well as on *Saturday Night Live* and *The X-Files*, Voyager still hasn't finished telling its story. Like human explorers who left old worlds for new, both robots are leaving the relative familiarity of the solar system for the great expanse of interstellar space. Voyager 1 is at the edge of the heliosphere, the bubble formed by the solar wind, and is speeding at over 61,000 kilometers per hour toward the heliopause, the boundary separating the bubble and interstellar space. Voyager 2 is not far behind.

After decades that have seen the death of Elvis, the birth of the Internet, the fall of the Berlin Wall, two space shuttle disasters, five presidents, and two Iraq wars, Voyager's odyssey endures. The secret to its success? Lots of ingenuity and a dash of luck.

An Unshakable Belief

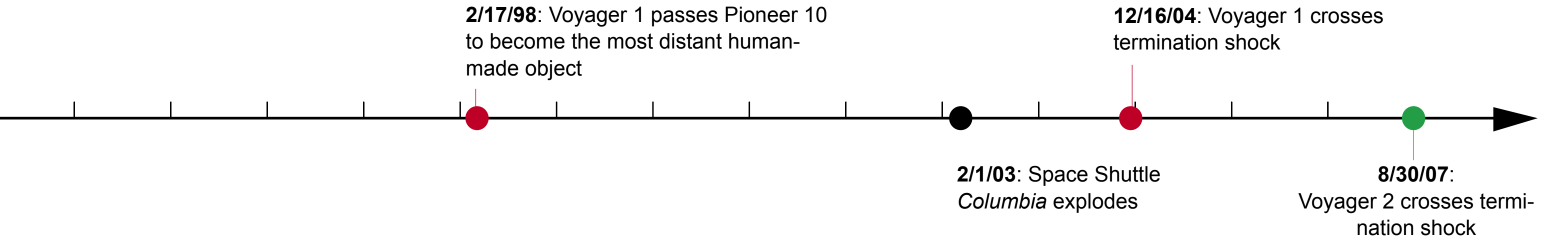
The Voyager mission depended on a planetary alignment that occurs once every 176 years, which graduate student Gary Flandro (MS '60, PhD '67) discovered in 1965. With the four gas giants lined up, Voyager could use each planet as a gravitational slingshot to shorten travel time to the next—a technique developed at JPL by UCLA graduate student Michael Minovitch in 1961. Mariner 10 first used the method in 1973, getting a boost from Venus on its way to Mercury. Instead of 30 years, Voyager's journey to Neptune took 12. But such a trip would never have happened if the alignment had come a few years earlier, before technology could turn the dream into reality.

The mission eventually became known as the Grand Tour, but the moniker first belonged to its predecessor, a more ambitious mission that aimed to send two pairs of spacecraft to explore all of the outer planets and Pluto, and would last for at least 12 years. Scientists and engineers began designing the mission in the late '60s and early '70s, developing the most advanced craft ever built at the time. But when the project was killed for budgetary reasons, researchers recast the mission as one that would stop after Saturn, needing to last only four years. Billed as a continuation of the Mariner program, they called it MJS '77, for Mariner-Jupiter-Saturn 1977. Later, the team would rename it Voyager.

Even though their stated goal was Saturn, many wanted to achieve the Grand Tour. "There were some of us that had an unshakable belief that with the MJS '77 spacecraft we could and should do more than Jupiter and Saturn," says Rochus "Robbie" Vogt, the Avery Distinguished Service Professor and Professor of Physics, Emeritus, who served on the Voyager science mission team. As the principal investigator of the cosmic-ray experiment, Vogt was especially interested in interstellar space, and made no secret of his ultimate goal.

During the design phase, Vogt kept pushing for more hydrazine, which powered the small jets that steered the spacecraft during flight and kept its radio antenna pointing at Earth. In a robot where every ounce of weight was a trade-off, negotiation wasn't easy. "I became known for my obsession with hydrazine," Vogt says. "It's just how clever you are with the money you're given with optimizing various trade-offs to get the things you want." In the end, he succeeded, but going farther than Saturn was still anything but certain.

At the time of the launch, the space age was only 20 years old, Stone reminds us. No one had any

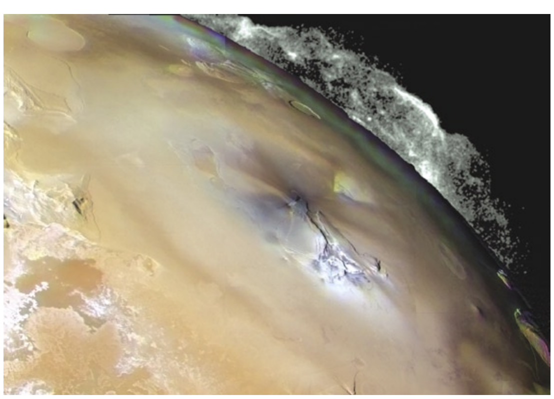


experience in planning a 20- or 30-year mission. But once Voyager 2 got to Saturn in 1981, the team pushed forward, and the mission became the Voyager Uranus Interstellar Mission. "We gave it our everything to make it possible, and it worked," Vogt says. "You have to be both very good and lucky. You need both, but if you're very good and do a very good job, you need less luck."

Stone attributes the spacecraft's longevity to its robust design, which the team began planning in 1972. Pioneer 10, a more primitive craft that arrived at Jupiter in 1973, found radiation levels to be 1,000 times higher than expected. Engineers then beefed up the circuitry in the Voyagers to withstand such radiation. Another crucial component was the radioisotope thermoelectric generators, which depended on the 87.7-year half-life of plutonium-238 for long-lasting power. With the sun so far away, solar power wouldn't have cut it.

"There is perhaps no better demonstration of the folly of human conceits than this distant image of our tiny world. To me, it underscores our responsibility to deal more kindly with one another, and to preserve and cherish the pale blue dot, the only home we've ever known."—Carl Sagan

Although primitive by today's standards, the computers on board the Voyagers were key advancements over Mariner technology. Because of the vast distances from Earth, commands would have taken hours to travel between craft and engineers. Additionally, during the years of cruising time, the budget couldn't afford a full-time team to oversee every spacecraft detail. Both factors meant the Voyagers needed to fly solo at times, with unprecedented independence to fix themselves should they encounter problems.



The eruption of Pele on Jupiter's moon Io. The volcanic plume rises 300 kilometers above the surface in an umbrella-like shape. The plume fallout covers an area the size of Alaska.

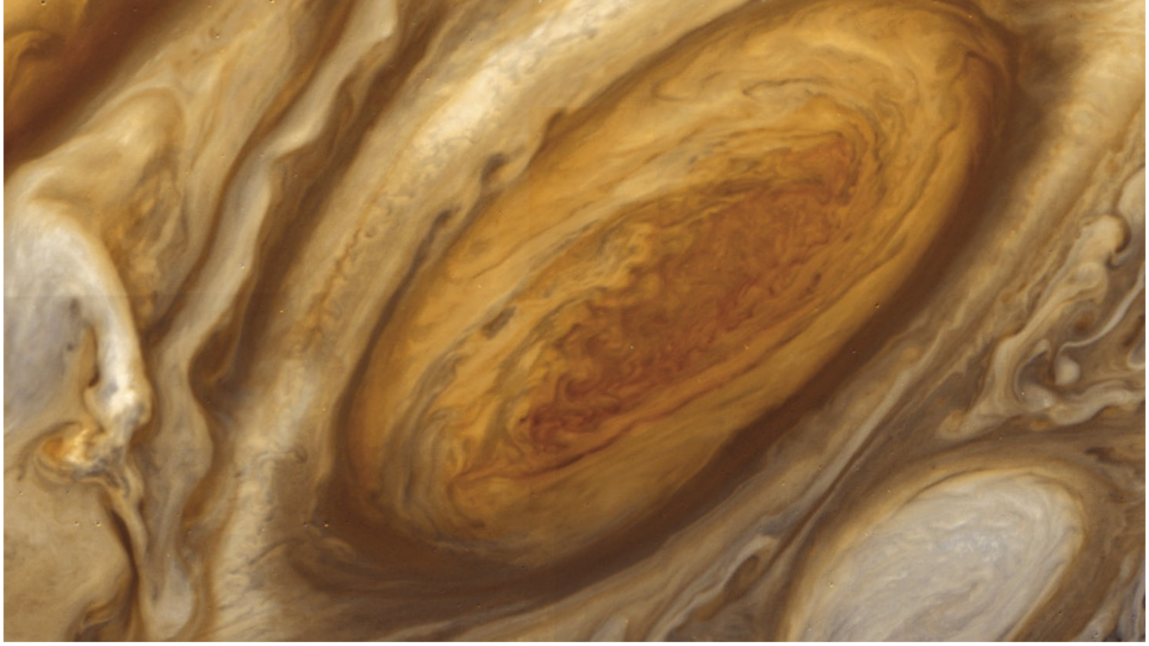
When Voyager 2 became a mission to Uranus, the team had to redesign and adjust hardware and overhaul software. The ability to reprogram spacecraft wasn't new, but it was essential to handle the extended missions. The new distances—Uranus, for example, is nearly twice as far from the sun as Saturn—meant communication would be an even greater challenge. Engineers rewrote software to make data transfer more efficient, and uploaded it onto the robot from Earth, a major accomplishment. The transmitter, meanwhile, radiates only 23 watts of power—about as powerful as a refrigerator light bulb. To increase sensitivity for the Grand Tour, engineers enlarged the ground-based antennas around the world that made up NASA's Deep Space Network.

Of course, everything wasn't smooth and easy—this was still rocket science, after all. No one had ever flown such a complicated spacecraft over such a long distance, and problems were inevitable as the team got to know the Voyagers. "The spacecraft was well designed," Stone says. "We just had to learn how to use it and learn how to program it." Still, the mission had some close calls. Voyager 1 launched two weeks after Voyager 2, and the second Titan rocket did not burn all of its fuel. As programmed, the upper-stage Centaur rockets then burned longer to put it on course—but with only 3.4 seconds of fuel left. Bruce Murray, professor of planetary science and geology, emeritus, Voyager scientist, and director of JPL at the time, would later realize that had Voyager 2 used the underperforming rocket, it would not have had the boost needed to reach Uranus. "The opportunity of the century would have passed us by," he wrote eventually.

Let the Discoveries Begin

Voyager 1 arrived at Jupiter in 1979, and when it approached the moon Io in March, it would make perhaps its most shocking discovery. Instead of another dead, cratered world like our moon, Io was chock-full of volcanoes ejecting plumes of sulfur at several hundred degrees Celsius.

Io is slightly larger than our moon, and conventional wisdom says that such a relatively small body



This photo of Jupiter was taken by Voyager 2 and shows Jupiter's Great Red Spot, which is three times as large as Earth. None of the structure and detail evident in these features had ever been seen from Earth.

should have cooled long ago, leaving it geologically dead. But tidal forces from Jupiter and fellow satellites Europa and Ganymede squeeze and tug at Io, creating friction and the heat needed to power more than 100 volcanoes. In fact, it's the most volcanically active body in the solar system. Stone calls Io's volcanoes the most memorable discovery of the mission. "It became symbolic of the surprises that were ahead of us as we continued our journey of exploration," he says.

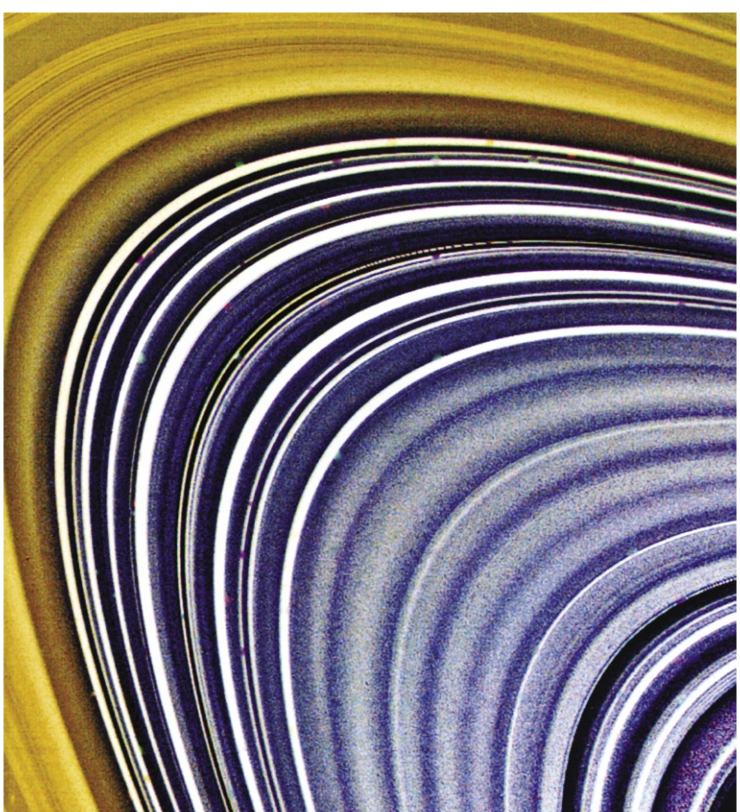
Voyager found the volcanoes with the help of a little luck and an alert engineer. The spacecraft had already flown past Io, and most of the team was resting in preparation for the next encounter. "People were exhausted from lack of sleep," Ingersoll recalls. "People were sleeping in their cars in the JPL parking lot, stretched out on the floor in the lab." Meanwhile, engineer Linda Morabito-Kelly was looking at some of the navigation images used to steer Voyager. She noticed a large, crescent-shaped object sticking out of Io. After ruling out calibration errors and other possible explanations, she realized this object was real, and, in fact, an erupting volcano. As Ingersoll says, "That was how the first volcano was discovered—not by the science team, who were all asleep in their cars at that point, but by one of the engineers."

For Ingersoll, an atmospheric scientist, the highlight of Jupiter was the turbulence surrounding features like the famous Great Red Spot, a giant storm that has been raging for at least 300 years. "I had a biased thinking that the flow in the vicinity of those spots was laminar, smooth, and well organized," he says. "It blew me away when the first close-up images came in, and it was not like that at all!" Scientists thought turbulence near the spot would disrupt it, but instead the adjoining clouds churn and swirl. Ingersoll likens the atmosphere to a food chain, and turbulence feeds the Great Red Spot the energy needed to maintain its structure.

The gas giants' atmospheres continued to surprise Ingersoll and the rest of the science team with the arrival of Voyager 1 at Saturn in 1980. Being roughly twice as far from the sun as Jupiter, Saturn receives a quarter of the sunlight. Scientists thought the reduced energy would translate to a calmer atmosphere. But astonishingly, Saturn's winds were even stronger than Jupiter's.

Saturn's most distinguishing feature is, of course, its rings. Voyager counted hundreds of small features within the main ones. It found odd patterns on the rings that looked like spokes. Scientists determined that the spokes were scattered sunlight, produced in a way that suggested they were made by dust specks a few hundredths of a millimeter wide. It also found "shepherding" satellites, small moons in inner and outer orbits around a ring. They give and extract energy to and from the ring, keeping it together as shepherds do with a flock. Previously, the DuBridge Professor of Astrophysics and Planetary Physics,

This view focusing on Saturn's C-ring (and to a lesser extent, the B-ring at top and left) was compiled from three separate images taken through ultraviolet, clear, and green filters. More than 60 bright and dark ripples are evident here.



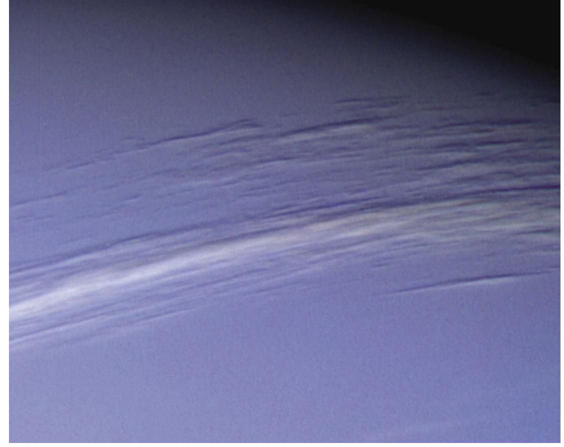
Emeritus, Peter Goldreich, had predicted the existence of shepherding satellites around Uranus, which Voyager 2 later confirmed.

Voyager 1 then swung around for a shot of Saturn's largest moon, Titan, which boasted an atmosphere of organic molecules such as methane. Unfortunately, the clouds were too thick for cameras to penetrate. The route needed to reach Titan put Voyager 1 on a course for interstellar space at a 35-degree angle up from the plane of the solar system, ending its planetary mission. The dream of a Grand Tour became reality as Voyager 2 headed toward Uranus after whizzing by Saturn. But its arrival on January 24, 1986, would be overshadowed by a national tragedy when, four days later, the space shuttle *Challenger* exploded upon liftoff, a few minutes past 11:30 a.m. local time. Ironically, that morning's *New York Times* had run an editorial, written before the tragedy, touting Voyager's triumph and urging NASA to pursue robotic exploration instead of manned missions. "Voyager 2 shows space exploration at its best," it read. "If NASA wants lasting public support for a vigorous space program, the wonder of seeing new worlds will do it a lot more good than soap opera elevated to Earth orbit." After some soul-searching, the Voyager team gathered to celebrate another Voyager success. There was, after all, lots of exciting science to do.

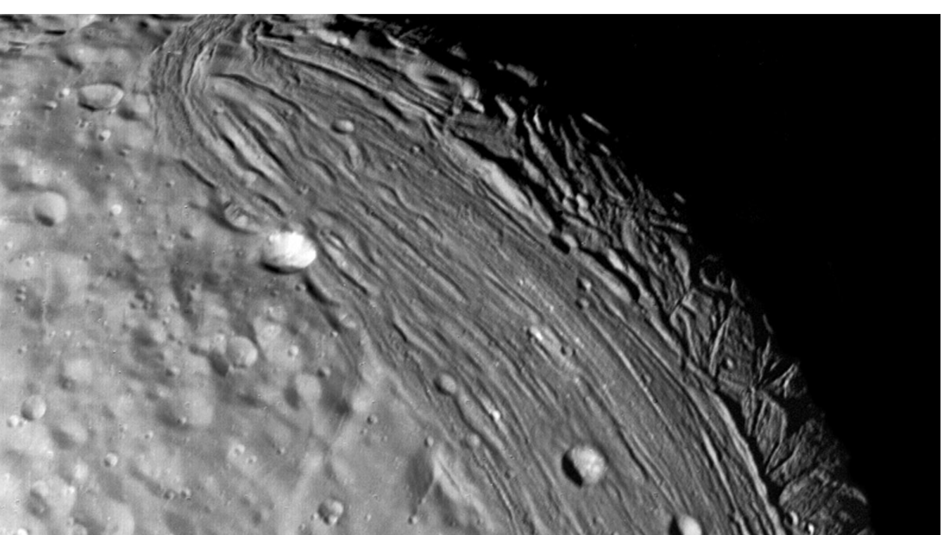
Uranus is tipped on its side more than 90 degrees, so that its north and south poles take turns facing the sun in summer and winter. Scientists wondered if the sun's energy might drive the atmosphere to flow from pole to pole, rather than the east-west direction of the planet's rotation. But Voyager observed the latter, showing that planetary rotation—and not the sun—was the atmosphere's controlling factor. "That was a real discovery," Ingersoll says. "I don't know if we could've guessed how it turned out."

If a tipped rotation axis weren't enough, Uranus's magnetic field axis proved to be slanted 60 degrees. Not only that, the magnetic axis was offset, instead of going straight through the planet's center.

The moons were just as perplexing as those of Jupiter and Saturn. Uranus's largest moon, Miranda, looked as if it had been taken apart and thrown back together, like a cubist painting. Sheer cliffs and canyons 15 kilometers deep covered its surface. Some scientists think a collision blew it apart before gravity reassembled it.



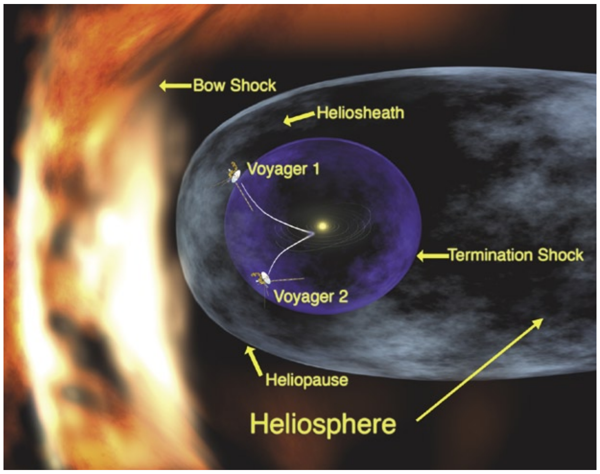
This image provides obvious evidence of vertical relief in Neptune's bright cloud streaks. Shadows can be seen on the cloud edges opposite the sun.



Miranda reveals a complex geologic history; at least three terrain types of different age and geologic style are evident at this resolution.

By late August 1989, Voyager 2 was fast approaching Neptune. In a couple of weeks, Hurricane Hugo would bear down on the Caribbean and the Carolinas. Scientists were tracking storms on Neptune as well, including the Great Dark Spot. Voyager had shown that the variability of Earth's atmosphere is the exception rather than the rule, so weather forecasting on the outer planets is a lot easier than on Earth. "The newspapers were giving twelve-hour forecasts trying to predict where Hugo would come ashore," Ingersoll recalls. To follow the Great Dark Spot, however, the team had to upload Voyager's instructions much sooner. "At the same time, we had to make predictions two weeks in advance about where the Great Dark Spot would be. We just used junior high school mathematics. We plotted the position of the Great Dark Spot over the preceding months, put it on a piece of graph paper, drew a straight line, and said, 'right there—that's where it's going to be.'"

As at previous encounters, Stone led daily press briefings, unveiling the latest pictures and findings. Neptune was the last stop of the Grand Tour, and in the months of the approach, scientists planned to end with a big press conference. "We wanted to go out in style," Ingersoll says. But many were nervous—what if the moons were dull, and there was nothing except for four storms they already knew existed? Cornell's Carl Sagan, a member of the imaging team, told him not to worry, Ingersoll remembers. If there was nothing but four storms, then that's all they would talk about. But with all the surprises Voyager had produced so far, maybe they should have known better by then. In addition to the swirling storms, they found blasting winds, discovered rings and ring arcs, and detected a tilted magnetic field like Uranus's. Neptune's moon, Triton, had faults, ridges, volcanic calderas, and erupting geysers, all on a frozen world without the gravitational squeezing that powered Io. "It was a fantastically interesting place," Ingersoll says.



This illustration shows the locations of Voyagers 1 and 2. Voyager 1 has ventured into the heliosheath, the region where the slowing solar wind presses out against the incoming interstellar gas. Voyager 2 joined its partner when it crossed the termination shock at the end of August 2007. (NASA/Walt Feimer)

Worthy of Legend

While the engineers, overcoming problems from billions of kilometers away, were heroes, Ingersoll says, "The other heroes were the planets themselves—they came through. They came through with better stuff than we could have anticipated." Because of Voyager, these distant planets and moons were transformed from distant dots to dazzling characters, heroes worthy of their legendary namesakes from the pages of Roman mythology and Shakespeare. "Every day, we were looking at things no one had seen before," Stone says. "It was a period of intense discovery." Each planetary approach lasted about three months, and during this time, raw images would flash on the monitors all over JPL and NASA. "People would be sitting in the cafeteria and [looking at the monitors] say, 'God, what is that?'" Ingersoll says. "It was the best science I've ever been involved with."

The mission itself has become legendary. During its planning stage in the early '70s, Voyager rode the confidence that stemmed from beating the Soviet Union to the moon in 1969. But moonwalks rapidly became commonplace, and with the Vietnam War, Watergate, continuing Cold War conflicts, and an arms race, American optimism waned. "The climate changed in this country when Americans developed doubts about themselves," Vogt says. Voyager, on the other hand, with its message to the stars in the form of a golden record encapsulating Earth in sounds, music, and pictures, represented the human spirit. In a time of uncertainty and mistrust, when the specter of nuclear war was real, Voyager exemplified the best of humanity.

Space, as an emblem of brighter possibilities, remained embedded in the American psyche. Along with the popularity of the *Star Wars* and *Star Trek* films in the late '70s and the '80s, Voyager did its part to fuel the fascination with space. "It resonated with this idea that space is a future for humanity via robotics or humans," Stone says. "Voyager was symbolic of humans reaching out into space."

The Final Chapter?

Voyager 1 crossed what's called the termination shock in December 2004. The solar wind spews outward from the sun at speeds of 300 to 700 kilometers per hour, and as it approaches the interstellar wind—streams of particles from other stars—it abruptly slows, forming the termination shock. Voyager 2 just crossed the shock at the end of August 2007. Both spacecraft are now exploring the heliosheath, the outer layer of the heliosphere. At 15 billion kilometers away, Voyager 1 is the most distant human artifact. No one knows for sure how big the heliosphere is, but scientists estimate the spacecraft will leave the teardrop-shaped bubble, cross the heliopause, and enter interstellar space in about 10 years. The Voyagers will then be cruising through particles not from the sun, but from other stars and the stellar explosions called supernovae.

Although Vogt left the mission to become Caltech's provost in 1983, he still keeps tabs on Voyager's findings as it approaches the goal he envisioned more than 30 years ago. "I wanted to get the hell out of the solar system and measure pristine, galactic stellar stuff—stuff we are made of," he says. The Big Bang created only the lightest elements, from hydrogen through beryllium. Anything heavier was created in the cores of stars and during supernovae. Spread across the universe by these massive blasts, the brand-new atoms eventually became everything from planets and moons to humans and rubber ducks. "This is something extremely romantic, to think that we are star stuff, that at one time the atoms we are made of were in a star that exploded, expelled us, and ultimately became the solar system and organic stuff," Vogt says.

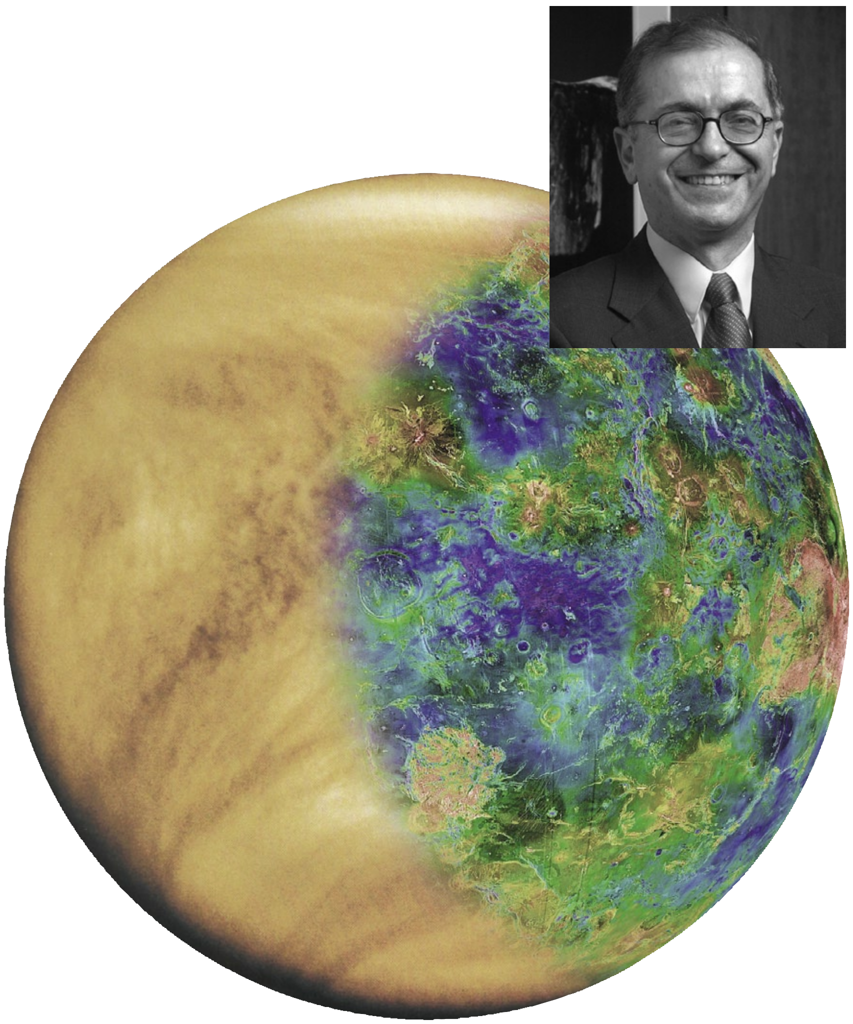
In the solar system, Vogt's cosmic-ray instrument measured the solar wind and magnetic fields. Now, in addition to understanding supernovae, it will help scientists learn how the sun interacts with the surrounding interstellar medium. In the end, Voyager's mission has always remained the same: to learn what's out there.

Even when the two spacecraft exhaust their power and communication with Earth stops, they will continue hurtling through space. Maybe they will encounter another civilization, and, if they do, they'll have quite a story to tell. □

PICTURE CREDITS: 19-23—NASA/JPL-Caltech; 19-21—Doug Cummings; 24—NASA/Walt Feimer

What Lies Beneath

by Douglas L. Smith



An ultraviolet image of Venus's clouds as seen by JPL's Pioneer Venus Orbiter in 1979 is "peeled" away to reveal Venus as mapped by more than a decade of radar investigations culminating in the Magellan mission. The colors are keyed to elevations, from blue basins to red mountains. Inset: Elachi was a member of Magellan's science team.

"I have never received in my life a paycheck which didn't have Caltech on top of it," laughs Charles Elachi, professor of electrical engineering and planetary science and director of the Jet Propulsion Lab. "You could say I'm a lifer." Elachi will have been at Caltech for 40 years come this fall, and in his tenure has helped explore Venus and a moon of Saturn, headed three projects that were flown on the Space Shuttle, and shepherded to maturity a technique that has revolutionized the earth sciences. He arrived as a grad student in 1968, earned his MS in electrical engineering in 1969, and got a summer job at JPL in 1970. "And one of the group's supes [JPL slang for supervisor] said, 'Well, gee . . . you look like you know something about electromagnetic waves. We're just starting to look at a Venus mission to image the surface with radar. Would you be interested?' And I said, 'Sure, that's great.'"

Venus's terrain cannot be seen directly, because it is hidden by a thick veil of sulfuric-acid clouds. Rough radar maps had been made from Earth that showed continent-sized features, but not much else. One of these had been made by Professor of Planetary Science, Emeritus, Duane Muhleman, using JPL's then-64-meter Goldstone antenna, part of the Deep Space Network, which is used to communicate with far-flung spacecraft. "So I was going to JPL one or two days a week while I was finishing my PhD," Elachi recalls. After being awarded his doctorate in 1971—his thesis being on the propagation of radar waves through periodic media—he joined JPL full-time to work on the Venus Orbiting Imaging Radar. But, he says, "the budget was not that great for planetary missions. So it took a long time to get that mission designed and approved." VOIR, pronounced like the French *voir*, as the project was known in JPL-speak, eventually flew in the 1990s under the moniker Magellan.

While thinking about mapping the arid continents of Venus, Elachi also began using radar to look at Earth's oceans. JPL's Seasat, an oceano-

This 50-kilometer-wide strip of SIR-A data, superimposed on a Landsat simulated true-color mosaic of the Sahara, shows ancient river beds buried beneath the sand.

graphic satellite, carried the first civilian spaceborne imaging radar. This instrument recorded the surface roughness of the ocean—what in layman's terms are called waves—to map wind speeds and directions. The radar also measured the sea-surface height to reveal hidden currents. Warmer water occupies more volume than cooler water, giving the ocean a topography all its own, and of course water flows downhill. Developing the hardware and the analytical techniques for Seasat meant testing the prototypes in a NASA Convair 990—a four-engined jet converted into a research aircraft. "That was a fun period, because I did a lot of flying on the aircraft, going to Alaska, and going to West Africa, particularly Dakar [Senegal]. We were stationed there for like three weeks."

Like all radars, Seasat bounced a microwave signal off a distant object, and calculated how far away it was by how long it took the signal to return. But this radar was in motion—the satellite moving forward, the instrument scanning from side to side. Thus the signal returning from any point on the surface below had its own particular two-component Doppler shift along and perpendicular to the radar's flight path. Since the radar's motion relative to the surface was very accurately known, some fancy but relatively straightforward computer processing could gather up all the echoes from any given point, combine them into a single pixel, and make a detailed picture of the terrain below. This technique is called Synthetic Aperture Radar, or SAR, because the aperture size of the radar camera is the distance it travels while one pixel on the ground remains within the field of view—a synthesis of many radar echoes, in other words.

Unlike an ordinary picture made with visible light, the brightness of each pixel in a SAR image is proportional to its roughness—calm seas appear black, for example, and choppy waves bright gray. On dry land this means that rocky deserts or leafy vegetation will appear brighter than parking lots. The surface's moisture content is revealed as well—the damper the soil, the more brightly it reflects. Perfectly dry sand is actually transparent to some depth, a property that would prove to be more than a thesis chapter.

Seasat flew for a mere three months in 1978, but it demonstrated SAR's usefulness, and has since led to several generations of orbiting ocean-mapping radars called scatterometers.

Bolstered by this success, Elachi, by now in charge of JPL's radar-mapping group, decided that they should try to put SAR on the Space Shuttle, which was to make its maiden flight in 1981. "Those were the days where we used to sit down and draw things on a map," Elachi says. "Not like now. We didn't have all the computers. In 1980, my wife and I bought a townhouse up in Mammoth. We used to take six, seven people, and between skiing, we'd sit down and plan the shuttle orbits. We'd strew all these big maps on the floor and draw by hand where we wanted to take the data and so on."

Elachi proposed a radar so big it would take up a shuttle's entire cargo hold—the bigger the antenna, the sharper its vision. The Shuttle Imaging Radar (later known as SIR-A) rode *Columbia* on its second flight, which lifted off on November 12, 1981, and landed all of two days later due to a leaky fuel cell. "So here I am in my late 20s, having the major payload on the first shuttle flight after the test flight," Elachi remembers. "And a couple of weeks before the launch, the NASA administrator called and said, 'This is the first mission that we have some science on the shuttle, so it'd better work!' So that added a little bit to the drama."

The mission succeeded beyond anyone's wildest dreams, revealing a subsurface network of ancient drainage channels beneath the bone-dry sands of the Sahara. But because the mission was cut short, the carefully planned observational campaign went straight out the cargo-bay door. Recalls JPL's Ron Blom, whom Elachi had hired as the team geologist, "All we could do was take images whenever we went over land. The fact that it happened to be the Sahara was pure serendipity. And when we saw the images, we couldn't believe it. There must have been some mix-up in the labeling—this couldn't be the core of the Sahara, one of the driest places on Earth."

Fortunately, a U.S. Geological Survey crew from Flagstaff, Arizona, happened to be working in Egypt, studying the Saharan terrain as a possible Mars analog. "They knew exactly where they were [on our images], and they had seen hints [of ancient washes] here and there," Blom continues. "But they couldn't get a global picture. And they realized that if they could validate this, they could map the whole Tertiary drainage of the region up to about 6,000 years ago." In fact, the USGS folks had already written a paper on those channels' existence, the galley proofs of which showed up in the desert in September 1982 after Elachi and Blom had joined the Survey party to see just how deep the radar had actually penetrated. Digging holes down to the buried streambeds showed that SAR could see through two meters of parched sand with ease; Elachi would later calculate that depths of up to six meters were theoretically possible under ideal conditions. The USGS paper, needless to say, wound up being substantially rewritten, with the JPL duo being added to the author list. It made the cover of *Science*.

The expedition, supported by the Egyptian government, used Russian jeeps to get around. "The windows didn't roll down," Blom recalls. "They were bolted in; they were designed for Siberia. And of course there was no air conditioning. So first thing every morning you made the choice of either eating dust all day and being semicool, or staying dust-free and roasting."

Wherever the team came across one of the underground washes, they found stone tools scattered everywhere. "You were literally walking on them," says Blom. "It was a deflationary surface, so they were all mixed together, bad for archaeology. But as recently as 6,000 years ago, this had been a savannah, and it had clearly been intermittently inhabited when the climate was favorable." Blom and the others picked up a few as souvenirs, but "I looked around, and there was Charles stuffing bags full of them. He understands intuitively what motivates people, and plays that back to them. He gave the rocks out to everyone at NASA HQ. And behold, SIR-B followed two weeks later."

Elachi is a bit more modest. "Fortunately, that mission worked very well. And within two weeks of that flight, NASA asked me to submit a proposal for a follow-up. And within another two weeks they approved it, which was unusual." SIR-B flew on the *Challenger* on October 5, 1984, and landed seven days later. SIR-B had the capacity to look at the same piece of terrain at multiple angles, improving feature discrimination.

Elachi was still a research fellow at Caltech during this time, spending a day or so a week on campus with Professor of Electrical Engineering Charles Papas, his PhD advisor. He also got an MS in geology from UCLA in 1983 to help him understand what the radar was seeing.

Elachi would soon be given yet another hat to wear. "That was a period of growth at JPL in scientific instruments. We had a number of first-rate, relatively young scientists who were all proposing very successfully, particularly in Earth observations. So all of a sudden, instruments became a big business." In 1987, Elachi was put in charge of all instrument development at JPL and was invited to sit on JPL's executive council.

Meanwhile, Magellan—the spacecraft formerly known as Venus Orbiting Imaging Radar—was ramping up, a scaled-back version having finally been approved. This stripped-down spacecraft had one main antenna, a Voyager spare, to both map Venus and send the data back to Earth. The loss of a second high-gain antenna and the fact that the one they *did* have didn't pivot (another cost-cutter) meant that the whole spacecraft had to rotate itself away from Venus and toward Earth once per orbit to transmit its images. Magellan rode the shuttle *Atlantis* into space on May 4, 1989. By mission's end, the radar had mapped 98 percent of Venus's surface to a resolution of about 100 meters, sharp enough to make out features the size of the Rose Bowl, in 3-D—a better topographic map of the whole planet than was available for Earth at the time.

Elachi was a member of Magellan's science team, headed by MIT's Gordon Pettengill. "Because of my background in radar, I was mostly making sure that we had the right parameters for the instrument. I looked at how the radar wave would be propagating through the heavy atmosphere of Venus, whether it would be refracted. I and a couple of other resident scientists at JPL worked very closely with the mission people at JPL and the spacecraft people at Martin Marietta [now the

JPL's radar-mapping group crowns Elachi the "Czar of SAR" circa 1979. Front row, from left: Sue Conrow; Annie Richardson; Judy Ribera; Elachi; JoBea Holt (MS '78, PhD '82), the SIR-B project scientist; and Mike Daily. Back row: John Ford; M. Leonard Bryan; Don Harrison; Ladislav Roth; Mike Kobrick, the SRTM project scientist; Vickie Arriola; Andy Gabriel (MS '78, PhD '81), the key developer of the InSAR method; Dee Baker; Blom; and Peter Palluzzi.

"In that period of 10 years, we took spaceborne synthetic-aperture radar from being a curiosity to becoming a credible scientific tool," Elachi beams.

In this SIR-C image, sand dunes are magenta and limestone is green. "Ubar" sits just above the dry wash (light band) at center. Many tracks (red streaks), both ancient and modern, converge on the site from the south, but only one leads out into the desert to the north.

Lockheed Martin Corporation] and the instrument people at Hughes Aircraft, making sure that we had the right wavelength and polarization, the right digitization, the right data deconverters. We were the link between the science team and the engineering team." Although the radar was built by Hughes, it was designed in Elachi's section at JPL; after the launch, his section did the image processing. He was also part of the JPL team that oversaw the spacecraft's construction.

While mapping Venus, Elachi still found time to head the SIR-C mission, the third shuttle radar. SIR-C was packaged with a German-Italian radar called X-SAR that used a different wavelength, which allowed it to see different things—an object reflects radar most brightly when it's about the size of the radar's wavelength. The combo flew twice on *Endeavour*, on April 9–20 and September 30–October 11, 1994. Like SIR-A, SIR-C broke new ground. Or, more accurately, revealed where the ground had been compacted. These passes over the Sahara revealed ancient trade routes through the desert, invisible to the uninitiated on the ground, but betrayed as thin dark lines where millennia of camel trains had trod the sand to firmness. The shuttle's flight path was adjusted to take it over Oman on the Arabian Peninsula, where the "lost city" of Ubar, a key staging area on the frankincense trade route, supposedly lay. T. E. Lawrence, better known as Lawrence of Arabia, called Ubar "the Atlantis of the Sands." In a Koran story very much like that of Sodom and Gomorrah, the wickedness of Ubar's inhabitants moved a fed-up Allah to cause the city to be swallowed up by the earth. And sure enough, the dark tracks converged at a small oasis in the Rub' al-Khali desert (Arabic for "Empty Quarter," and if the locals think it's empty, you *know* it's inhospitable!)—a sinkhole in whose depths archaeologists have since found the ruins of mighty walls, and artifacts dating back to the Bronze Age. (SIR-C's flight was delayed for several years by the *Challenger* disaster, and in the meantime carefully processed Landsat images had given some similar results. The full story of the search for Ubar can be found in *Caltech News*, April 1992.)

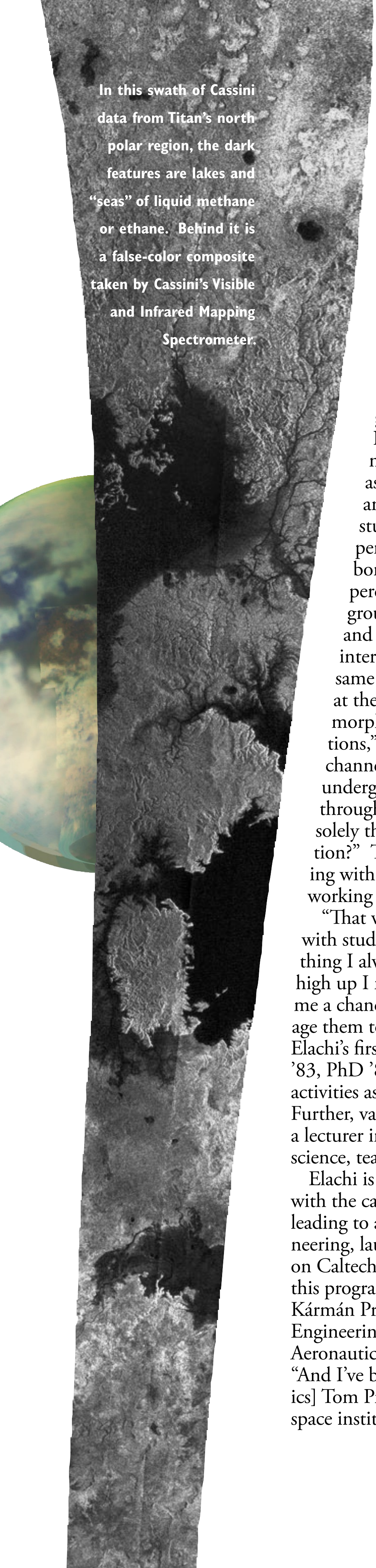
"I leave it up to the archaeologists to decide if it was really the city of Ubar, or some trading post along the way," says Elachi. However, since he was born in Lebanon, the quest had a special resonance for him. As a child, "archaeology was all around me, and everything was thousands of years old everywhere I went. I grew up a few miles from a place called Baalbeck, which has some of the most famous Roman ruins in the Middle East." Elachi has now been to 30 or 40 countries doing fieldwork, he estimates, including a number of archaeological expeditions. "That was fun. I've been to Tibet and western China and Australia and Oman and Arabia and Egypt."

Other team members used SIR-C to do archaeology as well. Diane Evans studied the temple complexes of Angkor Wat in Cambodia; others located lost cities in the Yucatan. More importantly, SIR-C's two flights, five months apart, demonstrated SAR's potential for mapping and monitoring vegetation changes. "In that period of 10 years, we took spaceborne synthetic-aperture radar from being a curiosity to becoming a credible scientific tool," Elachi beams. SAR has caught on worldwide. The Europeans launched their first SAR satellite in 1991 and are now operating their third. The Japanese have launched two, and the Canadians are about to launch their second.

SAR's latest incarnation, called the Shuttle Radar Topography Mission, or SRTM, has finally done for Earth what Magellan did for Venus. SRTM used two antennas to map features in a manner roughly analogous to stereo photography, and rode *Endeavour* on February 11–22, 2000. "The radar effort has gone from being a small group to now a couple of hundred people," Elachi says, "and JPL is probably the world leader in spaceborne imaging radar." Elachi, still boundlessly energetic, oversaw SRTM but was no longer the principal investigator, his managerial responsibilities having started to monopolize his time.

Yet another mission was in the offing. Cassini, which would orbit Saturn, was approved in the early 1990s, and Elachi formed a team to design and build a radar to map cloud-covered Titan, a moon of Saturn thought to have methane seas under its smoggy skies. "So here I was juggling starting Cassini, flying SIR-C, and operating Magellan. And at the same time, I was director for space science and instruments, responsible for all scientific activity and instrument development at JPL. So that was a very busy period, but I was still doing a lot of science at the same time as doing the management."

Elachi had been a lecturer at Caltech since 1982, teaching a very popular class two afternoons a week on the physics of remote sensing. "Arden Albee was my cofaculty, and he used to take the students into the field during spring break, mostly



In this swath of Cassini data from Titan's north polar region, the dark features are lakes and "seas" of liquid methane or ethane. Behind it is a false-color composite taken by Cassini's Visible and Infrared Mapping Spectrometer.

to Owens Valley and the Mojave. He'd show them on the ground how to interpret the images that they'd learned about in class." While Albee was helping the students match what they'd seen from space with what was in front of them, Elachi usually took some much-needed rest.

Elachi was promoted to professor in 2002, the year after he became director of JPL. (The appointment was announced on January 31, 2001, on the 47th anniversary of Explorer 1's launch. "So that was kind of a neat event," he smiles.) He doesn't take on grad students of his own, but he sits on PhD committees and coadvises. Right now, for example, he, Oded Aharonson, assistant professor of planetary science, and grad student Alexander Hayes are studying Titan's hydrological cycle, or perhaps one should say Titan's hydrocarbonological cycle. On Earth, rainwater percolates through rock and soil into underground aquifers. If the water table is high and the topography is low, these aquifers intersect the surface and fill lakes. Does the same thing happen on Titan? "We're looking at the lakes' geographical distribution and morphology, and their subsurface connections," says Aharonson. "There are surface channels, of course, but what's going on underground? Do they drain into each other through subsurface aquifers, or are the lakes solely the product of precipitation and evaporation?" Their work combines computer modeling with analyses of Cassini images, and Hayes is working on a paper for publication next year.

"That was something I always liked, dealing with students," says Elachi. "That was one key thing I always did in my career, no matter how high up I moved into management. And that gave me a chance to pick some of the best, and encourage them to come work at JPL." For example, Elachi's first teaching assistant, Jakob van Zyl [MS '83, PhD '86] is now in charge of all astrophysics activities as a member of the JPL executive council. Further, van Zyl is a Caltech faculty associate and a lecturer in electrical engineering and planetary science, teaching the class Elachi started.

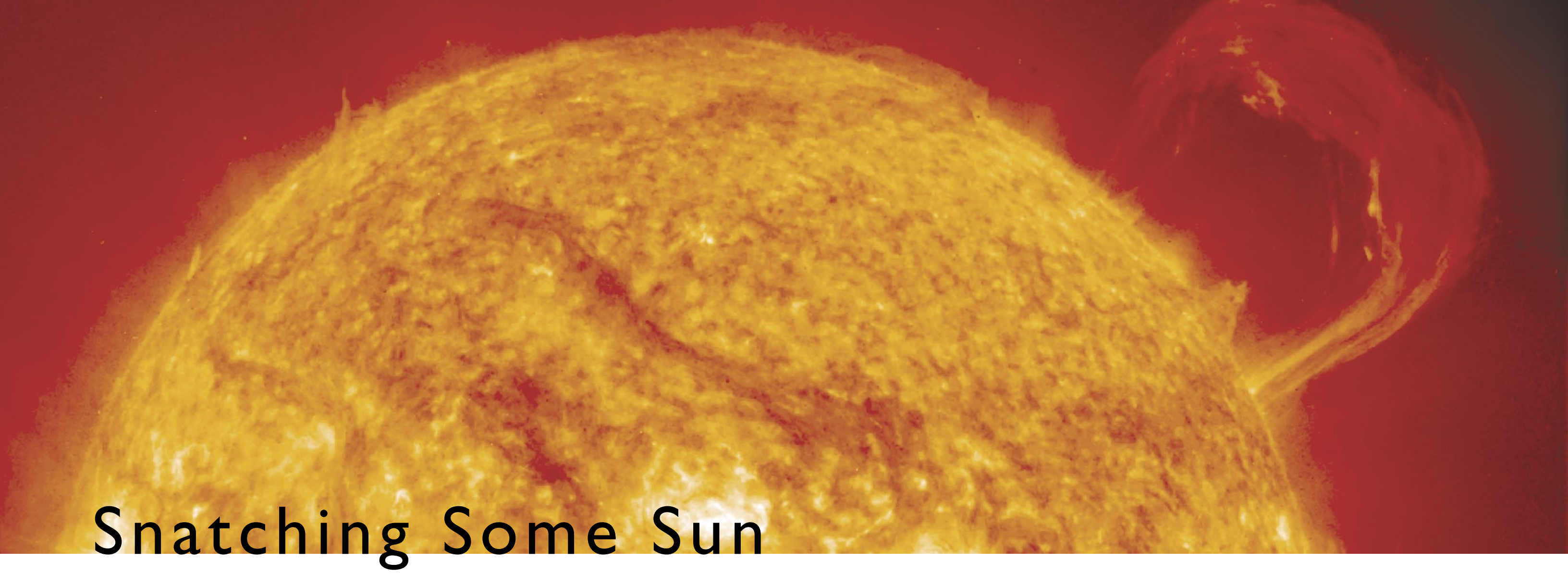
Elachi is also involved in two joint initiatives with the campus. He's helping set up a program leading to a master's degree in aerospace engineering, launched this year, which capitalizes on Caltech's association with JPL. (More about this program, initiated by Ares Rosakis, the von Kármán Professor of Aeronautics and Mechanical Engineering and director of Caltech's Graduate Aeronautical Laboratories, in an upcoming issue.) "And I've been working with [Professor of Physics] Tom Prince on the possibilities of having a space institute on campus—a think tank for what should be done in space science and technology in the future, but also policy discussions. Bring key players from around the world into an academic environment, and think about what should be done in the next couple of decades."

"What I enjoyed in particular is that most of my work was at the crossroad between engineering and science. I had to work with geologists and planetary scientists, atmospheric scientists, orbit people, spacecraft design people, electrical engineers, and that's what makes it fun." Blom thinks this is the key to Elachi's success as director—"JPL is a different animal to different people. The scientists think it's one thing. The engineers think it's another, and the Mars people a third. Everyone sees it differently. But Charles has been immersed in both engineers and scientists, and he knows how each thinks."

Elachi says that "for me now the joy of what I'm doing is really seeing all the young people at JPL carry it on. It looks like in the next decade we'll be launching as many spacecraft as we did in the last decade. We'll be looking for life in our solar system—Mars missions and Europa and Titan. Looking at the neighboring few thousand stars and seeing if there are planets around them. Taking their family portraits. And looking at the cosmic background, looking for gravitational waves, and what dark energy and dark matter are all about. And Earth observation—I started my career at JPL with Seasat, and my goal, before I retire, is to have an operational spaceborne imaging radar flying."

He may achieve this, too—a recent National Academy of Sciences report, setting goals for the earth sciences for the next decade, listed a mission called InSAR as one of the top three priorities. InSAR, for Interferometric SAR, would fly in a polar orbit to give global coverage of the planet and would track the movements of the ground under our feet—bulges that might signal upcoming volcanic eruptions, the stretching and compression of tectonic plates along fault lines that might herald an earthquake, and so forth—as part of a worldwide campaign to assess high-risk natural-hazard areas. InSAR would also measure and monitor ice motions, and keep tabs on the biomass—the amount and types of vegetation—tracking seasonal and longer-term variations to assess the effects of climate change. "It would be a nice bookend. It's been targeted for sometime in the 2012–2015 time frame." □

PICTURE CREDITS: 25, 28, 29 — NASA/JPL-Caltech; 29 — NASA/JPL/University of Arizona



Snatching Some Sun

by Marcus Woo

The Genesis sample-return capsule isn't buried in the ground—it's smashed. The capsule crashed near Granite Peak on a remote portion of the Utah Test and Training Range.

Out of the yawning September sky, pieces of the sun tumbled toward the Utah desert. They were captured solar particles, holding clues to the birth of the solar system, and being returned to Earth in a shiny, 200-kilogram capsule. The plan was for parachutes to slow the pocket-watch-shaped craft, allowing a helicopter to swoop in, snatch it from midair, and gently lower the fragile contents to the ground. But on this bright morning in 2004, the parachutes didn't open, and the helicopter didn't have a chance. The capsule spun and wobbled as it plunged into the ground at more than 300 kilometers per hour.

The capsule was a mangled mess. The ground had smashed it open, shattering the delicate wafers that held the tiny solar particles, spilling them onto the desert floor. To some, the three-year, three-million-kilometer trip, costing hundreds of millions of dollars, years of sweat, and decades of thought, looked like it was for naught. On the *NBC Nightly News*, anchor Tom Brokaw called the crash a "sad and bizarre end to this epic journey." For the mission called Genesis, the failed landing seemed like a literal fall from grace.

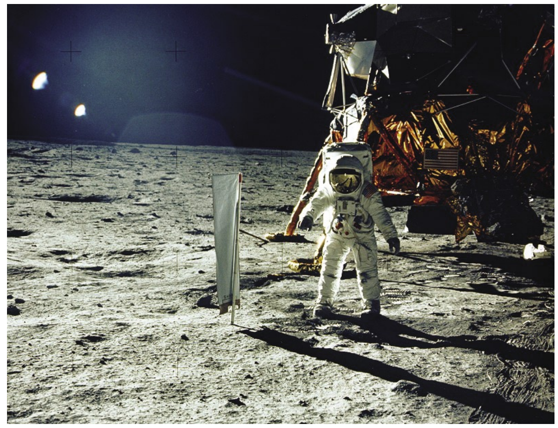
Mission scientists were more hopeful, however, and hunkered down to see what they could salvage. "We went out and picked up the pieces," says Donald Burnett, professor of nuclear geochemistry, emeritus, and the Genesis principal investigator. The particles scientists were looking for were individual atoms—the elements and isotopes that make up the sun. "You couldn't destroy the atoms in the crash," he says. "The only thing you can do is contaminate them." The atoms were embedded in the wafers, and as long as some surviving pieces were large enough for instruments to analyze, the mission was still alive. After several days of sifting and sorting, they found everything from powder to entire wafers. Cleaning off the Utah dirt and bits of capsule that were mixed into the samples would prove challenging, but the mission was anything but a failure.

Even now, scientists still have lots of cleaning to do, but after more than three years they are slowly arriving at some notable results, including the answer to a decades-long mystery about neon isotopes in the lunar soil. Researchers say they are confident they will complete most—if not all—of the experiments they planned for. All they need is enough time.

In the Beginning, There Was a Big Cloud

Genesis launched on August 8, 2001, but its origins lay more than 30 years earlier on the moon. The Apollo missions had amazed the world, capturing people's imaginations and a space-race victory for the United States. But the astronauts did more than plant flags and take small steps for man and giant leaps for mankind. They also did science experiments, including one designed by researchers at the University of Bern to catch solar-wind particles.

A giant force field called the magnetosphere surrounds Earth, protecting it from the solar wind and other energetic particles from the sun. If researchers want to collect solar wind particles, they have to do it away from Earth—in space or on the moon. During Apollo missions 11 through 16, with the exception of ill-fated number 13, astronauts collected the solar wind with a big sheet of aluminum foil—they used platinum for 16—propped up on a pole. But since they were on the moon for only a few days, the experiment didn't last long, ranging from 77 minutes for Apollo 11 to less than four days for 16. The foil took an inventory of the wind's elements and isotopes, which are atoms of the same element but with a different number of neutrons.



Apollo 11 lunar module pilot Buzz Aldrin sets up an aluminum sheet to collect the solar wind. This was the first of the Apollo missions' many solar wind composition experiments.

"Isotopic geochemists ooh and aah over a half-percent difference—this was 38 percent!" Burnett explains. "That was just mind-boggling to someone used to thinking of things that were a fraction of a percent."

In particular, researchers looked at the ratio of neon-20 to neon-22 (neon-20 has 10 neutrons while neon-22 has 12). The ratio is about 9.8 to 1 in Earth's atmosphere, but Apollo's lunar foils found a ratio of around 13.7 to 1 for the solar wind—a vast difference that stunned researchers. "Isotopic geochemists ooh and aah over a half-percent difference—this was 38 percent!" Burnett explains. "That was just mind-boggling to someone used to thinking of things that were a fraction of a percent."

But what's the big deal if some isotope ratios are different between Earth and the solar wind? It's that the relative amounts of isotopes and elements are fingerprints left behind by the formation of the solar system. Tracking the isotopic and elemental composition of planets, moons, and asteroids tells scientists how well their models explain the solar system's history. For example, measurements of hydrogen-isotope ratios in Venus's atmosphere suggest that the planet lost a lot of hydrogen in its past. Deuterium is hydrogen with an extra neutron, and deuterium-hydrogen ratios in the outer layers of the Venusian atmosphere are higher than the original amount in the universe as a whole. Since hydrogen is a component of water, the hydrogen loss implies water loss—the isotope measurements imply Venus could have once had bucketfuls of water.

To compare ratios among isotopes, researchers need to know the composition of the cloud from which the sun, planets, moons, comets, asteroids, and assorted rocks and dust specks all formed—the solar nebula. According to standard theory, the solar system used to be a cool cloud of molecular gas, only a few tens of degrees above absolute zero. Then something—possibly a bump from a shock wave made by a distant exploding star—caused it to begin collapsing on itself by its own gravity. As the cloud collapsed, it began to spin, flattening out like pizza dough twirled into the air. The cloud's core grew in density and pressure until it was hot enough for hydrogen atoms to slam into each other, releasing nuclear energy. The sun was born. Meanwhile, the outer regions of the cloud coalesced to form the planets and everything else.

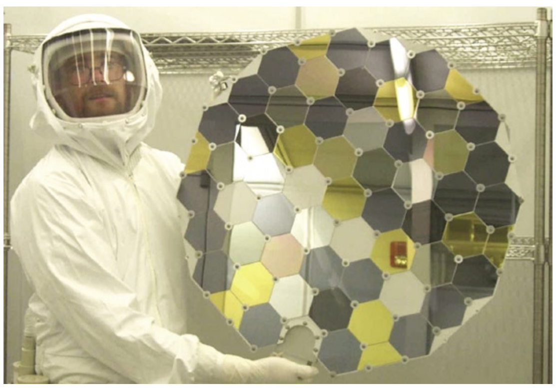
The sun makes up 99 percent of the solar system's mass, so for all intents and purposes it *is* the solar system—and the main product of the solar nebula. Inside the sun, many reactions and processes have changed its composition. But in the sun's outer layers, you should find the same distribution of elements and isotopes that once populated the solar nebula. The sun continuously ejects its outer layers as solar wind, and by capturing the wind, scientists have a piece of history, stretching back to the solar system's birth 4.6 billion years ago.

Comparing the composition of the solar wind—and therefore the solar nebula—with that of other bodies allows researchers to better piece together the story behind the solar system. The Apollo experiments, which first showed the astonishing difference in neon-isotope ratios between Earth and the solar wind, were the inspiration behind Genesis, Burnett says. But not until two decades after Apollo, in 1992, when NASA launched its

Discovery program to push for "faster, better, cheaper" missions to explore the solar system, did Genesis come to fruition. Led by Burnett and Marcia Neugebauer, a distinguished visiting scientist at JPL, the mission would be the first to return samples from outer space since the Soviet Union's Luna 24 brought back moon rocks in 1976.

Here Comes the Sun

Genesis would be a big improvement over the Apollo experiments. Instead of for a couple of days, Genesis collected solar particles for two years, and in place of aluminum foil on a stick, Genesis used 250 hexagonal wafers 10 centimeters wide, made of materials such as silicon, sapphire, diamond, and gold. The wafers were arranged on five collector arrays, three of which rotated in and out to sample the solar wind as experiments dictated, while the other two remained exposed at all times. The materials were chosen to enable researchers to analyze different elements and isotopes. Instead of just the few noble gases the Apollo experiments caught, Genesis cast a wide net to collect as much of the periodic table as it could, stockpiling data for future studies in order to make this the one and only trip ever needed to sample the solar wind. It's the most extensive and best-controlled solar wind collection ever done.



JPL's Andy Stone holds up one of the five collector arrays. Each array holds 50 hexagonal wafers of different materials.

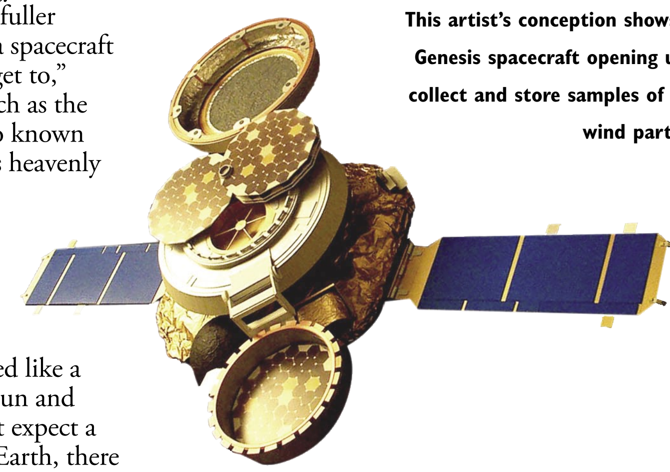
After launch, the spacecraft cruised for three months before arriving at a location between the sun and Earth called L1, or the first Lagrange point. Only 1 percent of the way to the sun, L1 is where gravity from the sun and Earth cancel each other out, resulting in a partially stable place for a spacecraft to occupy with minimal energy—and minimal cost (see *E&S* 2002 no. 4 for a fuller explanation). "It's a great place to park a spacecraft and observe the sun because it's easy to get to," Burnett says. Many other spacecraft, such as the Solar and Heliospheric Observatory, also known as SOHO, have also found a spot in this heavenly parking lot.

Unlike in a parking lot, however, spacecraft at L1 don't just sit in one place. Genesis, for instance, followed a halo orbit, in which it spent two years looping around an empty point in space. During its orbit, Genesis opened like a pocket watch, exposed its wafers to the sun and began to trap solar wind particles. Don't expect a lot, though. The wind is diffuse—near Earth, there are only five to ten particles per cubic centimeter. Genesis collected a total of 0.4 milligrams of solar wind.

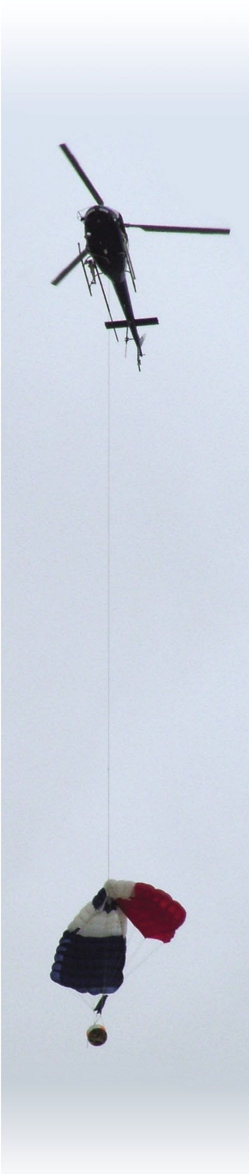
After 27 months of sunshine, Genesis started the five-month journey home on April 22, 2004. Upon arrival at Earth, the spacecraft released the capsule that contained the solar samples. As the spacecraft hurtled away into the depths of space, Earth's atmosphere slowed the capsule's descent. Its final trajectory sent it toward the U.S. Air Force's Utah Testing and Training Range, an arid landscape 130 kilometers southwest of Salt Lake City. There, in a scene worthy of an action movie, Hollywood stuntmen piloting helicopters were to snare the capsule as it drifted down by parachute, and bring the precious cargo to the scientists like a stork delivering a baby.

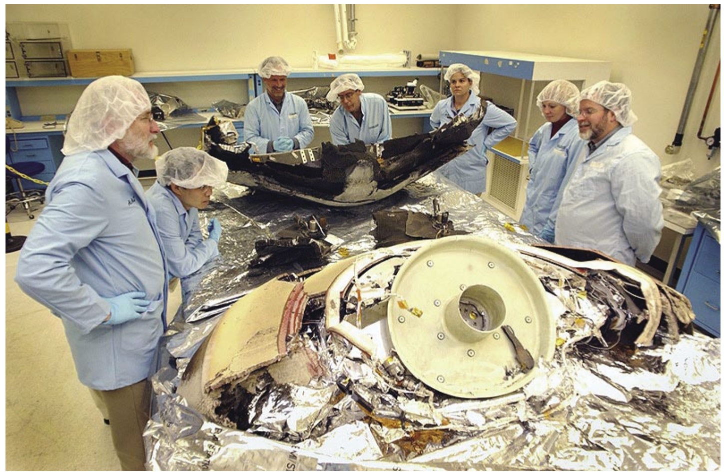
Unfortunately, the team never got to show off its deft maneuver, as the parachutes never opened and the capsule crashed, leaving the helicopters hovering without a package to snag. Had it worked, however, it would've been quite the spectacle—although the scientists weren't in it for the added drama. "We did it for a reason," Burnett says. "We were worried about things breaking." A conventional parachute-assisted landing would have been too risky for the thin and fragile wafers. If gusts of wind blew while Genesis landed, the capsule could hit the ground and tumble, smashing the precious cargo and costing extra time and money to sift through the pieces. That, of course, was exactly what ended up happening. The plan was sound, however, and the only safe option, Burnett says. "We thought it was worth an extra million dollars or so to pick the thing out of the air just to allow us to stay on schedule," he explains. "This was deemed technically feasible, and frankly, it looked like a lot of fun—and it was." During practice, the recovery team was perfect, but on the big day, the landing was anything but fun.

This artist's conception shows the Genesis spacecraft opening up to collect and store samples of solar wind particles.



A specially modified helicopter with a boom and winch underneath snags the parafoil chute attached to a model Genesis sample-return capsule. The hook on the end of the boom collapses the chute, allowing the helicopter to retrieve the capsule in midair.





Large sections of the Genesis sample-return capsule that survived the hard landing were shipped to Lockheed Martin's facilities in Denver, Colorado. Here, engineers begin inspecting the wreckage to figure out why the capsule crashed.

A Smashing Success?

"On September 8, 2004, the Genesis project literally hit bottom," Burnett says. Along with the team, he watched the descent on television monitors at the control center, several kilometers from where the capsule was supposed to land. The cone-shaped drogue chute, which would have provided stability until the main chute deployed, was supposed to have fired at an altitude of 108,000 feet. When the team realized the parachutes had failed, they hardly had enough time to react—the capsule would crash just 20 seconds later, Burnett estimates. But he didn't stick around to watch, he says. By the time the capsule had fallen to 3,000 feet, he had already taken off for the next building, where the recovery team was preparing to be helicoptered to the crash site, roughly 15 kilometers away. Despite the chaos around them, the science team was focused on the task at hand, too busy to worry about what went wrong, according to Burnett. The attitude was, "OK, it's crashed. Let's go out and see what we can get."

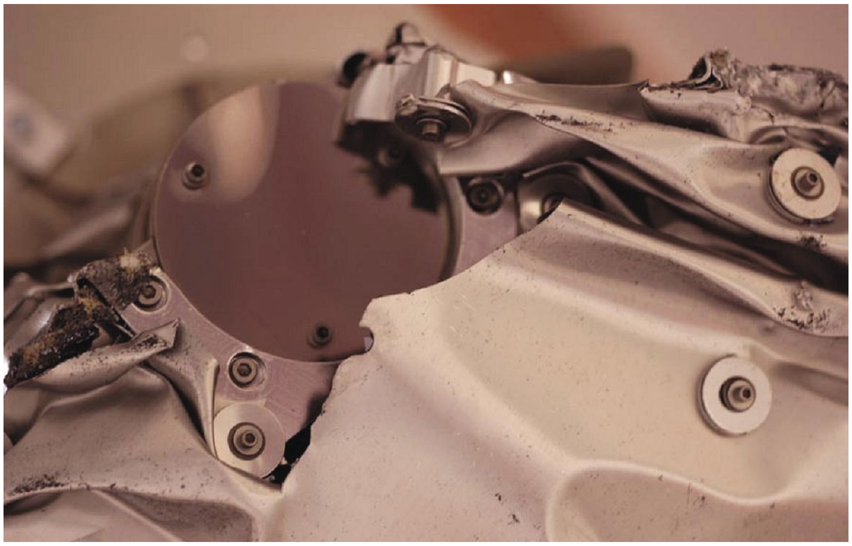
The team was afraid water would seep up from the ground at night and damage the samples, so they wanted to bring back the pieces the same day. The helicopters that were supposed to pick up the capsule from the air were instructed instead to carry the wreckage back to the control center. But by then, they had been flying around all day, and were running out of gas, Burnett recalls. Fortunately, the recovery team, which consisted of people from Lockheed Martin, which had built the craft, and NASA's Johnson Space Center, rescued most of the remains within a few hours—before the gas tanks went dry. They returned the next day to gather the smaller pieces, scooping up the dirt and bringing it back to the hangar where the team had begun digging through the mess of gnarled metal and shattered wafers. Meanwhile, JPL engineers had gone to a hardware store in Salt Lake City and bought every tool in sight, Burnett recalls. "They came back with this big truckload of tools and slowly started systematically crowbarring this thing apart."

With the JPL team prying the wreckage open for the science team to sort the contents, much of the work was finished within two weeks, according to Burnett. Some team members remained in Utah for several more weeks to complete the effort, and the wafer pieces were sent to the distribution center at Johnson Space Center in Houston.

Luckily for science, some macroscopic pieces survived. Had they all been crushed to smaller than three millimeters, instruments wouldn't be able to analyze them. Still, the ongoing process of picking through and analyzing so many bits has proven tedious—instead of 250 wafers, scientists have 15,000 pieces—and most of the pieces are tiny. "There are a lot more three-millimeter pieces than three-centimeter pieces," Burnett says. Meanwhile, the main problem is contamination. With desert dirt and minced scraps of capsule jumbled together, can researchers really clean the wafers?

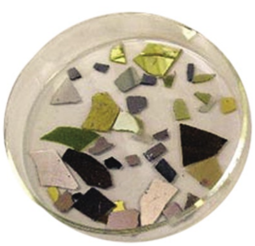
"We can!" Burnett says. "We can because the dirt is really on the surface and our sample is beneath the surface. It's not far, but it's safe—we can prove it's safe." The separation between the dirt and solar wind particles may only be 20 nanometers—20 billionths of a meter—so researchers can't just grind away the top layer. In one cleaning method, they put the material in a water bath. They then fire acoustic waves at microwave frequencies—hundreds of millions to hundreds of billions cycles per second—that jostle the water, dislodging the dirt. "We have to get rid of that dirt while basically taking off no material—not impossible, but a big challenge," he says.

In some experiments, researchers can dodge individual flecks of dirt. In others, dirt isn't even a problem, and for those, researchers already have noteworthy results. For example, contamination is a nonissue when analyzing elements like neon, since those elements aren't in the dirt to begin with.



The metallic glass wafer, designed to collect helium and neon isotopes, survived the crash. The material was the key to solving a decades-long mystery about the lunar soil.

The team also lucked out when special samples survived, such as a wafer made out of a material called metallic glass. "That's amazing," Burnett says. "If you had one material that I thought was too brittle and was going to break during the crash, it was that one." Developed in 1998 by JPL scientist Charles C. Hays while in the lab of William Johnson (PhD '75), Mettler Professor of Engineering and Applied Science, this metallic glass wafer is an alloy of aluminum, copper, nickel, niobium, and zirconium. Unlike regular metals, whose atoms are in a gridlike configuration, atoms in metallic glasses are arranged randomly, as they are in ordinary glass. This configuration makes for a better catcher's mitt for solar wind particles, Hays explains, as high-energy particles such as neon and helium, once embedded, are more easily trapped in the nooks and crannies of the material's random structure. Using metallic glass to catch solar wind particles is a first, and its survival has been crucial in solving a decades-long mystery about neon isotopes in the lunar soil.



The team recovered some relatively large wafer pieces from the crash site. The fact that these fragments survived means most, if not all, experiments can still be done.

Solving a Lunar Puzzle

Apollo's lunar soil samples, which had been exposed to the sun for thousands of years, returned some peculiar data about the solar wind. When researchers measured the neon-20 to neon-22 ratios in the samples, they found ratios clustering around two values, at about 13.8 and 11.2 to 1. The first value was a clear signature of the solar wind, since it agreed with what Apollo's aluminum foil experiments measured. The second value, however, was a mystery. Not only did it not fit with the familiar solar-wind signature, there was a lot of it, so much so that if these neon isotopes came from the sun, the data implied a strange surge of solar activity in the past.

A lower neon-20 to neon-22 ratio implied a higher prevalence of the heavier neon-22 isotope in the solar wind. The wind itself must then have had more oomph, penetrating deeper into the soil grains. To explain the curious data, scientists proposed a new component of the solar wind called solar energetic particles.

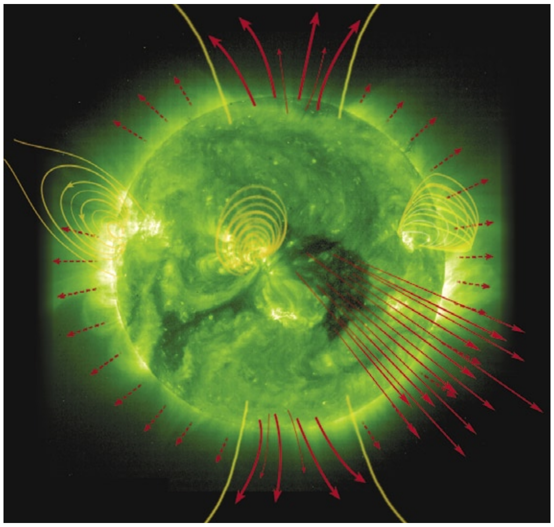
But using data from Genesis, a team from the Swiss Federal Institute of Technology in Zurich reported in 2006 that these solar energetic particles likely didn't exist, and that scientists had been misinterpreting the lunar soil data for 30 years. The key to solving the lunar puzzle was the metallic glass wafer. The researchers were able to release the isotopes layer by layer with a nitric-acid etching technique. The uniform etching revealed how the isotope ratios correlated with depth, which was not the case with the lunar soil. In the metallic glass, the researchers found that neon-20 to neon-22 ratios fell continuously the deeper they went. Deeper levels had the puzzling lower value found in the lunar soil, and the deepest levels had even lower values. In other words, the heavier neon-22 embedded itself deeper into the metallic glass without needing a more energetic source of particles. "It took Genesis samples to see this clearly," Burnett says.

Another advantage of the Genesis data was the lack of cosmic rays. Since the lunar soil was exposed for millennia, cosmic rays had been reacting with it, producing neon that polluted the data. At lower neon-20 to neon-22 ratios, beginning at values near the 11.2 associated with the alleged solar energetic particles, you can't tell whether you're looking at data from the solar wind or cosmic rays. But since Genesis was only up for two years, it avoided cosmic-ray effects, and gave clean data.

Furthermore, when the team compared their results with a computer model of how neon-isotope ratios correlate with depth, the data matched perfectly. The conclusion seemed clear: a simple, single-component solar wind explained the observations. The result might not have been as exciting as discovering a new type of solar wind or some bizarre solar behavior, but at least researchers solved the problem. "There was a mystery of what this stuff was, and we've solved it by doing a clean experiment, without any of the complications of a lunar sample," Burnett says.

Same Differences

In October, a team led by scientists at Washington University in St. Louis reported the second major set of Genesis results. They analyzed the population of neon and argon isotopes in the solar wind and addressed a key question about the crucial assumption upon which Genesis science is based—that the solar wind accurately reflects the solar nebula. The outer layers of the sun preserve the composition of the solar nebula, but the solar wind doesn't necessarily preserve the composition



This ultraviolet image of the sun, taken by SOHO, shows the outer atmosphere of the sun, the corona. The atmosphere is threaded with magnetic fields (yellow lines). Areas with closed magnetic fields give rise to slow, dense solar wind (short, dashed, red arrows), while areas with open magnetic fields—so-called coronal holes—yield fast, less dense solar wind streams (long, solid, red arrows). In addition to the permanent ones at the sun's poles, coronal holes sometimes occur closer to the sun's equator, as shown here just right of center.

of the outer layers. When the sun expels its outer layers as the solar wind, the process could change the chemical makeup. If this happens, then different types of solar wind should also have different compositions.

Genesis sampled the three types of solar wind: high-speed winds that can blow faster than 500 kilometers per second, low-speed winds that blow at less than 500 kilometers per second, and big blasts of solar material called coronal mass ejections. The team found no differences among all three types. Although the implications aren't clear yet, researchers say these high-precision results will be essential for future studies and theories about the solar system's history.

For instance, the study included the most precise measurements yet of argon-36 to argon-38 and neon-20 to neon-22 ratios in the solar wind. In both cases, the ratios are higher than those in Earth's atmosphere. Lower ratios on Earth mean there are less of the lighter argon and neon isotopes in our atmosphere now than in the solar nebula from which our planet formed. Where did the lighter isotopes go? Theory says lighter isotopes have a greater tendency to fly off into space during planet formation, Burnett explains, and so the Genesis data suggests Earth lost some of its atmosphere early in its history. Future analysis of other noble-gas isotopes from Genesis will further refine these models.

It's All Right

Why did Genesis crash in the first place? Investigators concluded a sensor that measured the capsule's deceleration failed to tell the parachutes to open. The G-switch sensor—a silver cylinder no bigger than a pencil's eraser that measures gravitational forces—was installed backward. The investigation report in addition faulted the project's review process for not catching the mistake. Citing the failures of the Mars Climate Orbiter and Mars Polar Lander, the report also criticized NASA's "faster, better, cheaper" philosophy for making missions riskier in the name of saving money.

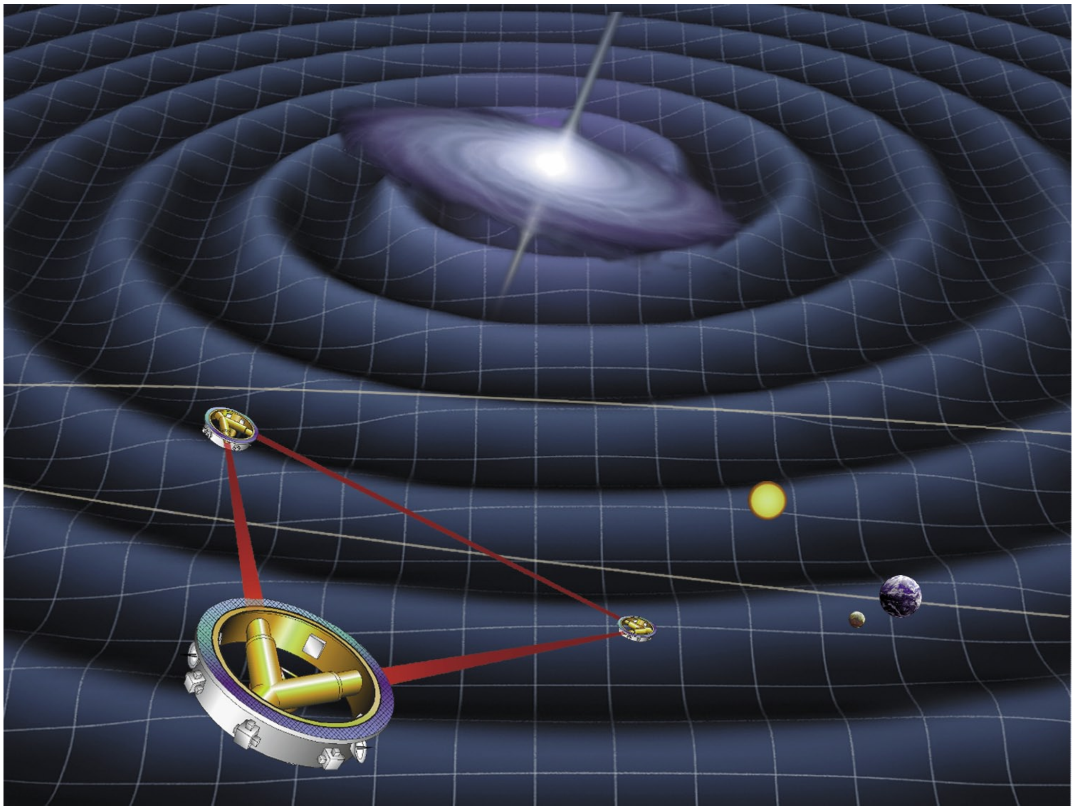
For Genesis, however, good science is emerging. Burnett has listed 19 main science objectives, and solving the lunar mystery and measuring the argon and neon compositions were two of them. Materials dedicated to the highest-priority experiment, which collected oxygen isotopes, also survived. As they continue to clean the samples, researchers are working hard to check items off Burnett's list. He can't swear all the science will be recovered, but he is optimistic. Still, he regrets the hard landing. "We were ready to go," he laments. "We even cancelled our last practice, we were in such good shape. It was really a shame we didn't get a chance to prove just how good we really were."

Perhaps as a memento of what could have been, Burnett keeps a photo of a helicopter successfully capturing a test capsule beside the door to his office. But the most famous picture, a picture he says he likes to avoid, shows the poor space capsule smashed into the dirt. "It looks like it's buried," he says, describing the semicircular hunk of metal sticking out of the ground. "It's not buried—it's smashed. It was round, now it's D-shaped. The ground was very unyielding at 200 miles per hour."

The landing wasn't pretty, but instead of a sad end, the best description for it may be the words of George Harrison: "Here comes the sun; it's all right, it's all right." □

This silicon carbide target is part of the oxygen isotope collector, Genesis's highest-priority experiment. It survived the crash intact.

PICTURE CREDITS: 29, 30, 32-33—NASA/JPL-Caltech; 30, 35—SOHO (ESA/NASA); 31-35—NASA/JSC



LISA will measure ripples in space-time.

A Space-time Symphony

If you could hear the sounds of space and time, the universe would be a noisy place. When those bizarre, light-bending, space-curving, and time-warping objects—black holes, neutron stars, and white dwarfs—meet, mingle, and merge, they disturb the fabric of space-time, sending ripples of gravitational waves across the cosmos. But it's not just black holes and their brethren that create these waves. The Big Bang itself, and maybe even more exotic objects called cosmic superstrings, all make their own undulations of space-time.

Although first predicted by Einstein's theory of general relativity in 1916, gravitational waves have yet to be detected. While scientists hope ground-based observatories like the Laser Interferometer Gravitational-Wave Observatory (LIGO), run by Caltech and MIT, will identify a signal soon, detection is virtually guaranteed by the much-anticipated Laser Interferometer Space Antenna (LISA). LISA will aim at much lower frequencies than LIGO, and will be capable of detecting more sources. When launched, it will be the only instrument of its kind in space, a mission that will observe the universe as never before, listening to the cosmic cacophony that so far has been silent to us.

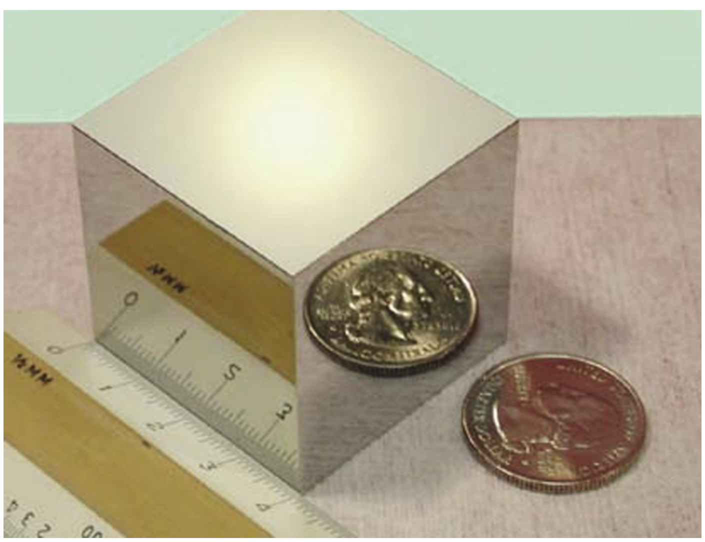
Gravitational waves are vibrations of space-time itself, and they jiggle everything they pass through, such as a planet or spacecraft—similarly to how sound waves jiggle the tiny bones in your ear, allowing you to hear. Unlike most telescopes, which point in a certain direction to detect signals, gravitational-wave detectors such as LISA measure waves from all directions, as an ear does. In this way, detecting gravitational waves is like hearing, and with so many potential sources out there, the trick is to figure out which is the black hole and which is the white dwarf. "It's like listening to an orchestra and trying to tell which is the cymbal and which is the flute, or which is the first violin and the second violin," says E. Sterl Phinney (BS '80), professor of theoretical astrophysics, chair of the LISA Science and Sources Working Group, and the leader of the team that developed NASA's Beyond Einstein program. LISA will address a myriad of topics, from the astrophysics of black holes to particle physics, to fundamental mysteries about the birth of the universe and the nature of gravity. In September, the National Research Council, which provides science policy advice for the government, recommended that LISA be made the flagship mission of the Beyond Einstein program.

Among the more promising phenomena the spacecraft will study is the merging of supermassive black holes. These events are some of the most violent and powerful in the universe, and likewise produce some of the strongest gravitational waves. When two of these behemoths meet, they spiral in toward each other. According to astronomers, nearly every galaxy has a supermassive black hole at its center, and when galaxies collide, the central black holes often merge—which can happen somewhere between once and 300 times per year.

Astronomers are finding that the evolution and formation of galaxies are inextricably tied to their merger history and to their central supermassive black holes. But since their black holes are always shrouded in gas, dust, and stars, scientists can't directly observe them. Gravitational waves, however, zip through everything at the speed of light, and with LISA, researchers would be able to make the first direct observations of merging black holes. "They will tell us something very fundamental about how galaxies evolved," says Tom Prince, professor of physics, the U.S. mission scientist for LISA and cochair of the LISA International Science Team.

LISA should also be able to detect a supermassive black hole eating a relatively tiny one, a few times the mass of our sun. But because the stellar-mass black hole is millions to billions of times smaller than the supermassive one, it works as what physicists call a "point test mass." As the smaller black hole circles its giant partner, it follows every curve of space-time. The gravitational waves betray its path, telling physicists how space-time bends around the supermassive black hole. For the first time, physicists would find out if black holes behave as they think they do, Phinney says.

Merging supermassive black holes could also serve as the most accurate yardsticks yet of the universe. A black hole binary system, in which two black holes orbit each other, loses energy as it produces gravitational waves. The strength of the waves reflects how much energy is lost. As the system loses energy, the two black holes spiral closer together, spinning around each other faster and faster, increasing the system's orbital frequency. How quickly the orbital frequency changes tells scientists how fast the system is losing energy, which then tells them how strong the gravitational waves are. Just as light looks dimmer with greater distance, the strength of detected gravitational waves drops if the source is farther away. By comparing the measured strength of gravitational waves with the theoretical value, researchers can figure out how far away the system is. If the two black holes are coupled with an electromagnetic source, such as when the black hole eats surrounding gas and dust, LISA will make the most accurate measurements yet of the universe's expansion. Measuring cosmological expansion means measuring dark energy, the mysterious stuff that makes up roughly 70 percent of the universe. "LISA could revolutionize dark-energy studies," Prince says.



At the heart of LISA are the free-floating test masses like this one. Tiny shifts in distances between the test masses would mean a gravitational wave is passing through. The cubes' polished surfaces reflect lasers between the spacecraft to measure the shifts.

Furthermore, gravitational echoes of the Big Bang give astrophysicists a powerful way to study the universe during its first second of existence. Conventional observations, by way of electromagnetic waves—light—only allow researchers to look back to when the universe was 300,000 years old. Before then, the universe was a hot plasma soup, too thick for light to pass through. But because gravitational waves can pass through the primordial soup, LISA may be able to reveal the universe in its infancy.

But wait, that's not all. One of the more exotic gravitational-wave sources could be vibrating cosmic superstrings, long, one-dimensional objects that stretch across the universe. Waves on those strings, which were produced during the Big Bang, would move at the speed of light. They would flop around like a loose garden hose, creating gravitational waves, Phinney explains. If these strings exist and are detected, they would be a great discovery, he says. "It's something of a long shot, but it's a really exciting opportunity."

While the science promises to excite and amaze, the spacecraft is a remarkable feat of engineering in and of itself. LISA consists of three identical spacecraft in a triangular formation. In order to detect the frequencies researchers want, the triangle has to be gigantic—five *million* kilometers per side, or the same distance you'd cover if you drove to and from Pasadena and New York about 1,120 times. Each craft holds two identical instruments, and each instrument encases a shiny, free-floating, four-centimeter cube that acts as a test mass. Laser beams that bounce between a cube in one craft and a cube in another form the three sides of the triangle. When a gravitational wave zips by, it shifts the distance between the test masses by a tiny amount. The laser beams also shift, giving scientists a measurement of the gravitational wave. The shifts in distance are so small that the instrument needs to be accurate to 10 *pico*meters—smaller than any atom. Meanwhile, all this is trailing Earth by 20 degrees of its orbit around the sun, a distance equivalent to 25 million kilometers.

One of the biggest challenges engineers had to overcome was that of designing a spacecraft that would protect the test mass and keep it in its smooth orbit. Given the extreme sensitivity of the instrument, normally negligible effects such as the force from sunlight and the gravitational field of the spacecraft itself must be accounted for. One solution was to install microthrusters to counteract every inadvertent bump.

In 2010, the LISA Pathfinder mission will test this delicate ensemble. The mission, led by the European

Space Agency and with JPL supplying the thrusters, will test the technology in a true zero-gravity environment. There's no environment on Earth that's as quiet as the space environment that LISA will experience, Prince says. So to make sure that researchers understand how the instrument works, they have to send a prototype into space.

The real LISA, a collaboration between NASA and ESA, won't fly until 2018 at the earliest. The greatest hurdle so far, Phinney says, is whether NASA will provide enough funding. "The two big questions are when it will happen and whether the U.S. will have a major role in it," Phinney says, noting that the U.S.—and Caltech in particular—has been a scientific leader for LISA over the past couple decades. "It would be a shame if the U.S. were to just drop out of it."

Funding and politics aside, the science of LISA sells itself, drawing enthusiastic supporters, Phinney says. Scientists are confident the mission will eventually launch. When it does, scientists can finally tune in to the universe and its space-time symphony. □—*MW*

Mars Rovers: The Next Generation

NASA scientists are seeking big pieces of an even bigger puzzle to help answer the biggest question about Mars—was it ever, is it, or could it possibly be a place for life to exist?

The size of a Mini Cooper and having more instruments than any previous Mars rover, the one-ton Mars Science Laboratory (MSL) will find some of those pieces. Expected to launch in September 2009, it will land in the summer of 2010. During the planned mission, which should last one Martian year (almost two Earth years) it will travel 20 miles.

"We're hoping that the Mars Science Lab will be able to go much further and last much longer than we anticipate, as the rovers Spirit and Opportunity have," says project scientist John Grotzinger, who came to Caltech in 2005, after years at the Massachusetts Institute of Technology. Those two rovers are still roaming Mars after landing in 2004; they were originally expected to last 90 Martian days.

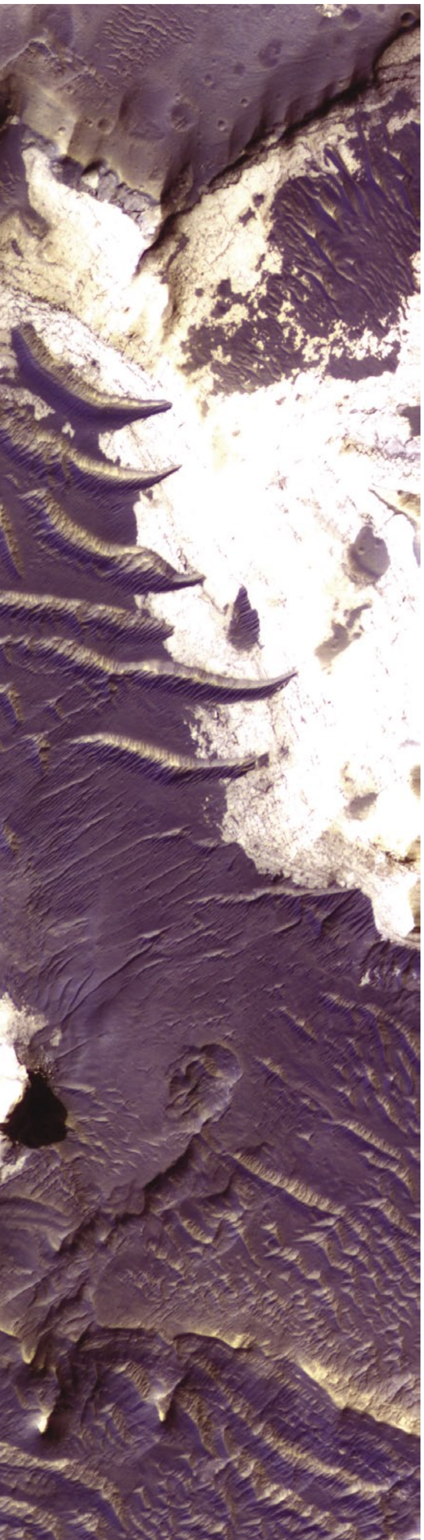
MSL will be fueled by nuclear power, so it will not be as restricted in its operations as the previous solar-powered rovers have been. The MSL can reach higher latitudes that get less sunlight each day. Previous rovers had to land within 20 degrees of the equator, but MSL should be able to get 10 degrees closer to the poles. At a conference in late October, the original 36 proposed landing sites were narrowed down to six sites and four alternates, all of which are ±30 degrees of Mars' equator. The farthest poleward proposed site is Terby Crater, at about 27.5 degrees south latitude.

MSL will pioneer a technique called "steered landing" that will get it as close as possible to its selected site. The previous rovers bounced and rolled in their protective airbags, giving little control over where they landed within their 50- to 100-kilometer target ellipse.

"It's still not perfect, but now we can land within the range of a city rather than an

This engineering model of the Mars Science Laboratory's chassis, dubbed "Scarecrow" because it does not have a brain of its own, makes its way down a hill in JPL's Mars Yard. MSL will be about twice as long and four times as heavy as the current Mars rovers, Spirit and Opportunity.

One proposed MSL landing site, Holden Crater, lies at 26.8 degrees south latitude. Seen here in enhanced color, Holden contains deep gullies carved by running water, as well as putative lake-bed deposits. One of the latter is shown here—the bright material at the base of the cliff.



entire county," says Deputy Project Scientist Ashwin Vasavada.

MSL is equipped with small rockets that fire downward for a few seconds at a time to control landing speed. The shape of the craft also allows the entry, descent, and landing team to control the angle of attack, which determines the lander's lift and forward velocity. MSL knows its desired trajectory, and sensitive gyroscopes allow it to correct itself, should something push it off course. These tools will shrink the landing ellipse to a mere 10 kilometers or so.

"Mars is now a place for sedimentologists," says Grotzinger, the Jones Professor of Geology. "Using the same techniques to see what the early earth was like, we can find out what Mars was, and is, like." On a table in his office sits a large rock from Australia, whose surface bears ripples that look just like the wave patterns that form in sand at the beach, where the tide ebbs and flows. Scientists have already seen ripples like these on Mars, implying that water once flowed there.

But now scientists are going beyond water, seeking compounds containing carbon, hydrogen, nitrogen, phosphorous, and sulfur, all essential ingredients for life, as well as various minerals that may indicate organisms that metabolized these compounds. A suite of instruments named Sample Analysis at Mars (SAM), provided by NASA Goddard, will analyze samples of material collected by MSL's robotic arm. SAM includes a gas chromatograph and mass spectrometer that will analyze rock and soil samples. A tunable laser spectrometer will determine the ratios of key isotopes in the air, providing clues to the history of Mars' atmosphere and water.

An X-ray diffraction instrument called CheMin, built by JPL, will identify and analyze minerals in rocks and soil. Previous Mars rovers have used spectroscopy to identify elements, but X-ray diffraction is far less ambiguous. "For understanding geologic history, this is especially important," says Vasavada. "The same chemical elements will take the form of different minerals depending on the environment in which they were formed."

These minerals arrange the same atoms into different crystal structures, meaning that the atoms have different three-dimensional spacings. A beam of X rays shot into each different structure will thus be diffracted at a different set of angles. Due to its bulk and weight, an X-ray diffractometer has never been put on a spacecraft before, but CheMin is about the size of a laptop computer bag.

MSL will be the first rover ever equipped with its own light sources. An ultraviolet light will be used to make minerals fluoresce, like the glow-in-the-dark geology displays at many science museums. This isn't being done to make trippy pictures—the fluorescence spectrum will help identify the minerals in the rocks.

Mounted on the rover's arm, the lights are part of the Mars Hand Lens Imager (MAHLI), which will take extreme close-up pictures of rocks, soil, and perhaps ice, revealing details smaller than the width of a human hair. MAHLI's color pictures will have a higher resolution than the Microscopic Imagers on Spirit and Opportunity, which only take pictures in black and white. Using its zoom lens, MAHLI can also focus on objects that the arm cannot reach.

Like Spirit and Opportunity, MSL's Mast Camera will see the rover's surroundings in high-resolution color, and its multispectral capability allows rock and mineral types to be identified in the landscape from afar. What's new is the capability to take and store high-def video—in stereo, no less! Now we'll be able to watch dust devils form and whip by in 3-D. MastCam has its own internal image storage, processing, and compression, taking this computationally intensive burden off the rover's main brain.

Another camera, called the Mars Descent Imager (MARDI), will take pictures as the MSL lands.

MAHLI, MastCam, and MARDI are being built by Malin Space Science Systems of San Diego, headed by Michael Malin (PhD '76).

The ChemCam, a collaboration between France and the U.S., will use laser pulses to vaporize thin layers of material from Martian rocks or soil from up to 10 meters away. A spectrometer will then identify the newly liberated atoms, and a telescope will capture detailed images of the area illuminated by the beam. ChemCam and MastCam will both sit on the rover's head-high mast, helping researchers decide which objects they should investigate next.

The rover's Radiation Assessment Detector, provided by the Southwest Research Institute, will provide crucial information for planning human exploration of Mars, and for assessing the planet's ability to harbor life.

Canadian researchers are also getting in on the action. The Canadian Space Agency will be providing the Alpha Particle X-ray Spectrometer, which will be located on the arm, and will determine the relative abundances of different elements in rocks and soils.

Russia's Federal Space Agency is providing the Dynamic Albedo of Neutrons instrument to measure subsurface hydrogen up to one meter below the surface.

This method has been used on JPL's Mars Odyssey to map subsurface water from orbit, but this is the first time a neutron spectrometer will land on the surface for a close-up look.

Finally, Spain and Finland are taking part with the Rover Environmental Monitoring Station to measure atmospheric pressure, temperature, humidity, winds, and ultraviolet radiation levels.

Like any other project, this mission has faced challenges. "We're in the sausage-making stage of it right now," said Project Manager Richard Cook, referring to the aphorism attributed to Otto von Bismarck, "Laws are like sausages. It's better not to see them being made."

Grotzinger was faced with the first of these challenges about six months ago when he took over Edward Stolper's position as project scientist. (Stolper, the Leonhard Professor of Geology, had been appointed Caltech's provost, and was unable to give MSL the time it deserved.) In the same week Grotzinger joined MSL, he was told that the project was $75 million over its original budget of $1.7 billion.

Grotzinger needed to cut costs but keep the science program strong. None of the rover's instruments have been removed from the payload, but some engineering changes have been made. These include reductions in design complexity—for example, a rock-grinding tool has been changed to a rock-brushing tool, and MastCam's zoom capability got scrapped. There will also be fewer spare parts, simplified flight software, and some ground-test program changes.

MSL will address the puzzle of life on Mars, but the answers won't come easily, Grotzinger says. "Like most things in science, there's not a silver bullet." □—*JS*

NuSTAR ReNued

NASA has given the go-ahead to bring a mission back from the dead. Although they cancelled it in 2006, officials have revived the Nuclear Spectroscopic Telescope Array, or NuSTAR. The spacecraft will be the most capable instrument yet to explore the universe using high-energy X rays.

"It's great that NASA was able to restart the mission," says Fiona Harrison, professor of physics and astronomy and NuSTAR principal investigator. "I'm incredibly excited about our planned science program, as well as the unanticipated things we are bound to discover with a new telescope this sensitive." NASA had scrapped the mission due to funding pressures within the Science Mission Directorate, but NuSTAR will now proceed to flight development, with an expected launch in 2011.

Researchers designed the mission to answer some fundamental questions about the universe: What powers the most extremely active galaxies? How were the heavy elements of the universe created? How are black holes distributed through the cosmos? NuSTAR will have more than 500 times the sensitivity of previous instruments that looked for black holes.

The members of Harrison's team have been working on NuSTAR technology for more than 10 years, developing optics that can focus high-frequency X rays for the first time. X rays are at the high-energy end of the electromagnetic spectrum, and easily penetrate most materials—which is why doctors use them to see through skin and flesh. X rays can only be reflected and focused in a telescope if they hit the mirror at a shallow angle, like rocks skipping on a pond. But since they hit the mirror nearly end-on, it has a very small collection area. In order to catch as many as possible, X-ray telescopes have several nested mirrors called shells. NuSTAR will have two such multiple-mirror systems, each with 130 cylindrical shells of reflective material. The system was demonstrated on a balloon-borne experiment called HEFT, for High Energy Focusing Telescope, that Harrison's group flew in 2005.

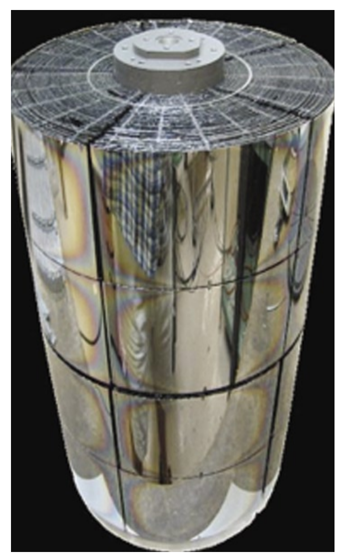
Each of the 130 shells is coated with an average of 300 thin layers of alternating high- and low-density materials of varying thicknesses, in order to reflect a whole spectrum of X rays. Other X-ray observatories, such as Chandra or the European Space Agency's XMM-Newton, don't have these multilayer coatings, which limits them to low-energy X rays.

NuSTAR's X-ray detector is a special CCD, or charge-coupled device, analogous to the one in your video camera. But this one, developed by Harrison's goup in Caltech's Space Radiation Lab, is made of cadmium zinc telluride.

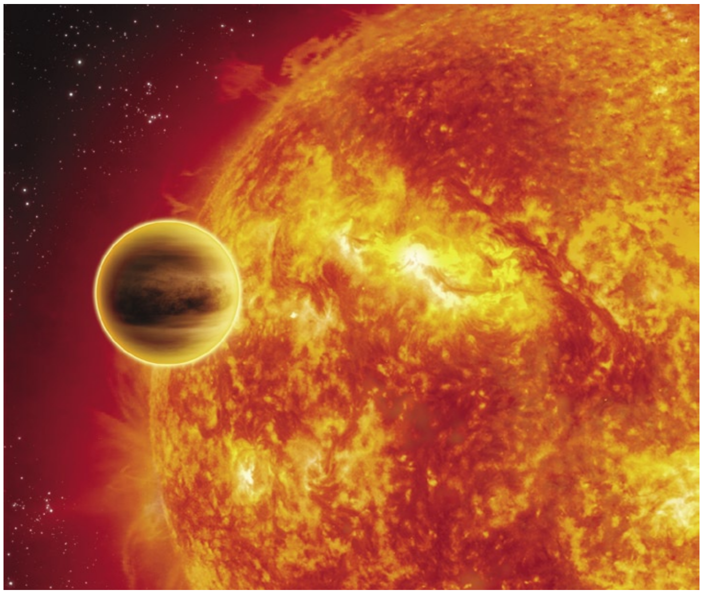
NuSTAR also incorporates an extendable structure developed by JPL and Alliant Techsystems Inc. for the Shuttle Radar Topography Mission that will fit the telescope into a small, inexpensive launch vehicle. Once in orbit, the arm will be extended to move the mirrors some 10 meters away from the detector, bringing the X-ray universe into focus.

In November 2003, NuSTAR was one of six proposals selected from 36 submitted to NASA's Small Explorers Program, which funds lower-cost, highly focused, rapidly developed scientific spacecraft.

NASA anticipates that NuSTAR will bridge a gap in astrophysics missions between the 2009 launch of the Wide-Field Infrared Survey Explorer and the 2013 launch of the James Webb Space Telescope. Besides using high-energy X rays to map areas of the sky, the spacecraft will complement astrophysics missions that explore the cosmos in other regions of the electromagnetic spectrum. □—*EN*



HEFT's mirror system has 72 shells. NuSTAR's will be nearly identical, but bigger and with 130 shells.



An artist's conception of HD 189733b in orbit around its star.

Hot and Steamy

It may not be the water-world that fields Kevin Costner's dreams, but the exoplanet HD 189733b has been found to have water vapor in its atmosphere. This observation provides the best evidence to date that water exists on worlds outside our own solar system.

The discovery was made by NASA's Spitzer Space Telescope, which possesses a particularly keen ability to study nearby stars and their planets. HD 189733b lies 63 light-years away.

"Water is the quintessence of life as we know it," says Yuk Yung, professor of planetary science and one of the authors of the study published in the July 12 issue of *Nature*. "It is exciting to find that it is as abundant in another solar system as it is in ours."

HD 189733b swelters as it zips around its star every two days or so. Astronomers had predicted that planets of this class, termed "hot Jupiters," would contain water vapor in their atmospheres, yet evidence has been hard to come by. "We're thrilled to have identified clear signs of water on a planet that is trillions of miles away," says lead author Giovanna Tinetti, a European Space Agency fellow at the Institute d'Astrophysique de Paris in France and former postdoc at Caltech's Virtual Planetary Laboratory.

Coauthor Mao-Chang Liang (PhD '06) of Caltech and the Research Center for Environmental Changes in Taiwan adds, "The discovery of water is the key to the discovery of alien life."

Wet hot Jupiters are unlikely to harbor any creatures. Previous Spitzer measurements indicate that HD 189733b is a fiery 1,000 degrees Kelvin on average. Ultimately, astronomers hope to use instruments like those on Spitzer to find water on rocky, habitable planets like Earth. "Finding water on this planet implies that other planets in the universe could also have water," says coauthor Sean Carey of the Spitzer Science Center, which is headquartered at Caltech.

A team of astronomers had found hints of water on another planet called HD 209458b by analyzing visible-light data taken by NASA's Hubble Space Telescope. The Hubble data were captured as the planet crossed in front of the star, an event called the primary eclipse. Tinetti and her team used changes in the star's infrared light as the planet slipped by, filtering the starlight through its outer atmosphere. The astronomers noticed that at each of three different wavelengths, a different amount of light was absorbed—a pattern matching that created by water. "Water is the only molecule that can explain that behavior," Tinetti says. "Observing primary eclipses in infrared light is the best way to search for this molecule."

The water on HD 189733b is too hot to condense into clouds; however, previous observations by several telescopes suggest that it might have dry clouds, along with high winds and a hot, sun-facing side that is warmer than its dark side.

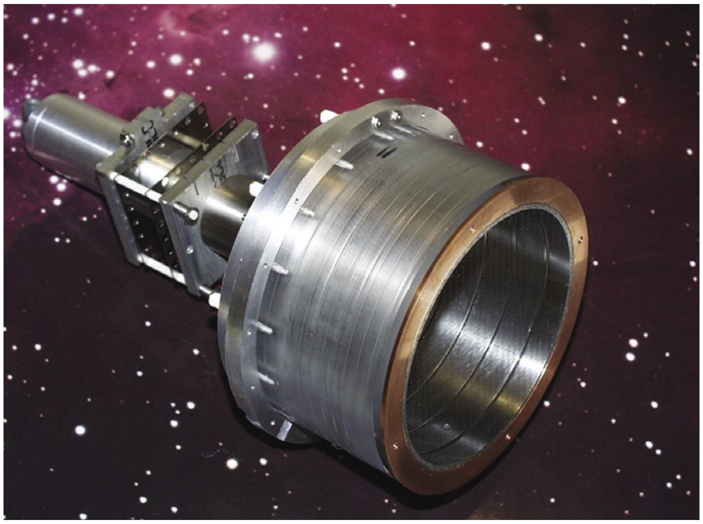
Other authors of the paper include Alfred Vidal-Madjar, Jean-Phillippe Beaulieu, David Sing, Nicole Allard, and Roger Ferlet of the Institute d'Astrophysique de Paris; Robert Barber and Jonathan Tennyson of University College London in England; Ignasi Ribas of the Institut de Ciències de l'Espai, Spain; Gilda Ballester of the University of Arizona, Tucson; and Franck Selsis of the Ecole Normale Supérieure, France. □—*RT*

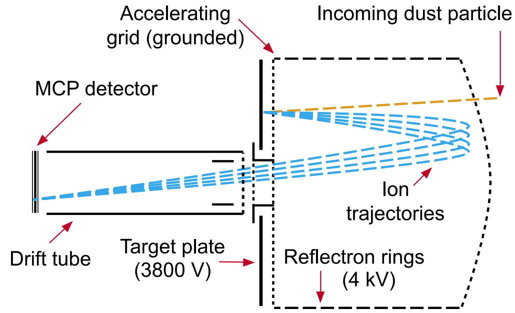
Cosmic Dust in the Wind

Don't let its seemingly vast emptiness fool you: the universe is a dirty place. Comets, supernovae, and solar winds spew microscopic particles of matter, called cosmic dust, across the universe. Instead of being a filthy nuisance, this cosmic dust may hold clues about the history of the solar system and the origins of life on Earth. "Origins, that's a big word at NASA these days," says Jesse (Jack) Beauchamp (BS '64), the Ferkel Professor of Chemistry. Along with Thomas Ahrens (MS '58), the Jones Professor of Geophysics, Emeritus, Beauchamp has built a device to extract cosmic dust's secrets. They call their creation the Dustbuster, and they hope it will be put on a future mission to the outer planets.

Unlike the Dustbuster you may have in your car or broom closet, this gadget isn't a vacuum; it's a mass spectrometer. On Earth, chemists, biologists, and those CSI guys use mass spectrometers to identify unknown molecules. It works on the principle that when a molecule or atom is charged, or ionized, its behavior in an electric or magnetic field will depend, partly, on its mass.

Cosmic dust flows through the outer reaches of our solar system at speeds of 10 to 80 kilometers per second. Any particles hitting a target plate on the Dustbuster are instantly vaporized, and the energy of the impact strips electrons from the molecules,





As the Dustbuster (left) flies through space, dust particles entering its maw (above) smash into a target plate that fragments them into positively charged ions and free electrons. The rebounding positive ions are given a uniform "kick" to the left by the accelerator grid and are then steered into the detector by means of an electric field created by the reflectron rings.

producing positively charged ions with various amounts of kinetic energy. Inside the Dustbuster, the ions are accelerated by an electric field and guided towards an ion detector through a part called the reflectron. This part negates any differences in kinetic energy between the ions produced by the impact. Since the electric field provides each ion with the same amount of energy, the time it takes each ion to reach the detector will depend on its mass. It's an ionic drag race—imagine a Honda Civic dueling a Hummer powered by a Civic engine. Just as the heavier Hummer will move more slowly, heavier ions will accelerate to lower velocities than lighter ions. Faster, lighter ions will arrive at the detector first, so monitoring when ions reach the finish line determines their masses.

"There's quite a history of using mass spectroscopy in space exploration, from the Viking program onward," says Beauchamp. On the recent Cassini-Huygens mission to Saturn, data from the Cassini Dust Analyzer (CDA) showed that Saturn's outer ring was formed from dust spraying off of the south pole of its moon, Enceladus. "Having seen the CDA, we were inspired to see if we could build something that was smaller in size, used less power, but had high performance," says Beauchamp. While the CDA is 17 kilograms and 1 meter long, the Dustbuster is only about 0.5 kilograms and 20 centimeters long. Two types of Dustbusters have now been built and tested: Dustbuster I is designed to sample cosmic dust found streaming through the solar system, while Dustbuster II is designed to sample the high flux of dust from comet tails.

How can something as simple as the mass of a molecule found in a tiny dust particle tell us about the history of our solar system? Cosmic dust's journey often begins in distant stars, from which it is shot out across the galaxy through their solar winds or, more dramatically, a supernova. Some cosmic dust accumulates inside interstellar clouds that become unstable and collapse, forming new stars and planets. Much of our solar system, including the matter in your own body, was once cosmic dust particles flying through the galaxy.

A dust particle's composition can be read like a passport. Inside stars, many of the heavier elements, like carbon, oxygen, and iron, are forged from lighter elements, like hydrogen and helium, through a process called nucleosynthesis. (Caltech physics professor Willie Fowler, PhD '36, won the Nobel Prize in Physics in 1983 for working out the details.) Isotopes of the elements—atoms that have the same number of protons, but a different number of neutrons—are also created through nucleosynthesis. Depending on the type of star and its stage in life, nucleosynthesis will produce different mixes of elements and isotopes, so by analyzing the cosmic dust, scientists can learn about the evolution of stars. Organic, carbon-based molecules are synthesized as the dust flies through different chemical environments in space, like on the tails of comets. Scientists are very interested in these, as such molecules may have served as precursors to DNA, amino acids, and other biological molecules on Earth.

Besides Beauchamp's work on the Dustbusters, he has also been working on a return visit to Saturn's moon Titan. "We have been heavily involved with looking at Titan as a model for early Earth," says Beauchamp. Lab experiments that simulate conditions on Titan and data from the Huygens lander have confirmed the presence of simple organic molecules there. "'Astrobiological hotspot' is a term I like to use. It's where you suspect there are the conditions for emergent synthesis of organic molecules," says Beauchamp. Learning how this occurs on the surface of Titan could help explain how the molecules of life were first synthesized on Earth.

To study these astrobiological hotspots, any probe returning to Titan will need a mass spectrometer. "Mass spectrometers are extremely valuable tools for such missions," says Kim Reh at JPL. Reh was part of a team that submitted a proposal to NASA in October for a mission to "prebiotic" moons in the outer solar system, like Jupiter's moon Europa and Saturn's moons Enceladus and Titan. Beauchamp was a consultant to the team. "NASA intends to review the results of this study by the end of this year and select one or two of these science targets for further study in 2008. The longer-term goal is to select a mission in 2009," says Reh. □—*MT*

PICTURE CREDITS: 36, 38—NASA/JPL-Caltech; 39—NASA/JPL/Universiy of Arizona; HEFT team; 41—C. Carreau, ESA; 42—Daniel Austin

A Chronology of JPL Spacecraft

Explorers 1-5 — **Launch Dates: Jan.–Aug., 1958**
Explorers 1, 3, and 4 discovered and probed the Van Allen Belts.

Pioneers 3 and 4 — **Dec. 6, 1958, and March 3, 1959**
Pioneer 4 became the first U.S. spacecraft in solar orbit.

Rangers 1-9 — **1961–65**
Rangers 7-9 returned images until their planned moon impacts.

Mariners 1 and 2 — **July 22 and Aug. 27, 1962**
The first to another planet, Mariner 2 studied Venus's atmosphere and surface, and measured the solar wind for the first time.

Mariners 3 and 4 — **Nov. 5 and 28, 1964**
Mariner 4 took the first close-up photos of another planet, Mars.

Surveyors 1-7 — **1966–68**
Surveyors 1, 3, and 5-7 were the first U.S. landings on the moon.

Mariner 5 — **June 4, 1967**
Originally a backup Mars craft, Mariner 5 went to Venus.

Mariner 6 and 7 — **Feb. 24 and March 27, 1969**
First dual mission to Mars; flew over the equatorial and south polar regions.

Mariner 8 and 9 — **May 8 and 30, 1971**
Mariner 9 was the first successful Mars orbiter.

Mariner 10 — **Nov. 3, 1973**
Pioneered the "gravity assist" concept, swinging by Venus en route to Mercury.

Vikings 1 and 2 — **Aug. 20 and Sept. 9, 1975**
The first Mars landings. Each Viking had an identical orbiter and lander; all four spacecraft completed extended missions.

Voyagers 1 and 2 — **Aug. 20 and Sept. 5, 1977**
They completed the Grand Tour of the solar system, and are now heading toward interstellar space.

Seasat — **June 26, 1978**
Tested four radar instruments that studied Earth and its seas.

Solar Mesosphere Explorer — **Oct. 6, 1981**
Traced the life cycle of ozone in the upper atmosphere.

Infrared Astronomical Satellite — **Jan. 25, 1983**
An infrared telescope orbiting above Earth's atmosphere.

Magellan — **May 4, 1989**
Mapped Venus's surface. Pioneered the aerobraking technique, using a planet's atmosphere to steer or slow down.

Galileo — **Oct. 18, 1989**
Orbited Jupiter and dropped a probe into its atmosphere; made many flybys of its major moons.

Ulysses — **Oct. 6, 1990**
A collaboration with the European Space Agency, Ulysses monitors the sun from an orbit around its poles.

Topex/Poseidon — **Aug. 10, 1992**
A French-U.S. mission, it measured sea levels every 10 days with an accuracy of less than 10 centimeters.

Mars Observer — **Sept. 25, 1992**
Lost shortly before arrival at the red planet.

Mars Global Surveyor — **Nov. 7, 1996**
This orbiter operated longer than any other Mars mission.

Mars Pathfinder — **Launch Date: Dec. 4, 1996**
The lander and its Sojourner rover explored an ancient flood plain called Ares Vallis.

Cassini-Huygens — **Oct. 15, 1997**
A European-U.S. mission orbiting Saturn, Cassini sent the Huygens probe to Titan, Saturn's largest moon.

Deep Space 1 — **Oct. 24, 1998**
Tested new technology and took photos of comet Borrelly's nucleus.

Mars Climate Orbiter — **Dec. 11, 1998**
This interplanetary weather satellite was lost on arrival.

Mars Polar Lander/Deep Space 2 — **Jan. 3, 1999**
Aiming for the edge of Mars' south polar cap and carrying twin soil probes (Deep Space 2), it was lost during final descent.

Stardust — **Feb. 7, 1999**
Collected and returned a sample of dust from comet Wild-2.

Wide-field Infrared Explorer — **March 4, 1999**
A small telescope that lost its cryogenic coolant soon after launch.

Quick Scatterometer — **June 19, 1999**
Measures ocean wind velocities and directions.

Active Cavity Irradiance Monitor Satellite — **Dec. 22, 1999**
Monitors the total amount of the sun's energy reaching Earth.

2001 Mars Odyssey — **April 7, 2001**
Now orbiting Mars.

Genesis — **Aug. 8, 2001**
Collected and returned samples of solar wind particles.

Jason 1 — **Dec. 7, 2001**
A follow-up oceanography mission to Topex/Poseidon.

Gravity Recovery and Climate Experiment — **March 17, 2002**
A U.S.-German mission consisting of two spacecraft flying together to measure Earth's gravitational field.

Galaxy Evolution Explorer — **April 28, 2003**
A small ultraviolet telescope that studies galaxy formation.

Mars Exploration Rovers — **June 10 and July 7, 2003**
The Spirit and Opportunity rovers continue to explore opposite sides of Mars.

Spitzer Space Telescope — **Aug. 24–25, 2003**
A large infrared telescope. One of NASA's Great Observatories.

Deep Impact — **Jan. 12, 2005**
Sent an impactor to smash into comet Tempel 1's nucleus.

Mars Reconnaissance Orbiter — **Aug. 12, 2005**
Analyzing Mars's surface to bridge the gap between surface observations and measurements from orbit.

CloudSat — **April 28, 2006**
Provides a never-before-seen 3-D profile of Earth's clouds.

Phoenix — **Aug. 4, 2007**
A high-latitude lander en route to Mars equipped with a robotic arm to dig into layers with water ice.

Dawn — **Sept. 27, 2007**
The first craft to orbit two bodies after leaving Earth. It will orbit Vesta and Ceres, two of the solar system's largest asteroids.

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