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IN THIS ISSUE

A robotic explorer moves cautiously among the ruins of an alien city on a distant world, looking for signs of life. Well, not exactly—these are lava arches at a deep-ocean vent on the East Pacific Rise, 2.5 kilometers down. But still, in such an extreme environment, how can you tell if a discoloration on a rock is living bacteria? JPL researchers have built a "point-and-shoot" laser-induced fluorescence detector that identifies organic compounds—a prototype for a system that may one day look for life in the oceans of Europa. The story begins on page 18.

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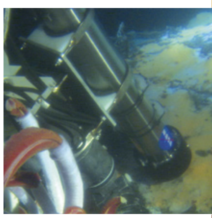

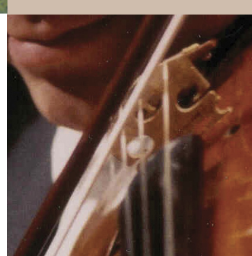

On the cover: For the past five years, Caltech's Cosmic Background Imager has been probing the microwave background radiation for tiny temperature fluctuations that hold clues to how the universe formed. One of the best places on Earth to view that radiation happens to be Chile's high Atacama Desert, and doing science in such a remote location can bring problems only slightly less difficult than looking back 13.8 billion years. For more on how some hardy radio astronomers did it, see the story beginning on page 8. (Photo by Ricardo Bustos.)

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A 50-foot robot called "Family of Explorers" won the Crown City Innovation Award at the 2005 Rose Parade. A joint entry of the Jet Propulsion Lab and Caltech, the float incorporated floral likenesses of the Cassini probe to Saturn; the Stardust comet sample-return mission; the Jason oceanography satellite; the Genesis solar-wind sample-return mission; the Galaxy Evolution Explorer (GALEX) ultraviolet space telescope; the Spitzer Space Telescope, which sees the cosmos in the infrared; the Gravity Recovery and Climate Experiment (GRACE), whose tandem orbiters map Earth's gravitational field; and the indefatigable Mars Exploration Rovers, Spirit and Opportunity. Can you spot them all?

A JPL/Caltech committee solicited design ideas from the Lab and from campus. The float was built by the Phoenix Decorating Company, and was decorated by hundreds of volunteers from the JPL and Caltech communities and several local high schools. Caltech, which manages JPL for NASA, funded the construction.

Thom Mayne to Design Cahill Center

Internationally recognized architect Thom Mayne and his firm, Morphosis, based in Santa Monica, have been chosen to design the Cahill Center for Astronomy and Astrophysics, which will house the astronomers, astrophysicists, and theorists who now work in several campus buildings. Mayne has received 52 awards from the American Institute of Architects, and his recent works include the Caltrans District 7 headquarters in downtown Los Angeles. Called the next Frank Gehry by some, he is known for visually impressive structures that integrate themselves into their surroundings.

The roughly 100,000-square-foot Cahill Center will join the Keith Spalding building on the south side of California Boulevard, north of the athletic fields. The facility will have five floors, two of them underground, and will contain offices, laboratories, remote observing rooms, conference rooms, a library, an auditorium, and classrooms. The design is expected to be completed this spring and, in the words of Caltech president David Baltimore, "will provide the campus and Pasadena with a highly visible icon." □

Crystal Power

"Californians are notorious for their love of crystals and their infatuation with computers," says Erik Winfree, PhD '98, assistant professor of computer science and computation and neural systems (CNS). "Now we've merged these passions by creating a crystal that computes as it grows." At a molecular level, crystals are simple units in a repeating pattern—like wallpaper, or tiles on a bathroom floor. But Winfree; Paul Rothemund, a senior research fellow in CNS and computer science; and former staff scientist Nick Papadakis have designed DNA "tiles" that assemble themselves into a fractal pattern called a Sierpinski triangle, which never repeats itself and becomes more elaborate as it grows. A Sierpinski triangle can be drawn by repeatedly applying a simple mathematical rule. The researchers encoded this rule in how the tiles interlock—the first time a computation has been embedded in a crystalline form. And the crystal grows spontaneously, which is really convenient when you need to build structures one molecule at a time.

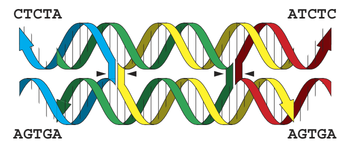
The tiles are roughly 12 by 4 nanometers, or billionths of a meter—tiny knots of DNA so arranged that at each corner of the tile is a free strand, or "sticky end," that can bind to other sticky ends. The key, says Rothemund, is that the tiles "have *programmable* sticky ends. For example, a tile with the sticky end AGGTA would bind to a tile with a sticky end TCCAT, because A binds to T and G binds to C, and not to other tiles."

Because the tiles act as a molecular version of what computer scientists call a universal Turing machine, says Winfree, in principle "this trick allows *any* computer program to be translated into a set of DNA tiles"—an idea he first advanced in his PhD thesis. The tiles, when dissolved and the solutions mixed together, precipitate out in what he calls an "algorithmic crystal." An algorithm, Rothemund explains, is a computer program in the abstract—"it has no preference for Windows over Mac." The program runs as the crystal grows, and each row in the crystal records one time-step in the program's execution. This set of "snapshots" of the computer's processor creates the crystal's pattern, he says. "If, for example, the algorithm multiplies two numbers, all of the intermediate steps with their placeholders and carry digits would be written into the pattern of tiles." Once the algorithm runs its course, the crystal stops growing, and the answer is written in the final row of tiles.

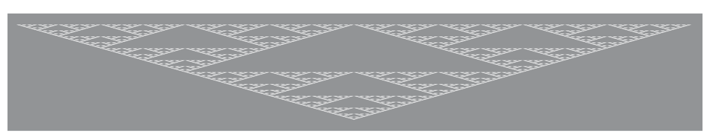
The Sierpinski triangle embodies the addition of the binary numbers 0 and 1. The tiles build the growing crystal in offset rows, like bricks in a wall. The sticky ends are engineered to make 1s find places where a 0 lies next to a 1 in the row below, and 0s bridge pairs of 0s or pairs of 1s. Shake gently, add a pinch of salt, heat to near boiling, cool, and voilà! The 1s are made twice as thick as the 0s, so the resulting pattern can be "read" by an atomic force microscope, "much as a blind person reads the raised dots of braille with a finger," says Winfree. Errors in the self-assembly process usually cause the pattern to go awry after a couple of hundred tiles, but, Rothemund says, the experiment still demonstrates "that one can think of the process of crystal design as an exercise in programming."

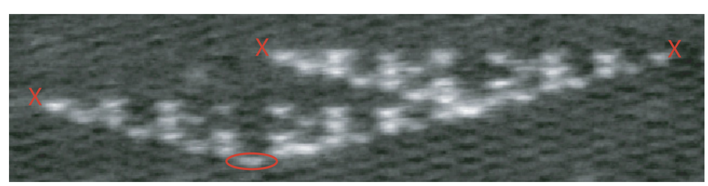
Winfree, Rothemund, and grad student Matt Cook have applied for a patent "for algorithmic crystals whose patterns may be used to template nanoscale circuits an order of magnitude smaller than any circuits currently made." But more importantly, Rothemund says, this work shows that algorithms are inherent in the creation of complex ordered systems such as oak trees and insects. "We believe that computation is ubiquitous in the development of biological organisms, and that the story of how algorithms lead to order in the natural world is just beginning to unfold."

Rothemund is the lead author of the paper describing this work, which appears in the December issue of the online journal *Public Library of Science (PLoS) Biology*. □—*DS*



One of the DNA tiles used to create the Sierpinski triangle. Four separate DNA strands (red, yellow, green, and blue) wind around one another; the black arrowheads show where a strand jumps from one double helix to the other. At each corner of the tile is an unpaired bit of DNA whose five-letter sequence acts as a "sticky end" to selectively bind to other tiles. The Sierpinski triangle required four different types of tile, each with a specific array of sticky ends.





Top: A Sierpinski triangle built from a single white "1" block at the apex. Bottom: A piece of a Sierpinski triangle made from about 300 DNA tiles. The gray blobs are 0s, white blobs are 1s, and the small gaps between tiles are black. The crystal grew as rows of 0s until an error (circled) inserted a 1; three additional errors (red Xs) stopped the pattern's propagation.

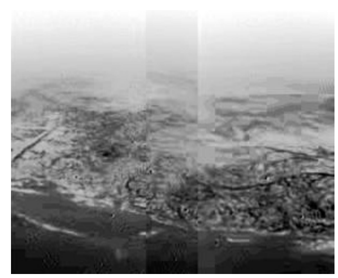
Below: *NUMB3RS* may do for academia what the *CSI* franchise has done for forensic science. The new crime drama stars David Krumholtz as Charlie Eppes, a math prodigy on the faculty of CalSci, an L.A.-area university that looks a lot like Caltech. "Everything is numbers," says Charlie, who helps brother Don (Rob Morrow), an FBI agent, solve cases ranging from serial murder to bioterrorism. Series creators and head writers Cheryl Heuton and Nick Falacci are Altadena residents and Feynman fans who had long wanted to showcase the mathematical mind, but needed a tried-and-true format to sell the concept. Good call—*NUMB3RS*'s first appearance in its regular time slot pulled over 15 million viewers and was the 11th most watched show of the week. Heuton and Falacci wanted a Caltech feel, so some scenes are shot here, like this one of Charlie and string-theorist colleague Larry Fleinhardt (Peter MacNicol) walking through the Kerckhoff arcades, and Krumholtz spent several weeks on campus over the summer observing the natives. And the equations Charlie scrawls are real—Professor of Mathematics Gary Lorden (BS '62) provides the formulas and terminology. *NUMB3RS* airs Friday nights at 10:00 p.m. on CBS.

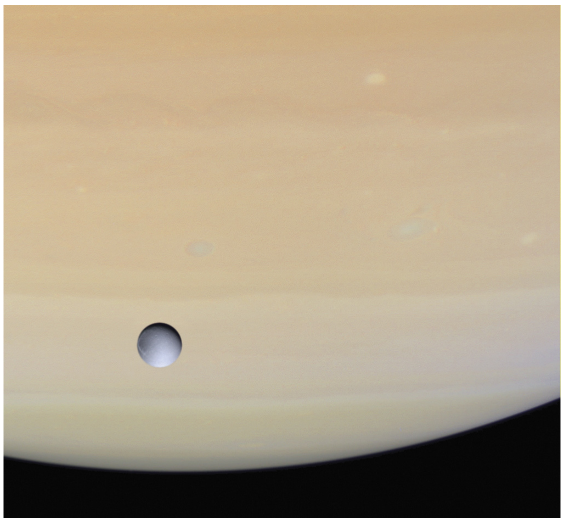
Observing the Roiling Earth

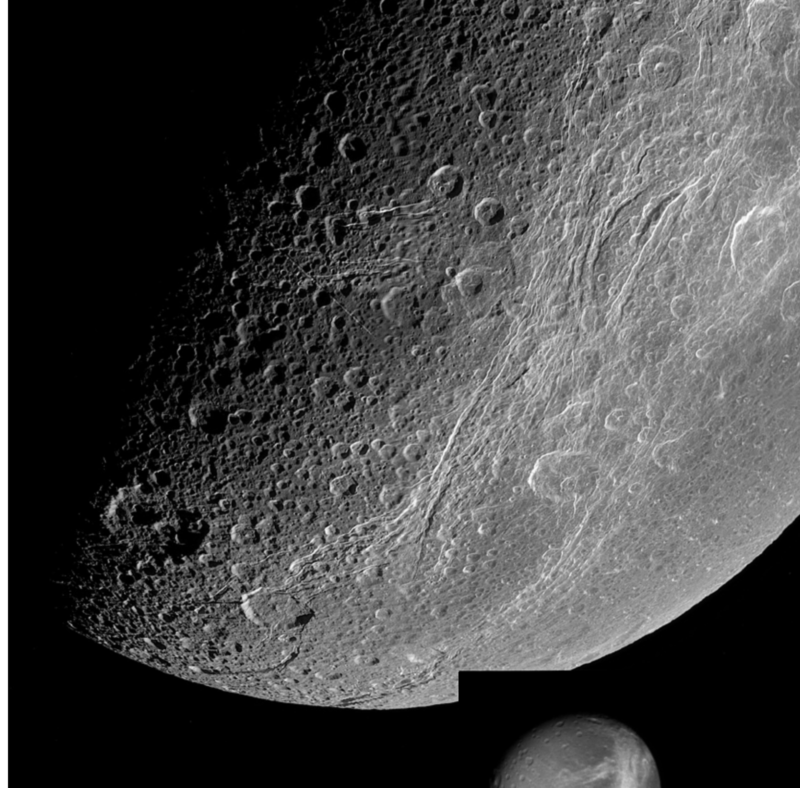
Earthquakes and continental drift are both the result of plate tectonics, but nobody knows what makes the plates move. Now, thanks to a $13 million grant from the Gordon and Betty Moore Foundation, Caltech has established the Tectonic Observatory, under Professor of Geology Jean-Philippe Avouac, to "provide a new view of how and why the earth's crust is deforming over timescales ranging from a few tens of seconds to several tens of million of years." The observatory will focus on major field studies at key plate boundaries in western North America, Sumatra, Central America, and Taiwan. (Caltech faculty have been studying these regions for decades. In fact, Kerry Sieh, the Sharp Professor of Geology, just returned from a post-quake resurvey of Sumatra. His dispatches from the field can be read at http://today.caltech.edu/today/story-display?story%5fid=5903 .)

In addition to seismometers, the observatory will use GPS to measure the relative velocity of points on the earth's surface to within a few millimeters per year, satellite images to map broad displacements of the ground over time, geochemical fingerprinting methods to analyze rocks from Earth's deep interior that have been brought to the surface by volcanic eruptions or erosion, and advanced computational techniques "to allow us to develop models at the scale of the global earth," says Avouac. Deployment of a network of 50 seismometers has already begun along a major subduction zone in Mexico. —*MW*

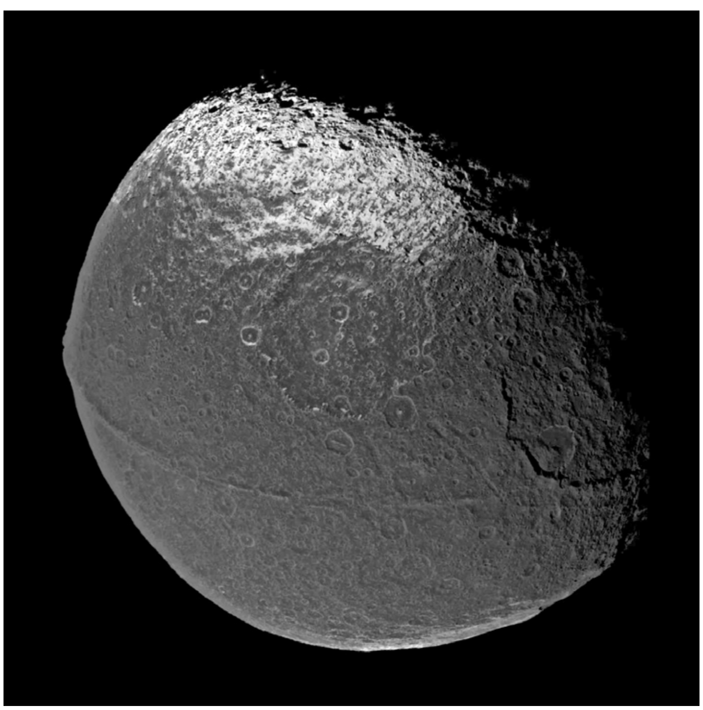
Right: JPL's Cassini gave the European Space Agency's Huygens probe a lift and relayed its signals back to Earth; Huygens landed on Saturn's moon Titan on January 14, returning data all the way down through its thick, hazy atmosphere and for 72 minutes afterward. A composite shot from eight kilometers up (top) shows what could be mistaken for the central California coast, but these hills and channels were carved by methane rain; the dark foreground is believed to be a methane-soaked, ice-crusted mudflat the consistency of crème brûlée. The approximately natural-color image from the surface (bottom) shows pebble-sized chunks of ice.



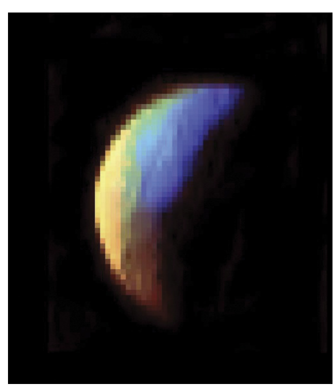




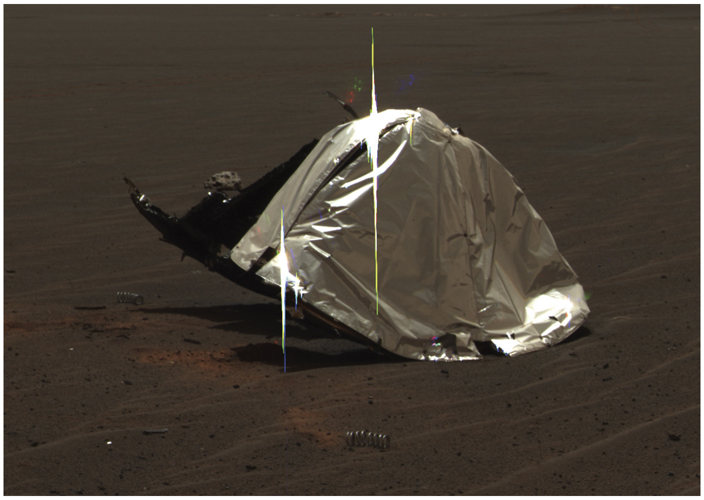
Cassini, meanwhile, continues to tour the Saturnian system, snapping this natural-color shot (left) of Dione against the parental planet en route to a flyby of that moon on December 14. Grayish Dione's most prominent features are bright, wispy streaks (above, right) that were thought to be surface deposits of some sort. But close inspection (above) showed that they're shiny cliffs of ice that have been upthrust along fractures in Dione's crust.

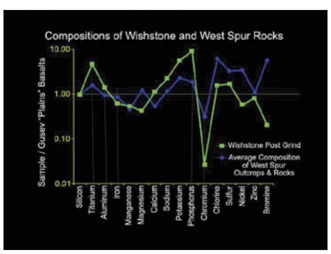


Left: Next up was Iapetus, which Cassini buzzed on New Year's Eve, discovering a feature unlike anything ever before seen in the entire solar system. For at least a quarter of the moon's circumference, a ridge some 20 kilometers wide and, where it can be seen in profile, about 13 kilometers tall runs along the equator like the seam on a cheap metal globe. Future studies may determine if Iapetus actually unscrews.



Left: In this infrared composite view, the blue region, which is bright in visible light, represents water ice. The dark brown area is rich in organics, and the yellow zone is a mixture of the two. The organic stuff coats Iapetus's leading hemisphere, making it look chocolaty to the eye, and may be swept up by the moon's orbit.



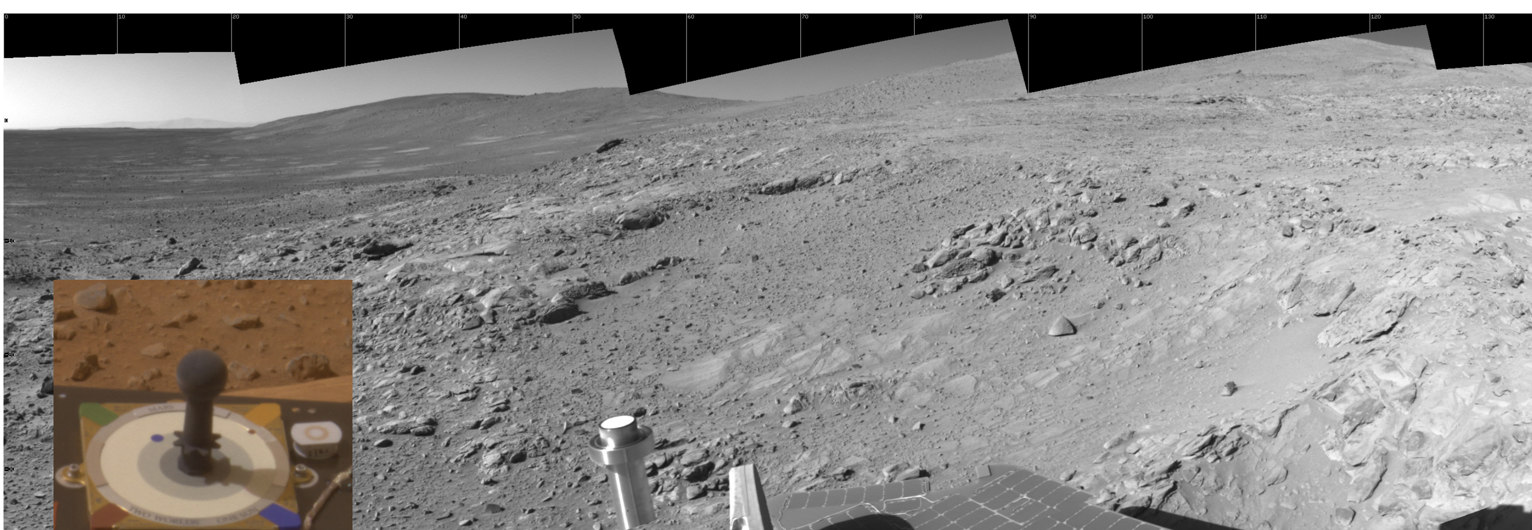


JPL's doughty Mars Exploration Rovers, Spirit and Opportunity, just celebrated their first Earth-year anniversary on the Red Planet. Opportunity is now examining its own heat shield (above), which had landed a kilometer or so away. The engineers were astonished to find the shield had actually turned itself inside out, like an umbrella in a high wind. In the background is a basketball-sized nickel-iron meteorite (left), the first ever found on another planet. If meteorites prove common on Meridiani Planum, it may mean the terrain is eroding away to expose them.

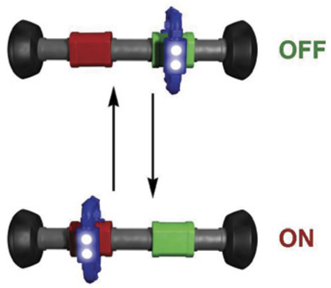
Meanwhile, Spirit continues climbing into the Columbia Hills. This 360° panorama (below) of its perch on the West Spur was shot on sol, or Martian day, 305. The graph (left) shows the ratios of elements in the hillside rocks to those in volcanic basalts from the plains, which are plotted as 1.0. The new rocks, particularly one called Wishstone, are extremely high in phosphorus, which may mean they were altered by water. Both rovers are slowly being covered by a thin layer of Martian dust—Spirit about 70 percent faster than Opportunity—as shown by the two inset photos. While this robs them of some solar power, there's plenty of life in them still.

Getting in on the Ground Floor

"There's plenty of room at the bottom," as Caltech Nobelist Richard Feynman once famously remarked in these very pages. Well, the bottom is beginning to get a little more crowded these days. Over the past decade, nanotechnology has become a hot field, and President Clinton visiting Caltech in January 2000 to announce the launching of a "National Nanotechnology Initiative" didn't hurt any. Nanotechnology, broadly speaking, includes anything from silicon micromachines made from the same stuff that computer chips are, and by the same methods; to proteins and other cellular apparatus modified for new uses; to individual molecules designed to act as electronic components, and, if you're clever, to assemble themselves into



Spirit sol 9 (Jan. 11, 2004)



Left: A rotaxane switch. In the ground, or OFF state, the blue ring sits on the green site. A positive voltage oxidizes the green site, pushing the ring to the red site, flipping the switch; adding electrons to the system restores it to its initial state. The ON state is metastable, meaning that, if left alone, it will eventually "relax" back into the ground state.

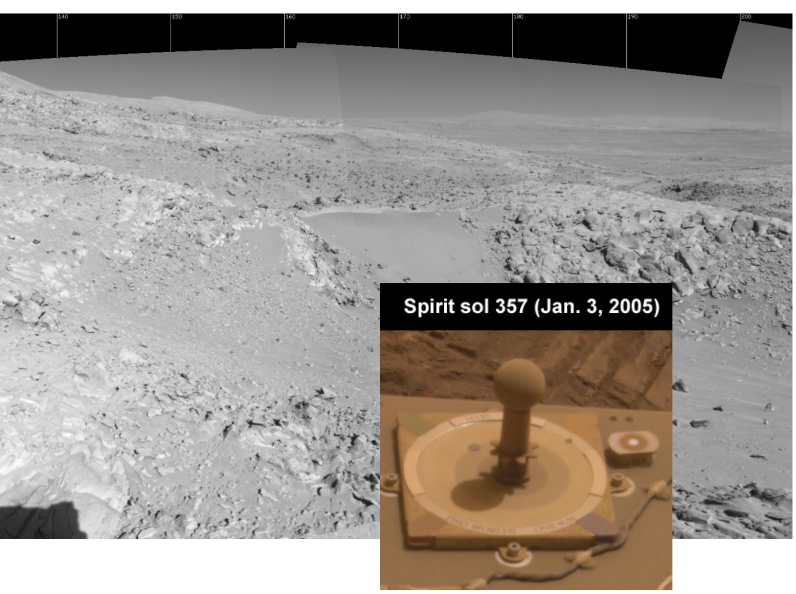
Speaking of Feynman, here he is on a postage stamp to be issued on April 5. Other prominent American scientists will be similarly honored in May—Dr. Bunsen Honeydew and Beaker appear in the series commemorating Jim Henson and the Muppets.

working circuits.

In the latter category are molecular switches developed by researchers in the labs of UCLA's Fraser Stoddart and James Heath, the Gilloon Professor and Professor of Chemistry at Caltech. The switches are based on structures called rotaxanes, invented in Stoddard's lab, in which a ring-shaped molecule slides back and forth on a molecular shaft like a washer on a bolt; in lieu of a nut, the shaft's ends bulge. A pulse of positive voltage sends the washer to one end of the shaft, turning the switch ON; a negative pulse turns it OFF by returning the washer to its original position.

Heath's lab has built a 64-bit random access memory circuit out of rotaxanes, and is working on a 16-kilobit one. These molecules work in solution, which makes chemists happy, and in the solid state, which makes engineers happy. The switches can be flipped at will even when they're deep in a layer of rubber-like material. But the speed at which they flip depends on what they're in, Stoddart says—what happens instantaneously in solution can take 10 minutes in the solid state, allowing the switches to be used as memory elements.

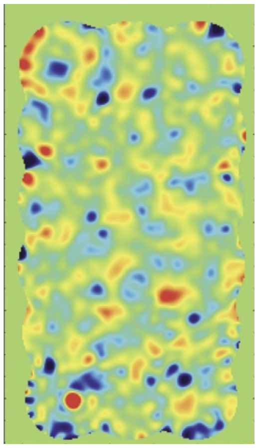
Some two dozen Caltech faculty are carving out niches at the bottom, and last November the Gordon and Betty Moore Foundation provided $25.4 million to establish a campuswide Nanoscale Systems Initiative, augmenting the $7.5 million grant last March from Fred Kavli and the Kavli Foundation to establish the Kavli Nanoscience Institute. Michael Roukes, professor of physics, applied physics, and bioengineering at Caltech and founding director of the initiative, says Caltech will exploit its strengths in nanophotonics and nanobiotechnology.



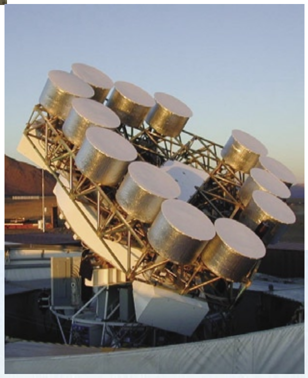
Nanophotonics uses the quantum interactions of light and atoms to make microlasers, optically active waveguides that can "steer" light around corners or act as switches, and other gadgets to harness photons for telecommunications and even, perhaps someday, quantum computers.

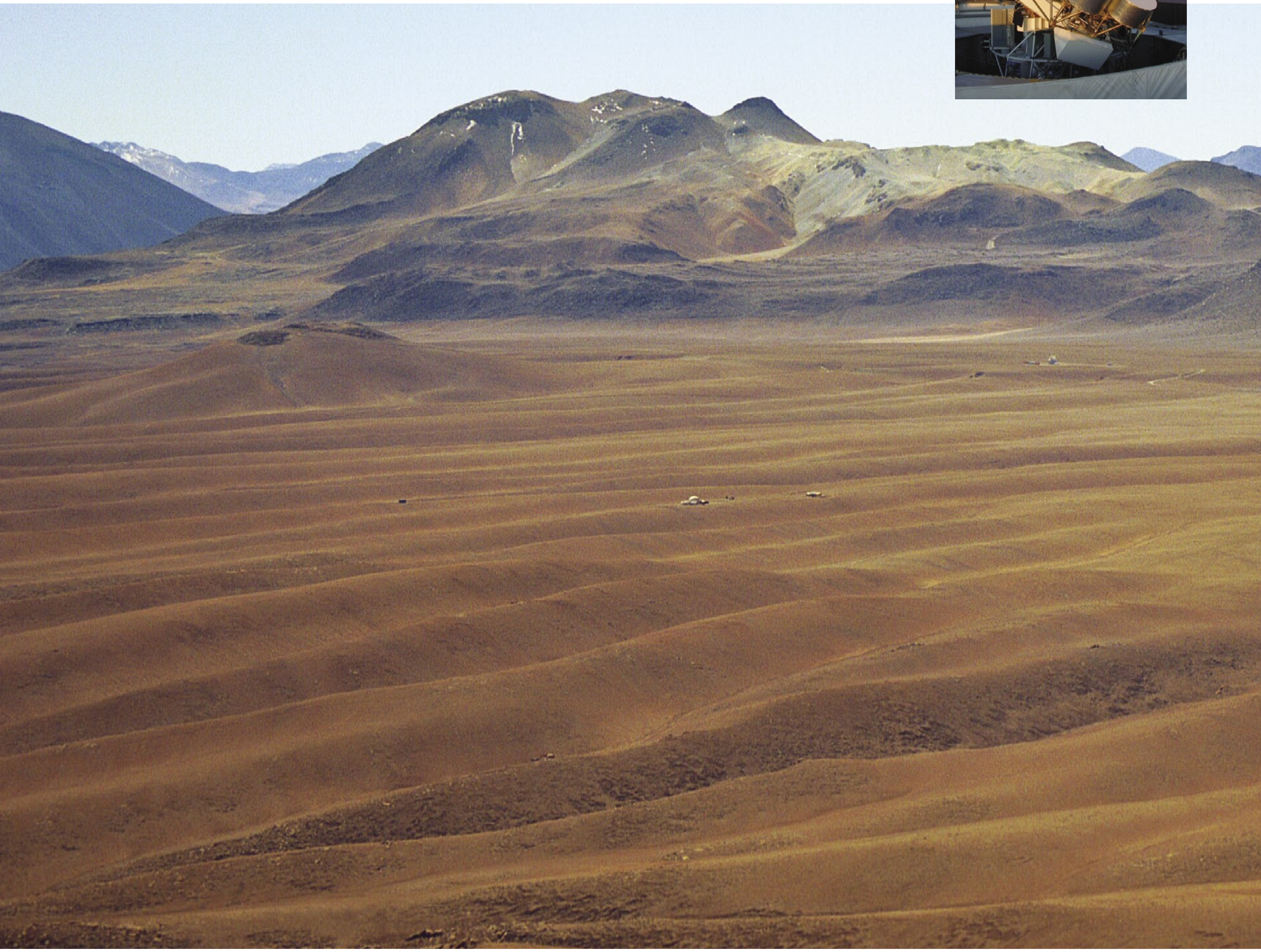
Nanobiotechnology merges inanimate objects with the molecular and cellular machinery of living systems. One of its first uses will be in the emerging field of "systems biology," which views biological systems in terms of their underlying "circuit diagrams"—mapping how signals are sent within a cell by a series of Rube Goldberg–like interactions between individual molecules, for example, or how the interplay of genes turning one another on and off causes an innocuous mole to turn cancerous. Much of this work is based on testing lots and lots of infinitesimal samples in parallel for some kind of biological activity, and with nanobiotechnology, analyses of individual cells or molecules could become routine and automatic.

And while supporting individual scientists who will continue to work the frontiers of fundamental nanoscience, the initiative will also provide centralized nanofabrication facilities that will let engineers exploit economies of scale and develop real-world nanotechnology. Says Roukes, "If we can reproducibly create new nanoscale tools, even in modest production, we'll be far ahead of the curve." Any real-world nanomajig will require the harmonious integration of many kinds of parts—sensors, electronics, readouts, control units, and mechanical pieces—and learning how to assemble all this stuff will be not unlike building a Model T from scratch. But as we get better at it, nanodevices will become as common in the lab as pH meters. And then who knows what will happen. . . . □—*DS*



Below: For more than five years the Cosmic Background Imager has had the vast, high Chajnantor plateau virtually all to itself. Its dome can be made out in the center of the picture below, with its generator about an inch to the right. The clamshell dome (right) is made of sailcloth, flexible enough to withstand 100-mph winds; when it opens, the CBI can train its 13 antennas (far right, in their original configuration) on the microwave background radiation, emitted 400,000 years after the Big Bang. Recent polarization experiments on the tiny temperature fluctuations in this radiation have revealed primordial matter bunching into the seeds of our present-day galaxies (left).





"You go up there with this instrument, and you're collecting photons that haven't interacted with anything for the last 13.8 billion years."

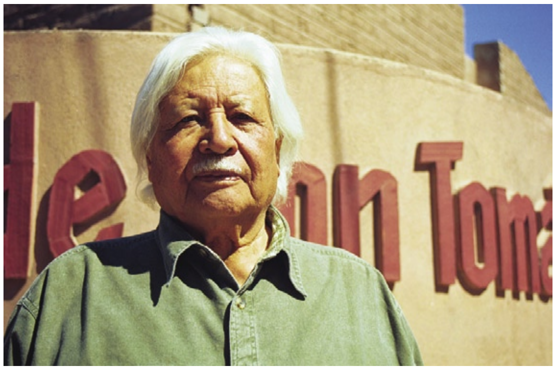
The Caltech–Chile Connection

by Jane S. Dietrich

From its high, dry site on the Llano de Chajnantor in Chile's Atacama Desert, the Cosmic Background Imager (CBI) peers back 13.8 billion years, searching for tiny fluctuations in temperature encrypted on the microwave background radiation, the fossil radiation left over from the birth of the cosmos. That radiation, the most ancient light in the universe, was emitted just 400,000 years after the Big Bang (the equivalent of about 45 minutes after conception when compared to a human life). It's the epoch when light and matter decoupled, when protons and electrons got together to form atoms, so that the electrons stopped scattering photons, freeing them to travel across time and space into the CBI's antennas. Tony Readhead finds it "miraculous." You go up there with this instrument, and you're collecting photons that haven't interacted with anything for the last 13.8 billion years."

Those collected photons gave Readhead and his colleagues the first glimpse, in January 2000, of primordial matter beginning its collapse into the clumps that would eventually evolve into clusters of galaxies. More recently, polarization observations have revealed the dynamics of that clumping—data just published last fall.

Plucking 13.8-billion-year-old photons out of the sky is not, obviously, an easy task. Llano de Chajnantor, at 5,080 meters (16,700 feet) in the driest place on Earth, looked to be an ideal place from which to attempt to see this ancient light. The area was first explored in 1994 by a combined team from the American NRAO (National Radio Astronomy Observatory) and the University of Chile Astronomy Department, prompted by earlier measurements of the atmospheric opacity obtained by a team of Japanese astronomers in the nearby highlands. In that year the NRAO put up a test site, getting "incredible" results. "It's the best easily accessible site in the world for radio astronomy," Readhead, the Rawn Professor of Astronomy and the CBI's principal investigator, claims, with at



Near the end of its journey from Pasadena, the crated telescope approaches San Pedro de Atacama.

Don Tomás Poblete (above) built a comfortable headquarters for the CBI crew at his San Pedro de Atacama hotel, La Casa de Don Tomás (top, with the Licancabur volcano in the background).

least 330 observing days annually and almost no moisture to interfere with the incoming radio waves. "Easily accessible" may be in the eye of the beholder, but Readhead and his optimistic team were the first to seize the opportunity to build an observatory there, with a little help from some new Chilean friends—not just other astronomers, but also a lawyer and a landowner.

Chile's high, dark expanses with exposure to the southern sky and unrivaled "seeing" have lured foreign astronomers for decades, and the nation has always welcomed the astronomers and tried to make it comfortable for them to come. Numerous American, European, and, lately, Japanese telescopes dot the lengthy Andean range. While most of these observatories are located within logistical reach of Santiago or at least another city, Readhead's coveted site lay in the remote northern desert near the Bolivian border, where virtually nothing grows and few human artifacts existed.

"Pioneers have all the fun," Readhead now says, somewhat wryly, remembering the myriad problems. His was a comparatively small operation—just himself and a handful of Caltech postdocs, research faculty, members of the professional staff, and grad students—without the enormous resources of the larger astronomical communities, many with government backing. This was not Big Science, by any means. Readhead had started designing the CBI in 1987, working on key aspects of the architecture with Charles Lawrence at JPL, grad student Steve Myers, and several Caltech undergraduates in the early '90s; then he, Steve Padin, member of the professional staff, and engineer Walt Schaal (BS '58) proceeded with the detailed design in 1993 (*E&S*, 1996, No. 4). It was initially funded jointly in 1995 by the National Science Foundation, a generous gift from Maxine and Ronald Linde and funds from the Provost's Office, and was built at Caltech next to the cogeneration power plant's cooling towers on Holliston Avenue.

But before tackling the logistical problems of importing a telescope to Chile and hauling it up a remote mountain, first the legal issues had to be faced. The Santiago branch of a large American law firm proved both expensive and ineffective. In June 1997, however, at the NRAO in Charlottesville, Virginia, Readhead met with Leonardo Bronfman, former chair of the University of Chile astronomy department and member of the Chajnantor exploration team, who offered the support and collaboration of his department and pointed out a unique law that enabled foreign astronomical institutions affiliated with that university to bring instruments into the country free of the 35 percent import duty and to operate without paying the 19 percent sales tax. Subsequently, Readhead was introduced to Juan Enrique Ruiz, a lawyer at the university who was experienced in helping foreigners set up complex technological enterprises in Chile. Ruiz, along with Bronfman and Jorge May, a radio astronomer at the University of Chile, smoothly guided the Caltech group over the bureaucratic hurdles and through the paperwork—"all the stuff we didn't have a clue about how to do," says Readhead. For example, they helped him obtain the official permission to install the CBI at the Chajnantor site, a science preserve then administered by the Chilean Consejo Nacional de Investigación Científica y Tecnológica, which was also very supportive. Ruiz remains a loyal friend of the project and still helps out—most recently with new generator contracts—largely out of good will rather than for a hefty fee.

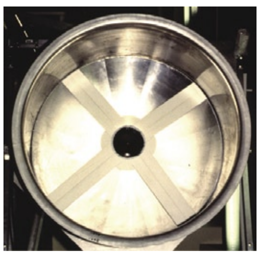
The Chajnantor site is remote, but there *is* a pleasant village 40 kilometers away and about 2,500 meters lower. An oasis frequented by pre-Columbian inhabitants, the town of San Pedro de Atacama was founded by conquistadors in the 16th century and remains popular with tourists who love the desert, particularly Europeans. It doesn't have paved roads, but it does have a couple of decent restaurants and a handful of hotels. Because the

CBI was originally planned as a two-year project, it didn't make any sense to buy or build a permanent place to stay, but the astronomers would have to sleep somewhere. While the CBI construction was finishing up in Pasadena, Readhead was scouting his Atacama site, where Angel Otarola of the European Southern Observatory (ESO) helped him get set up and happened to introduce him to Don Tomás Poblete, who owned a fruit farm near Santiago. (In the early 1900s, Poblete's father had emigrated at the age of 12 from southern to northern Chile, newly acquired from Peru and Bolivia, and made his fortune selling produce to the mining companies.) Poblete never lost his love of the northern desert and had built a home in San Pedro de Atacama—and a comfortable adobe hotel on his property.

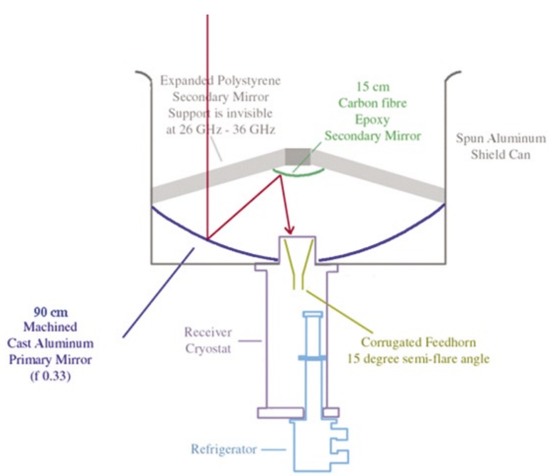
"In a country of charming people, Don Tomás and his wife, Milka, and son, Jorge, are five standard deviations above," says Readhead. Poblete offered to build an apartment for the Caltech astronomers at his hotel. When he unveiled the CBI headquarters (five bedrooms, two computer rooms, and a kitchen) in August 1999, "it was fantastic," says Readhead. It was half again as big as had been contracted for, and "every room was a bigger surprise. Don Tomás told us he asked himself 'What would *I* want if I were to stay here for two years? And this is what I've built for you.'"

When a few local people (impossible to put on the distant Caltech payroll) needed to be hired, Poblete took them on as employees of his hotel. The Casa de Don Tomás is probably the only hotel in the world with telescope technicians on its payroll. Poblete remains close to the project and still showers the astronomers with hospitality and assistance. "San Pedro is the last dream of my life," says Poblete, who believes that what the astronomers have brought, especially knowledge, is good for the village. "Your dreams are my dreams," he told them.

The Cosmic Background Imager was crated up to leave Caltech in July 1999, arriving in Chile in August. By October, the telescope was at the site, snug inside its dome, its generators humming (sometimes). By January it was ready to go to work.



Above: One of the 13 antennas in its aluminum shield can, which is diagramed below. Far right: In the on-site lab, University of Chile grad student Cristobal Achermann and local technician José Cortes repair one of the refrigerator units which keep the receivers at -450° F.

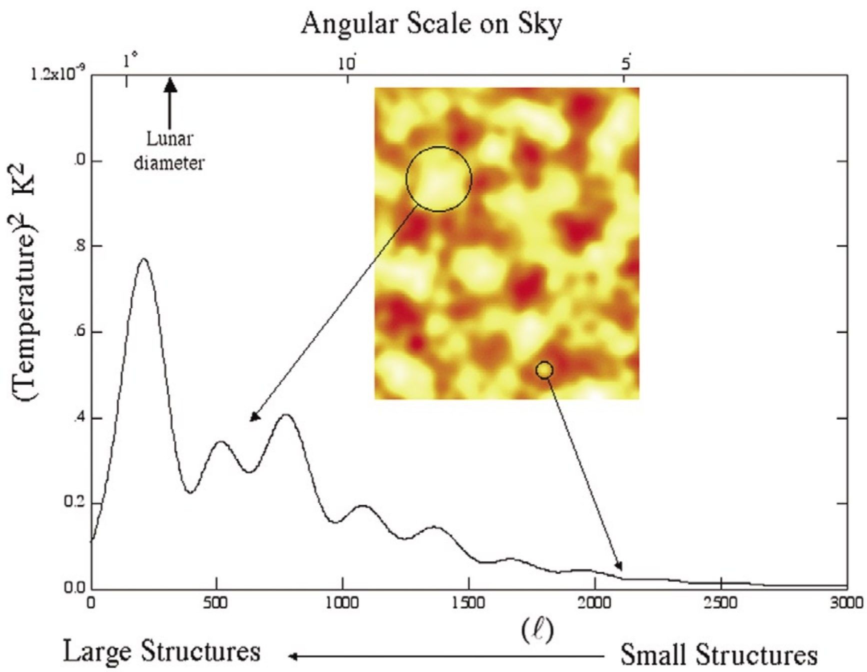


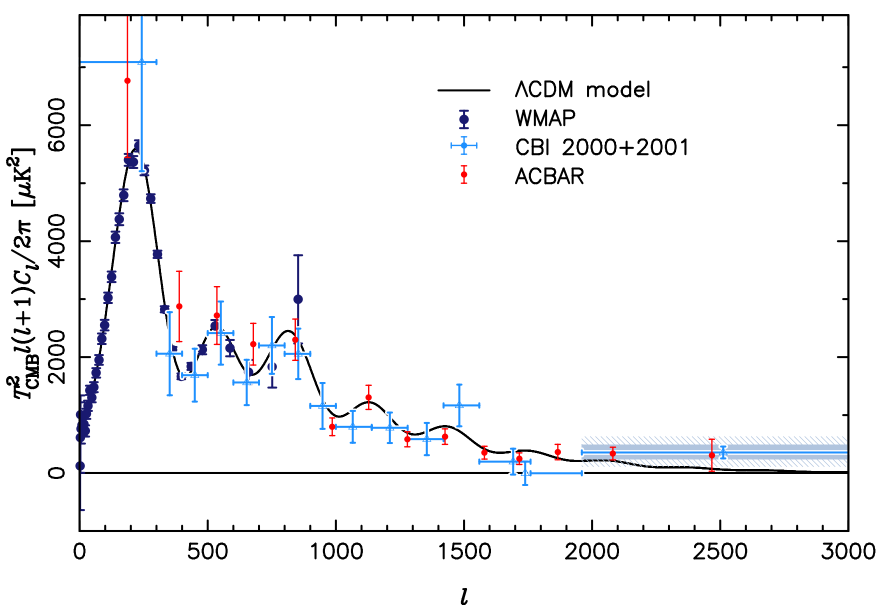
The CBI is a millimeter-wavelength radio interferometer, the first in Chile, and consists of 13 antennas arrayed on a platform 6 meters in diameter. Each 0.9-meter antenna has its own receiver, sheltered by a shield can to prevent cross talk from leaking between its neighbors. Although it's tiny compared to the 40-meter antenna at Caltech's Owens Valley Radio Observatory (OVRO), "it's a very powerful instrument," says Readhead, 75 times more sensitive than the 40-meter for this particular kind of work. Each of the 13 antennas can be paired with any of the 12 others, and the signals from the 78 possible pairs at 10 different frequencies multiplied and correlated to act as an array of 780 interferometers.

Steve Padin, the team's chief scientist, designed the complex correlator (which correlates the signals from each pair forming an interferometer) and much of the other instrumentation. Readhead describes him as a "world-class instrumentalist" and calls Tim Pearson, senior research associate, who was responsible for the data-reduction and analysis software, "one of the best writers of astronomical software in the world." Also among the original group were staff scientist Martin Shepherd, "a truly outstanding programmer," who designed the computer-control and data-acquisition systems; John Cartwright (PhD '03), who built the amplifiers that determine the telescope's sensitivity and carried out pioneering polarization observations for his thesis; grad students Jonathan Sievers (PhD '04) and Patricia Udomprasert (PhD '04); and engineers Walt Schaal and John Yamasaki.

Because the receivers need to be kept at about −450° F (6 K, or degrees above absolute zero), closed-cycle helium refrigerators are an essential part of the design and a continual challenge to maintain. When a "fridge" breaks down, you can't just call in someone from Atacama Appliance Repair. In the first years, the fridges were sent all the way back to the U. S. for maintenance, but now the local technicians and grad students, equipped with the equivalent of a private machine shop and hardware store (from nails and screwdrivers to replacement parts) do most of the repairs on the site.

Why do the receivers have to be so cold? They're trying to detect temperature differences of only millionths of a degree (or microkelvins), which indicate density differences in the microwave background radiation. The microwave background was discovered accidentally in 1965 by Arno Penzias and Robert Wilson (PhD '62) of Bell Labs, and was seen as proof that the Big Bang theory of the universe, which predicted such radiation, was correct. Since then, astronomers and physicists have been training their sights on it, with ever more sensitive and sophisticated instruments, to tease out cosmological clues about the embryonic universe—how galaxies and stars were born. Using





Top: The CBI's image of the galaxy seeds represents temperature fluctuations (red represents cooler spots and yellow, warmer) that indicate density differences in the cosmic background radiation. It's an area of the sky 2° across, or about four times the diameter of the full moon. The curve is the temperature fluctuations predicted by the inflationary-universe model, the larger structures at higher peaks and the smaller ones barely above the axis.

Bottom: Two years' worth of CBI observations are compared with other experiments searching the microwave background. WMAP (Wilkinson Microwave Anisotropy Probe) is a NASA/Princeton satellite mapping the whole sky at large angular scales, while ACBAR (Arcminute Cosmology Bolometer Array Receiver), at the South Pole, measures the background radiation at a wavelength of 2 mm, as opposed to the 1-cm wavelength received by the CBI. ACBAR, a UC Berkeley project, has a number of Caltech collaborators.

OVRO's 40-meter telescope in the 1980s, Readhead saw no temperature fluctuations in the microwave background. After writing a paper in 1989 showing that this implied that galaxies would not have had sufficient time to condense unless most of the matter in the universe were "dark matter," he was teased for proving that we didn't exist. Then the COBE (Cosmic Background Explorer) satellite, launched in 1989, became the first to show that the background temperature was not uniform, confirming what had been suspected—that inscribed on the radiation is the cosmic DNA that spells out how galaxies were conceived, as well as such fundamental cosmological parameters as the size, age, and geometry of the universe.

But the Big Bang theory still presented a bunch of problems: Why did the universe expand? Is the expansion accelerating or decelerating? How can it be so uniform in all directions when its components can't communicate because their separation is greater than the time it takes light to travel between them? Inflation theory, which proposes a massive expansion in the first fraction of a second after the Big Bang, offers solutions to these problems. "It may not be true, of course," says Readhead, but data from the CBI and other instruments so far appear to buttress the predictions of an inflationary universe.

One of those predictions is that the universe is very nearly "flat"—not flat in the sense of a pancake, but flat in the sense of Euclidian space in which two parallel lines will never converge or diverge, so that the universe will expand forever. This prediction was proven true a few years ago by Andrew Lange, the Goldberger Professor of Physics, whose BOOMERANG experiment observed the microwave background from a balloon high above Antarctica (*E&S*, 2000, No. 3). BOOMERANG's picture of the microwave background radiation also showed differences in density in much finer detail than that of COBE's map, which resolved features in the sky the size of 14 moon diameters. Lange's detectors could see structures the size of 0.5 moon diameters.

The CBI, however, has much finer resolution still; its most widely separated pairs of antennas can resolve details as small as 0.1 moon diameters. The first CBI data provided independent confirmation of the almost "flat" universe, but what was more remarkable were its pictures of the seeds from which all structures in the universe eventually evolved beginning to condense out of the primordial soup. On the CBI's first night of observation, January 11, 2000, "we actually *saw* the seeds of galaxies for the first time," says Readhead. "We saw what it would have looked like." (Even though this is a radio telescope, the astronomers are seeing what human eyes would have seen. The radiation has been redshifted and stretched to the longer wavelengths of radio waves, but when the photons were emitted, they were the shorter wavelengths of light photons.)

Even rugged four-wheel-drive trucks can find it rough going in the desert or on the rudimentary Atacama roads. And some-times, when the roads are impassable, a little tow from a friend is welcome.

Seeing the microwave background in such fine resolution made up for the hassles that are inevitable when operating at an unsupported remote site. The power generators have been challenging to maintain in conditions where the temperature can drop to –20° C with winds of over 50 miles per hour and blizzards occur a few times each year. So a lot of effort has to be expended on maintaining infrastructure. "We've had 12 or 15 total losses of power over the five years of operation," says Readhead, "and each time that happens, all 13 of our cryosystems warm up. Although it's clearly not the case, it sometimes feels as though keeping things running is as big a challenge as doing the actual experiment."

"Some people think that astronomy is something that's romantic and fun—looking at the stars at night, you know, and that's it," says optical astronomer Maria Teresa Ruiz, chair of the astronomy department at the University of Chile, whose enthusiastic help has been essential to keeping the CBI running. "Most of the work is not like that. Most of it is hard work, some boring parts, and you have to endure that and have enough inspiration to get you over that so you can get to the fun part."

Radio astronomers in particular have a hands-on culture. Readhead recalls his early days at the University of Cambridge, when renowned astronomer Martin Ryle, who later won the Nobel Prize, invited the young grad student to visit the new One-Mile Telescope. "It was pouring rain. We went down to this basement full of electronics, and water was pouring in. So he turned around and said, 'Come on.' We went up to a little shed, and he picked up a pick and handed me a shovel, and we started digging a storm-water drain right then and there. It was hard work, and after about half an hour or so picking and shoveling away in the rain, he turned to me and said emphatically, '*This* is radio astronomy.'"

Floods aren't exactly a problem in the Atacama Desert, but snow and blizzards at the high altitudes are, and the CBI's sturdy four-wheel-drive pickups, which are more at home in this challenging terrain than in Beverly Hills, have often had to abandon the unplowed roads and take their chances navigating boulder fields. Trucks usually travel in twos in snow conditions, since one must always be prepared to tow the other out. Readhead tells a story of four trucks once getting stuck in the snow before a rescue mission succeeded.

Trucks weren't the only thing to get stuck. "The first blizzard we had up there, the generators stopped, and we couldn't get up to the site for three days. By the time we got through, there was no longer any evidence as to why the generators stopped because everything was melting by then." So when the next blizzard hit on a late afternoon, Readhead and Padin jumped into a couple of trucks and headed up to the telescope to figure out why the generators stopped when it snowed. "The last few kilometers were almost total whiteout, and for the next 24 hours it was a continual blizzard. What we found was that the air filter was getting filled with snow, which then turned to ice, and that the generators had failed because the air filters got clogged with ice. For the next 24 hours (we didn't sleep all night and the next day), we went out to the generators—130 meters from the control room—every hour. It turned out that 130 meters is a long way in a whiteout; we were both very glad that there were two of us up there, because you had to be darned careful that you didn't wander off in a random direction. We would take out the air filter, put in a new one, take the other one back and leave it next to our chillers, which put out a lot of heat. We'd thaw it for an hour or so and shake out all the ice and take it back to the generator. It was blowing and it was incredibly cold.

"Finally Steve figured out that we should block off the main air intake so the air would be drawn into the secondary air intake that passed over various parts of the generator, which would melt the snow before it got to the air filter. We got big sheets of cardboard to put over the primary air filters, but we had to tie them onto the grills because the wind was blowing like crazy. We had our oxygen of course, which was essential. You could just about tie one knot before your fingers got too frozen to tie the next knot. So we were alternating—he would tie one knot while I held the flashlight and then we'd switch. We finally got the cardboard over the air filter and that solved the problem. Then we were snowed in for three days. But it's very safe up there as long as you've got power, oxygen, food, water, and heat."

Doing any kind of work at 16,700 feet requires portable oxygen packs, such as emphysema patients carry, and the CBI crew doesn't hesitate to use them while doing anything requiring physical exertion outside or in the dome, which is open to the thin air. The shipping containers that serve as lab, control room, and sleeping quarters for two have enhanced oxygen, that is, enhanced to the level of oxygen at about 10,400 feet. Lack of oxygen affects one's thinking, and when they realize that their sentences are making no sense, the astronomers reach for their oxygen tanks or head indoors.

For the first two years, either Readhead or Padin was always at the site, with alternating shifts of recruits from Pasadena. Two years is a long time in the desert, where the living is *not* easy, and most of the original staff wanted to go home. And the experiment was originally supposed to be over in two years anyway. But Readhead wasn't done yet; he had much more that he wanted to see out there, and he thought the CBI was still the perfect instrument to see it with and Chajnantor the best place to see it from. At the South Pole, its sister instrument, DASI (Degree Angular Scale Interferometer—a smaller version of the same design, with most key hardware and software elements duplicated from the CBI blueprints), was looking for, and had found, polarization in the microwave background radiation, another feature predicted by inflation theory. If inflation is correct, the cosmic microwave background would have been polarized as light and matter were decoupling, when some electrons were still scattering some photons. Viewing the tiny differences in temperature between light waves aligned in different directions (anisotropies) gives astronomers an idea of the dynamics of matter in the epoch of the microwave background.

For the polarization experiment, the antennas had to be close-packed in the center of the instrument—so snug that it's difficult to reach into them for maintenance (unless you're very skinny). Compare this with the antenna configuration on page 8.

John Kovac of the DASI group (under John Carlstrom at the University of Chicago, who, as associate professor of astronomy at Caltech had worked with Readhead in the CBI's early days) had developed some "superb" polarizers, which would also be available to the CBI, now about to be virtually orphaned in the desert. Readhead passionately wanted to look for polarization at the CBI's smaller angular scales and superior site. The Kavli Foundation was interested in supporting the polarization upgrade, but what about staffing? "Then Jorge found us these fantastic engineers," he said.

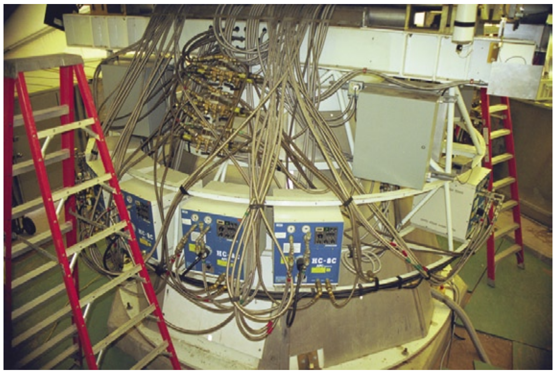
"Tony was complaining that it was very expensive running the CBI, and I said, 'Why don't you hire Chilean engineers?'" said Jorge May, a radio astronomy professor at the University of Chile, who was among the discoverers of the Atacama site. Specifically he meant engineering *students*, a solution that turned out to benefit all parties. "It's good for our economy," said Maria Teresa Ruiz. "We don't have a lot of technology development in Chile. The CBI is on a very modest scale, but these guys who work with Tony on this instrument—they really are working with technology that is at the edge of what's now being developed.

Right: Preparing for a night of observing, Readhead climbs up to detach a pump that has been pumping down one of the receivers all day. Far right: The cable spaghetti around the instrument's base leads to the receivers and cooling circuits.

And I'm sure eventually they will be able to do things in Chile for companies in different areas of the Chilean economy. Being trained in forefront technology is very important—the way of thinking about things, finding your own solutions. It's that kind of thinking that we need for our country.

"Only the inspirational part of astronomy gets to the general public and to the government," Ruiz continued. "It's not like in biology where you can discover things that are worth money. Other sciences—they all have this practical aspect. There are no patents to be had in astronomy. But what many people have not realized is that there's a lot of technological development that goes on—spinoffs—that can be applied to things that involve some money."

May, who had been an engineer before becoming a radio astronomer, first recommended Pablo Altamirano, an electrical engineering grad student at the University of Chile. In addition, the University of Concepción was particularly open to the idea of a radio astronomy program within the engineering department, and Ricardo Bustos switched from the University of Chile to the University of Concepción for his PhD on the CBI. "They're absolutely superb at diagnosing problems and then fixing them," boasts Readhead. The two Chilean students, later joined by another two (Cristobal Achermann and Rodrigo Reeves), performed the polarization upgrade on the CBI, which involved dismantling the 13 receivers, rewiring everything, and reconfiguring the antennas—moving them from the perimeter to an array (with six adjusted to right-hand circularly polarized radiation and seven to left-hand) in the center of the platform, so closely packed that the engineers and technicians had to become contortionists to get to them. "If the central receiver fails, the only way you can get to it is by worming your way up this cable rack," says Readhead, who isn't eager to try it himself unless he has to. "And if you do the wrong thing you can easily short out the cooling system. Then



Right: At sunset, Achermann unfastens the dome latch, and the clamshell opens behind the shipping containers housing the lab and control room. Below: In the control room, Achermann (background) catches photons, while technician Cortes monitors the various parameters of the instrument's operation. Before coming to work on the CBI, Cortes had never touched a computer keyboard.

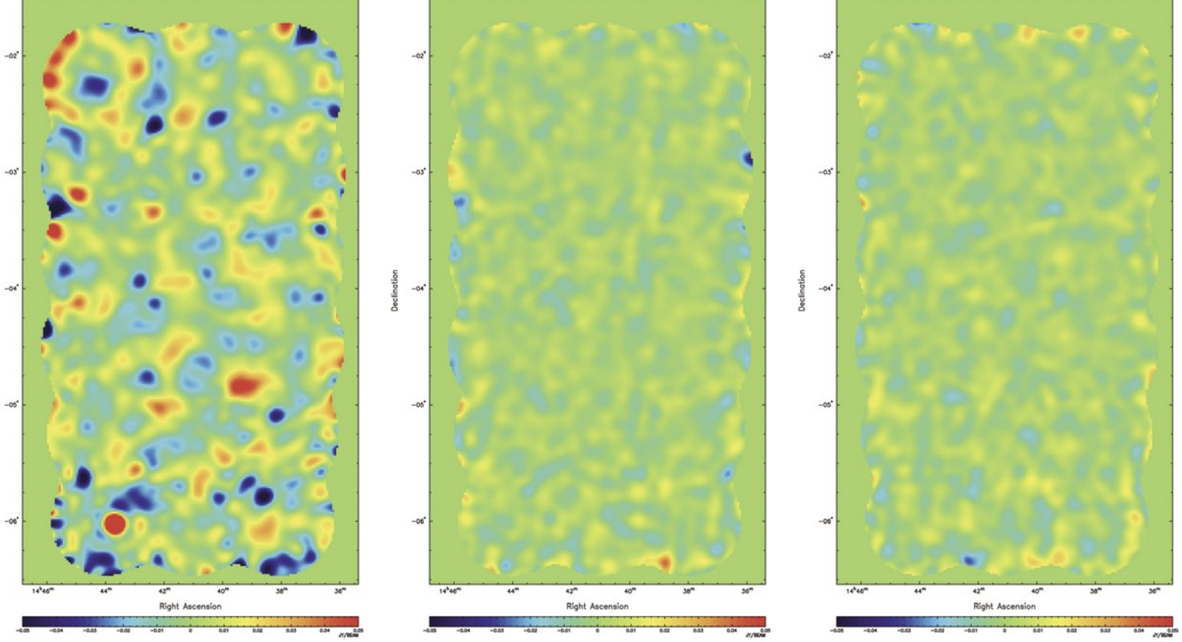
you've blown everything—you've got 13 receivers that are warming up and you've got a big problem on your hands."

Recruiting the Chilean grad students had one unintended consequence. "Tony is so inspiring for these guys," says Ruiz. "These are engineers. But after a year of working with Tony, they all want to be astronomers. They're so important for the project, but now they all want to get PhDs in astronomy. That's *his* fault; he shouldn't be so inspiring."

Still, Achermann and Reeves are sticking closer to engineering and writing dissertations on the instrumentation that they helped develop for the CBI. Currently, the two are alternating time slots for running the telescope—three weeks at Chajnantor and two weeks back at the university. At Chajnantor, they're completely in charge of the project and of running the site. "It's a tremendous responsibility," says Readhead. With help from the San Pedro technicians, they maintain the telescope, including troubleshooting ("I feel like a SWAT team," says Achermann, who describes the telescope as "like a big toy."), and do all the observing as well—the fun part. Another electrical engineering student, Nolberto Oyarce, is the most recent team recruit.

"There's no way we could have done it without them," says Readhead, but the University of Chile has also benefited from this unique arrangement with Caltech. From the beginning, its astronomers have had access to 10 percent of the observing time on the CBI and have been coauthors on most of the CBI papers. The instrument has been ideal for teaching radio astronomy, and students, including undergraduates, have worked there in the summer, collecting and analyzing data. The university had been trying to figure out how to train engineers and technicians to staff all the new foreign telescopes about to arrive in Chile, and the CBI has provided a perfect model, according to Ruiz. Just last spring, the university established a new PhD program in electrical engineering with a major in astronomical instrumentation—a direct spinoff from the CBI project. And that's all in addition to the know-how the students are gaining by working with the polarizers.

With the polarizing upgrade complete, observations began in September 2002. But the search for polarized light—finding anisotropies in already incredibly small temperature fluctuations (smaller by a factor of 10 than previous observations)—took a dogged 300 nights of observing (in contrast to the eureka moment of CBI's first night). Just as polarizing sunglasses transmit only the light that is aligned with the glasses, the CBI's polarizers pick out only the polarized light from the total intensity (including unpolarized radiation). The team observed four patches of sky, all together an area about 300 times the size of the moon. By April 2004, the data were complete enough for the team to be confident that they had indeed seen polarized light, evidence of how the matter condensing into



These recent images cover a patch of sky about 2.5 x 5 degrees, one of four areas the CBI observed between 2002 and 2004. The left-hand image shows the total intensity (unpolarized radiation) of the microwave background signal. The other two images of the same patch map the radiation polarized vertically (center) and at 45° (right) and show that it is much weaker than the total intensity—about 10 percent of it. The polarization signal is also contaminated by noise from the telescope itself, so the CBI astronomers must use statistical analysis to extract the polarization information. (Reprinted with permission from A.C.S. Readhead et al., *Science*, vol. 306, no. 5697, 836-844, © 2004 AAAS.)

galaxies is actually moving. Published in October 2004 as the cover article in *Science*, the work confirms DASI's results and extends them to the higher resolution that can actually see the galaxy clusters. The CBI data also shows that the polarization signal is out of step with the total intensity signal—that is, the peaks of the polarized signal correspond to the valleys of the total signal and vice versa—a sure indication of the motion of the primordial plasma as it falls into the seeds of galaxy clusters, confirming one of the basic predictions of the theory.

Cooperation with other experiments will be essential as the observations become orders of magnitude more difficult. Readhead predicts that what the CBI is doing with its sister instruments is going to lead to a revolution in fundamental physics. Cosmology and particle physics have come together, he claims, cosmology providing the "laboratory" for high energies unattainable in earthly accelerators. "And whenever two scientific disciplines come together and find they have common ground, you get incredibly interesting things going on at the interface," he says.

Things like dark matter. What Readhead is seeing is fluctuations in the dark matter itself—nonbaryonic stuff that is not made up of protons and neutrons, as is all the matter we can see around us. Nonbaryonic matter, which is thought to account for about 22 percent of the energy of the universe (dark energy makes up another 74 percent) would have the much larger density fluctuations necessary to form galaxies in the billion years or so it took to form them. But, because it doesn't interact so strongly with light, it produces the small temperature fluctuations in the microwave background on the scale of galaxy clusters—implied by OVRO's 40-meter telescope back in the 1980s (when Readhead "proved that we don't exist") and finally seen for the first time by the CBI. Readhead describes the ordinary matter of the galaxies as collapsing into "wells" in the dark matter. "So it looks to us as if galaxies are isolated," says Readhead, "but the stuff that has really formed them and caused them to be there is all around them, still touching," even though we can't see it now. He's hoping new detectors will enable him to see it more clearly *then*.

A new type of detector, called MMIC (Monolithic Millimeter-Wave Integrated Circuit) Arrays, is being developed at the Jet Propulsion Laboratory by Todd Gaier, Charles Lawrence, and Mike Seiffert, and will be installed in a new experiment on the CBI platform, called QUIET, for Q/U Imaging ExperimenT. The 1,000-element array, the first radio "cameras," which will improve the CBI's sensitivity to a fraction of a tenth of a microkelvin, should be ready in 2006. A second string to QUIET will be the importation of a new 7-meter telescope to complement the range of angular scales observed with the upgraded CBI. Readhead, who considers himself lucky to be working at a time when so much new technology is constantly coming on line, likens it to a new window that has opened. "You don't know what you're going to see through that new window," he says, which is exciting to an astronomer but hard to explain to funding agencies.

Readhead is hoping for NSF funding next year for QUIET and hopes to make the Chajnantor Observatory a permanent Caltech facility. While the project has received most of its support from NSF, more than 40 percent has come from Caltech. Besides the two Chilean universities, the Canadian Institute for Advanced Research, the Kavli Institute for Cosmological Physics at the University of Chicago, and the National Radio Astronomy Observatory have collaborated on the CBI. In addition to the Lindes' founding gift, Cecil and Sally Drinkward gave to the project, and continuing support has come from Barbara and Stanley Rawn, Jr. The Rawns most recently have provided funds for a Caltech graduate student and a postdoc; Clive Dickinson (the most recent recipient of the Michael Penston Prize for the best astronomy or astrophysics thesis in the United Kingdom) arrived last summer from the University of Manchester to take up the latter post. And some members of the Associates on a President's Circle trip to Chile last year, were so impressed with the CBI's well-run organization (as well as with the science) that they offered substantial contributions on the spot.

The Cosmic Background Imager is no longer alone on the Chajnantor plain. ASTE (Atacama Submillimeter Telescope Experiment) arrived at the Pampa la Bola, just below Chajnantor, in 2002, and its Japanese scientists are now sharing Don Tomás's suite with the diminished Caltech crew (although the fastidious Japanese maintain their own pristine refrigerator, separate from the sloppier American/Chilean group). APEX (Atacama Pathfinder Experiment), a German-built antenna, is just coming into operation. A Caltech/JPL/Cornell collaboration is surveying a nearby peak as a site for a 25-meter submillimeter antenna, as is Princeton for ACT (Atacama Cosmological Telescope).

But what will alter the landscape the most is ALMA (Atacama Large Millimeter Array), a massive American-European-Japanese undertaking, scheduled to join the CBI in 2008. No less than 68 twelve-meter telescopes (plus 12 seven-meter ones), of which APEX is a prototype, will mushroom across Chajnantor. There will be a paved road (ALMA has already graded a better dirt road across the plain) and a reliable source of power; Readhead's Chilean proteges will have plenty of job opportunities; and the astronomers in San Pedro de Atacama may well outnumber the tourists and the ubiquitous local dogs.

Ruiz and some ALMA staff met not long ago with some of the local farmers and villagers about the changes that are coming. "I gave them a talk," she says, "the same talk I give to the general public about the evolution of the universe, with pictures and everything. And then representatives from ALMA gave short talks about what they would do there—how they would operate and how they would create new jobs, because they will need people to clean and cook and things like that. So then came the question time. And this guy raised his hand and he said, 'More jobs is very good news because we need jobs in this area, but it is not the most important thing. The most important thing for us is our kids, and we would like to know how you can help us get a better education for them so that they can become astronomers and do all of these discoveries that this lady is telling us about.' I thought that was fantastic," says Ruiz.

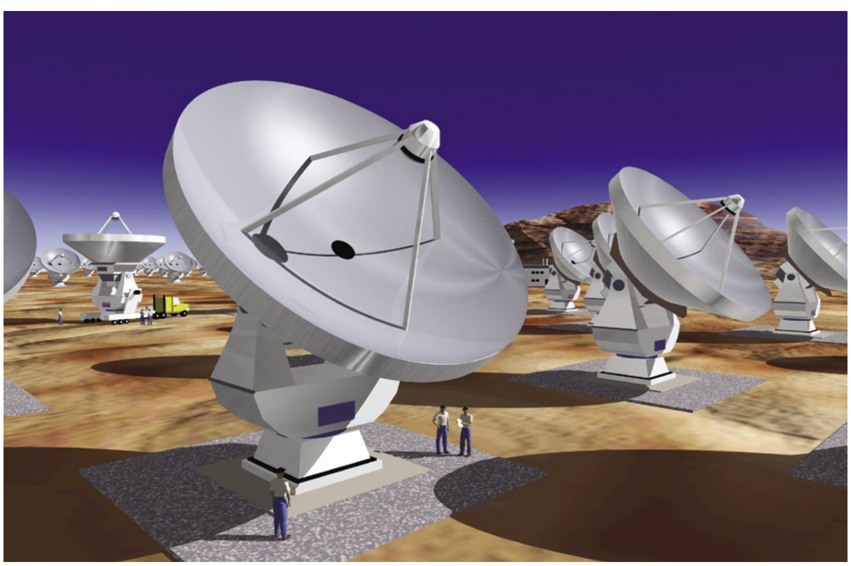
Readhead hopes that CBI/QUIET will still be there, probing the cosmic background radiation for more clues to the nature of dark matter and dark energy and also, as the instrument's sensitivity increases, opening up new areas of study in the radiation from our own galaxy. He and his collaborators have already discovered a new form of "anomalous" galactic emission that is not understood, and he already has plans for what should come next.

Throughout the CBI's existence, Caltech's president, provost, and the division chair of physics, mathematics and astronomy have supported it strongly. Recently, new collaborations with the Jet Propulsion Laboratory, with the English universities of Oxford and Manchester, and with the Max Planck Institute for Radio Astronomy in Bonn have brought additional support, as well as ideas for novel instrumentation. A lot remains to be learned from the cosmic background radiation, and this ground-based site can accommodate larger, cheaper instruments than can be launched into space, such as European Space Agency's Planck satellite, scheduled for 2008.

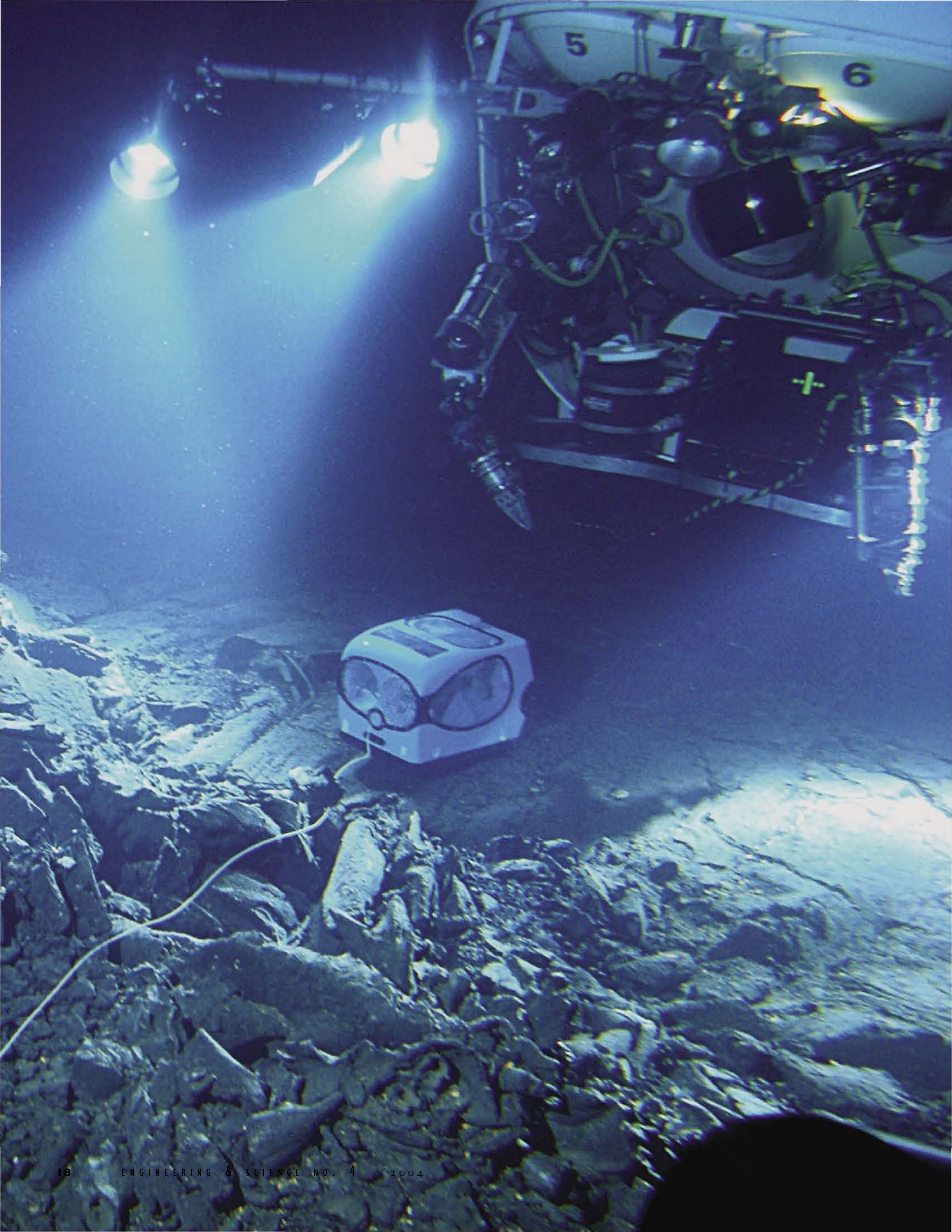
The future of the observatory will depend on continued innovation in a very competitive field, as well as continued support from NSF and generous private donors, but Readhead is confident that the importance and excitement of the science, the potential of the new instrumentation, and the extraordinary quality of the atmosphere at the site will ensure its survival.

Readhead remembers what it was like as the lone settler on Chajnantor. "It's wonderfully romantic when you're the only one on that site and you're up there observing," says Readhead. "That's one of the things I like the most—to be up there observing on my own." Life will be much easier now (easy might trump romantic), and Readhead welcomes all his imminent new neighbors, as the CBI continues to push the latest technological developments to the limits of what is achievable from the ground. □

A big family is moving in next door. Over the next three years, ALMA (Atacama Large Millimeter Array) will plant 80 antennas on the Llano de Chajnantor. A multinational undertaking, it will be the world's largest millimeter-wavelength telescope. (Artist's rendering courtesy of the European Southern Observatory.)



PICTURE CREDITS: 8, 10, 11, 15–Jane Dietrich; 13–José Cortes



What do you do when filmmaker James Cameron, of *Titanic* fame, invites you to dive to the bottom of the sea with him—as long as you bring along your coolest gadgets? It's like being offered a free rocket launch and a place on the spacecraft. Of course, you accept the invitation!

Voyage to the *Aliens of the Deep*

by Arthur Lonne Lane

Above: McDUVE, JPL's instrument, is readied to scan a volcanic rock surface for signs of life once Mir's lights are turned off. On the facing page, Mir 2 hovers over Mike Cameron's "fly-by-wire" hydrobot after its control and data optical tether crossed an invisibly small and very hot water vent that burned through the fiber in a second. Without command capability, the hydrobot sank to the ocean floor, a heart-wrenching moment for those watching in the Mirs. How it was retrieved is told on page 23.

What do you do when filmmaker James Cameron, of *Titanic* fame, invites you to dive to the bottom of the sea with him—as long as you bring along your coolest gadgets? It's like being offered a free rocket launch and a place on the spacecraft. Of course, you accept the invitation!

That's how JPL astrobiologist Pan (Pamela) Conrad and I were able to build a point-and-shoot instrument to look for organic biosignatures in extreme environments, and test it out at hydrothermal vents in the Pacific while being filmed for Cameron's latest movie, *Aliens of the Deep*. Part science documentary, part imaginary journey to Jupiter's moon Europa, the film is currently showing at IMAX 3-D theaters around the world. This is part of "The Making of " story you won't find on the extended DVD, taken from the daily e-mail journal I sent back to the team at JPL. But first, some background on how JPL joined forces with Hollywood.

Jim Cameron and Mike, his engineer brother, have a deep interest in space science and exploration. They learned about our work developing detectors for organic material in and around hydrothermal vents during a visit to JPL in 2001. Jim was planning a voyage to the German battleship *Bismarck*, 3,700 meters below the North Atlantic, to film *Expedition: Bismarck* and to examine some hydrothermal vents near the Azores, so he invited us along. But four weeks' notice was not enough to find funding and convert our instrument, tested to a man-rated 2,000 meters depth, into one safe at 4,000-plus meters, so we had to pass up the opportunity.

We were given a second chance in April 2003, when Jim called with an invitation to join a cross-disciplinary, multi-institutional science team for his next movie, *Aliens of the Deep*, but once again the timescale was too short; he was leaving for the Atlantic Ocean in six weeks. But a Pacific Ocean part would be filmed in October. Now *that* was warning time enough. Pan, engineer Lloyd French, and I quickly wrote a proposal, got the go-ahead and some money from chief scientist Tom Prince and director Charles Elachi, and assembled a small team that also included Gindi French (Lloyd's wife), Bob Wilson, Rohit Bhartia, Barbara Kachachian, Everett Salas, Colin Mahoney, members of "Team I," an instrument engineering group, plus Ray Reid and Bill Hug of Photon Systems. Michael Eastwood interfaced with Cameron's organization. We had just four short months.

The development of our instrument, McDUVE (short for multichannel, deep-UV excitation fluorescence detector), proceeded in the normal, chaotic manner of a very rapid, multidimensional implementation task: some component suppliers were on time, some were late, and some never delivered what they promised. Components failed, software broke, and testing systems didn't always perform to spec. But by early August we were on track for an October 8 delivery. Then the inevitable happened. Cameron shortened one segment of the timeline, and we now had to be in Acapulco on September 24 or miss the boat! Just about the time that news arrived, one deep-ocean pressure test produced crazing and microfractures in several of the instrument's quartz windows, so that we also had to design, fabricate, and test an additional pressure dome for the windows.

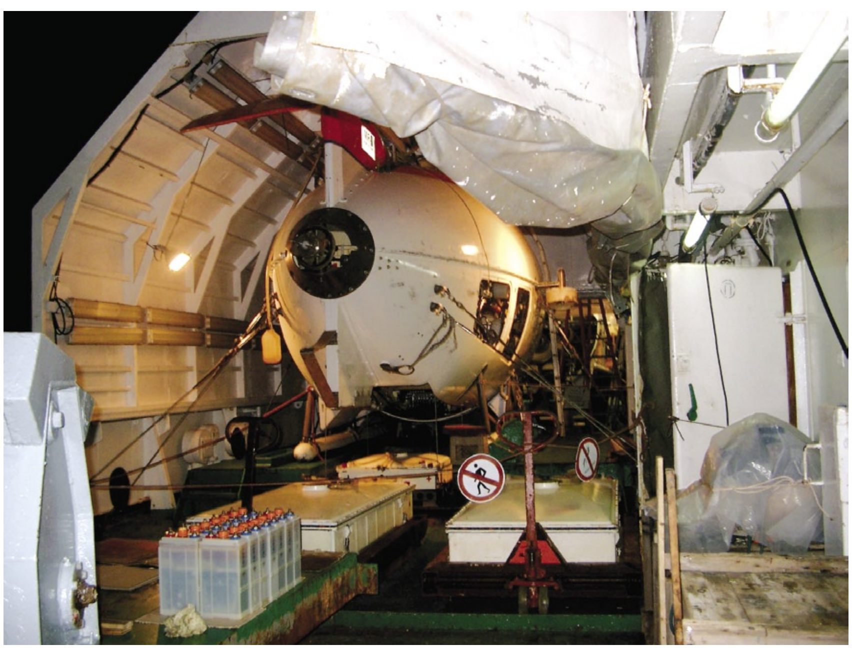
One week before the shipment date, however, the entire instrument system came together and played as a unit. The control and data acquisition software was a bit incomplete, but a modification could be delivered to us at a port of call during the cruise. We completed the work in 91 days from start to finish, with no weekends and no holidays, so when my journal begins on our last day at JPL, we're all pretty exhausted. But our problems aren't over yet.

Wednesday, September 24, 2003. We're boarding the Russian research vessel *Akademik Mstislav Keldysh* in Acapulco tomorrow. Some

Designing, funding, and building a fluorimeter in just 91 days was a challenge, and Pan Conrad (center), Rohit Bhartia, and Everett Salas (in the patterned shirt) were still fine-tuning the instrument in the corner of an Acapulco hotel room the day (and night) before the voyage.

of our equipment has been trucked there by Jim Cameron's production house, and eight more boxes are supposed to go by FedEx today for overnight shipment. But when we got them to FedEx, we were told they had given us the wrong information, and would not be able to deliver them in time. The only option left to us was to take everything with us as luggage on our flight to Acapulco. We quickly had to commandeer two of the instrument's software developers, Rohit Bhartia and Everett Salas, to fly with us so that we had enough fares to cover the baggage allowance, and then we hurriedly unpacked all our carefully packaged equipment and tossed it into an assortment of suitcases and carry-ons. Once on the plane, all four of us immediately fell asleep, as we had been sleeping only four hours a night for the previous week.

The next frightful point was Mexican customs, which we thought would be a nightmare. I fully expected to have to consider paying bribes to keep them from taking our hardware. Amazingly, the customs agent at Acapulco understood that we were scientists going to work with all the equipment on a ship and had no intention of selling any of it locally. He waved us through.



Rear view of one of the Mirs in its hangar on the deck of the *Keldysh.* The Mirs can descend to 6,000 meters and are fitted with powerful lights, ideal for movie-making. Cameron also used these submersibles in *Titanic*, *Ghosts of the Abyss,* and *Expedition: Bismarck.*

Thursday September 25. While we loaded our equipment onto the ship, Rohit and Everett worked in my small, but comfortable, single cabin putting the final touches to the control software (having already worked through the previous night in our Acapulco hotel rooms).

We finally left Acapulco at about 10 p.m., after saying good-bye and many thank-yous to Rohit and Everett. Exhaustion set in by 11 p.m., and I was soundly asleep in seconds, while the ship steamed to area 9N on the East Pacific Rise. This is the famous area where deep-ocean hydrothermal vents were first sighted (by humans) in 1977.

Friday, September 26. Today was mostly a day for adjusting to the ship and getting to know the people aboard. Leading the Russian team is Anatoly Sagalevitch, program director of the Shirshov Institute of Oceanology and "father" of the Mir deep-diving submersibles. Piloting the Mirs are Genya and Viktor, and then there's a sizable crew associated with the submersibles, and a few Russian scientists with whom we're sharing lab space. Jim has brought along scientists from Woods Hole Oceanographic Institution; Columbia University; Scripps Institution of Oceanography; UC Santa Barbara; Stanford; NASA Ames; and Johnson Space Center, plus a 20-strong film crew. There's also Jim's brother Mike and his small support team for the two hydrobots carried by the Mirs. Mike designed and built these small, remote-operated vehicles himself. Also tossed into the complement are two paying American guests, who will be diving with the Russians.

Saturday September 27. Pan and I spent the day unpacking our 15 boxes and cases, and setting up our lab in the small area we've been allocated. Just before 1 a.m., we quit for the day. This expedition is turning out to be no picnic.

Sunday, September 28. We arrived at the dive location in the early morning. Anatoly and Jim have decided that McDUVE will be mounted on the forearm of Mir 1's hydraulic manipulator arm; not the easiest decision to make, because now the arm will not be able to gather samples, pick up dropped items, and guide the hydrobots. But, to our benefit, it means that we can now point the instrument up close and personal at targets of interest. Genya's team fitted mounting brackets and installed the oil-filled pressure-compensated cable that links McDUVE to the laptop computer in Mir's cabin in preparation for the first dive on Tuesday. I'm going down to test the instrument's ability to withstand deep-sea pressures, but not to do any experiments with it yet.

Tuesday, September 30. DIVE DAY! I stopped most of my fluid intake at midnight, so no coffee or tea for me this morning. There's a urine

The Science Mission

We wanted to search for organic chemicals distributed on the vents and rocks, and distinguish whether they were living or nonliving—knowing what constitutes a signature of life is an important objective for astrobiologists.

We also wanted to see if complex organic materials were being synthesized in the plumes of hot water and condensing minerals coming out of the vents. Some people think that these deep-ocean plumes may have been where life originated; newly developing complex organic molecules would have been shielded from the heavy bombardment of particles that occurred during the nascent stage of Earth's formation. (The same process may have occurred elsewhere in the solar system, which is one reason why a mission is being planned to explore the ocean that lies below the frozen surface of Europa.)

And we wanted to study the variation in the distribution of organic chemicals in the water column above the vents to see how far these chemicals might rise and be available to other ocean creatures.

There were many other experiments to try during this unique chance to explore the nearest thing to alien territory available without a long trip through the solar system, but we limited ourselves to these.

We also wanted to advance the type of instruments that might be sent to Europa, Titan, and the deep atmospheres of Jupiter-like planets. If our instrument couldn't withstand the harshest of earthly analogs, it might not be robust enough to withstand a deep-space mission.

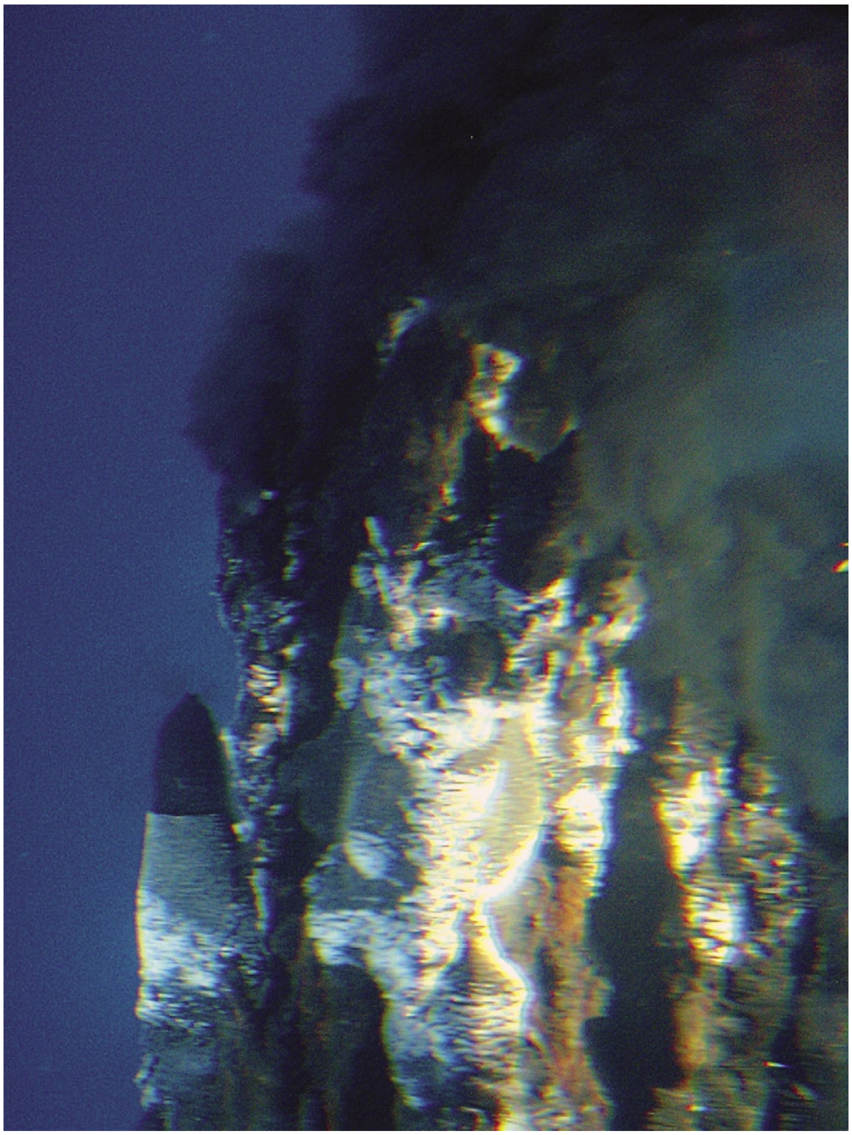
To measure the presence of organic chemicals, we used the fact that many of them "glow" under the stimulation of coherent light, the type that comes out of a laser, producing a phenomenon known as laser-induced native fluorescence: when hit by a wave of light energetic enough to stimulate fluorescence, different types of material fluoresce at different wavelengths, depending on the complexity of the molecule. This method can distinguish between some of the different amino acids and a number of cyclic-ring organic molecules.

About a meter long, 15 centimeters in diameter, and a hefty 40 kilograms in weight, McDUVE was built to withstand the external pressure of more than 400 atmospheres (6,000 pounds per square inch) we would find at the depths we were diving to. A titanium pressure housing protected electronics and optics, and included a demountable front-end dome with UV-transparent quartz windows, and a rear endplate for electrical access by a pressure-compensated cable. We controlled the instrument from inside Mir 1 by using a laptop computer attached to this cable, and powered the system from the submersible's batteries.

A deep-UV hollow cathode laser (224.3 nanometers) stimulated fluorescence in the organic molecules, and five photomultiplier tubes detected wavelength bands in the optical region, defined by 50-nanometer-wide optical filters. Four of these detected the deep-UV and blue end of the spectrum, and one covered the deep red to very-near-infrared (700–850 nm). We used a red channel because little exploration had been done in this wavelength region underwater, so we thought we'd go fishing with this new and very sensitive capability.

Top: This view of McDUVE taken in Mir 1's hangar shows how it was attached to the manipulator arm. Above the JPL logo is an ingenious fast-response thermal-data logging sensor (aka temperature probe) designed by Mike Cameron. We placed it just above and slightly forward of McDUVE's light shield to give us a history of the water temperature the instrument was looking through. (The black object by the front of the instrument is a lamp on the side of the ship.) Above: The small hole in the center is the UV laser output window, and the four red circles are entrances for the photomultipliers. The fifth circle is a titanium plug installed at the last minute when one window showed microcracks. It blocked the green channel, but saved the instrument from water damage.

The remainder of the dive was a trip to a magical world. Apart from the weightlessness, the wonderment and sensations must be similar to being in space. I saw huge, broken lava bubbles with collapsed roofs, strange archways, white crabs, giant shrimps, and strange-looking fish.



The black smoke coming out of this hydrothermal vent chimney on the East Pacific Rise supports a rich ecosystem entirely independent of solar energy. Superheated water welling up from below the ocean floor is rich in dissolved minerals, mainly iron, zinc, copper, and sulfides, which precipitate out as soon they hit the cold ocean water, forming the clouds of black particles. Sulfide- and sulfate-reducing bacteria can live on these minerals, and other animals in turn live on them. The existence of so much life in one of the most hostile environments on Earth raises the hope of finding life below the frozen surface of Europa.

bottle on board the Mirs, but to avoid using one is better. Once McDUVE was mounted, I donned a fire-retardant coverall and got the rest of the hardware together along with log books, a few sweets, a soft hat, and extra socks for keeping warm after the shell has chilled down to below 10 °C (the water at the bottom is close to 2 °C). I climbed into Mir 1 with Genya and Jim, and stowed my little bag of clothes and goodies, and then the top hatch was locked in place. Three adults inside a two-meter-diameter ball with a lot of electronics and energy converters generate a lot of heat, and I was sweating quite a bit. Out the small viewport on my side of the sphere, and through the larger viewport Genya uses for driving, I watched the deck crew loosening the tie-down cables. Then the crane lifted us up and over the side of the *Keldysh* to the dark-blue water below. Pan waved me off—she was just itching to go also—and within a minute we were in the water. One of the support team jumped on top of Mir to undo the cable tie to the crane and affix a rope attached to the support motor launch, which maneuvered us away from the ship. We bobbed about in the waves for 10 minutes (the surface zone is the problem area for seasickness) but then we were on our way down, and the sea darkened rapidly as we descended. Suddenly, at 200 meters depth, there was a loud pop. My mind quickly assumed that McDUVE had had a window failure and the instrument was flooded with seawater. An instant wave of dismay flashed over me. Everything ruined! A second later there was another pop, and a fraction of a second after that a third, all coming from the front of the Mir. I knew that if there was a water flood into McDUVE, only one implosion was possible, so something else was happening. Jim and Genya were visibly concerned; these are not the kinds of noises one wants to hear deep in the ocean. Then we realized that the Plexiglas sample-collection carousel had not been loaded with seawater before the dive, and the build-up of pressure on the top surface plate over the empty sample cups had imploded the structure. Genya turned on the front lights, looked down, and saw the broken parts floating upward as we descended. The fluorimeter was OK.

An hour later we were at 2,500 meters and near the bottom. The remainder of the dive was a trip to a magical world. Apart from the weightlessness, the wonderment and sensations must be similar to being in space. I saw huge, broken lava bubbles with collapsed roofs, strange archways, white crabs, giant shrimps, and strange-looking fish. These fish had what looked like eye structures, but to what purpose? At this depth of the ocean there is no surface light. There might be some bioluminescence, but could a fish see that?

Jim shot a number of scenes, changing the lighting and view angles, and working the 3-D imaging system. He filmed a scene where Mike, who was nearby in Mir 2, piloted his hydrobot over to a

Pan talks on camera about her research, with UC Santa Barbara marine biology graduate student Dijanna Figueroa, foreground, Loretta Hidalgo, MS '02, and Mike Cameron.

small, white octopus resting on a ledge. Mike extended the bot's gripper arm toward the octopus and it gingerly extended two tentacles toward the arm and tried to grab it. For about five seconds there was a short tug-of-war, and Jim caught it all in 3-D.

As the bot was heading back to Mir 2, its optical fiber command and data cable (which connects it to Mike's control station in Mir 2) crossed a small surface vent spewing out clear, hot water. The cable burnt and ruptured, and the lifeless bot slowly sank to the ocean floor. Thus began the great bot recovery operation. With us in Mir 1 trying to be a second set of eyes at a different angle, Mir 2 left its high perch on a ledge and descended to the floor where the bot lay. After several unsuccessful attempts to use the manipulator arms to pull the disabled vehicle into the garage slot on Mir 2, Viktor tried using one arm like a bat to lift it off the floor, and the other to swat it into the garage opening. Ever tried playing volleyball on the ocean floor? After several tries, it finally worked, and we began our leisurely 90-minute float back up to the surface. At about 100 meters depth, Genya turned on the high-intensity lights so the recovery team could find us (to the folks on the *Keldysh*, we looked like a phosphorescent whale), and that's when I saw the most amazing collection of strange, gelatinous creatures. They were translucent white with an orange disk, and each was about the size of a thick cigar. I saw a hundred or more between 100 and 70 meters depth, and then they were gone. At the surface we bobbed about for 15 minutes before we were caught and towed to the lifting crane. It had been an amazing 12-hour ride. Back on deck, we were greeted by the film crew and the Russians, something that is done for each crew that goes down. Later, Pan and I checked the fluorimeter: no damage, no water inside, no window problems. It was ready to do great new science measurements.

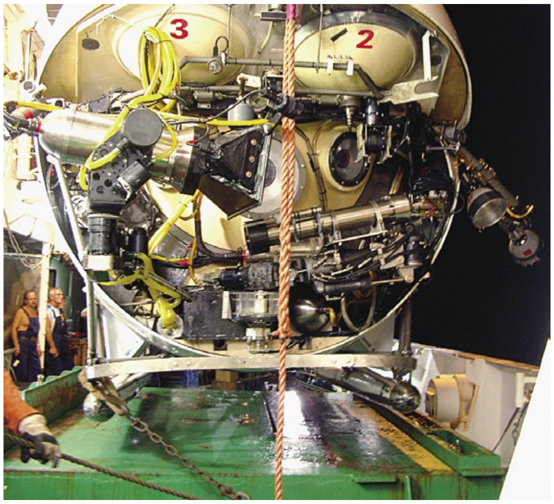
Wednesday, October 1. The third dive is planned for tomorrow, but Jim Cameron decided not to have JPL present on this one, so Pan will have to wait until we get to the 21N site.

Thursday, October 2. We spent most of today working on McDUVE in the lab, studying the anatomy of the software that controlled the electronic state of the instrument. We had very little in the way of precision optical components with us, so it took a number of trial-and-error optical setups to get conditions properly adjusted to enable us to measure gains that differed by factors of 10. By dinnertime we had puzzled our way through several configurations but were not able to explain some observations with respect to the control settings, so after dinner we put in a call to Rohit. With the assistance of Ray Reid, Bill Hug, and their electronics fabricator in Fallbrook, Rohit answered several of the questions, and we used that information to push a little further that evening.

Later, Jim Cameron decided to show a few blocks of the imaging product he was developing, and sent a message to all of us to join him in the viewing room around 9 p.m. The 3-D images were again very spectacular, but the highlight of this showing was Dumbo, a meter-sized white octopus (below) that seemed quite unafraid of the noisy and very much larger Mir.

Friday, October 3. Seismologists Maya Tolstoy and Dave DuBois from the Lamont-Doherty Earth Observatory in New York had their one and only dive from 6:30 p.m. Thursday night until 7 a.m. this morning (remember, below about 900 feet there is almost no sunlight, so day/night distinctions are meaningless), and once the dive

Propelled with the help of two flapping "fins," this friendly octopus filmed in the Atlantic part of the movie just had to be Dumbo.



This view of Mir 1 being craned back on deck after Pan's dive shows the large 3-D camera on the left-hand side, with McDUVE below and to the right of the camera's front end.

was finished, we began to steam back to Cabo to drop them off. Jim and some of the film crew also left the boat; they were going to film elsewhere for a few days, while we were going to 21N without them.

It was now 10 days since we'd left Pasadena, and I was running out of socks and underwear, so washday was at hand. We'd been given some advice about the laundry service when we came on board: If you really like what you have and want it to remain like that, don't submit it to laundering by the ship's staff. Rust stains would always appear like magic on the garment, underwear would be starched and ironed, and a simple collection of items could run up a $40 bill. Seems the Russian ladies who handle the laundry are making four times the captain's salary. So I decided it would be best if I washed my own socks and underwear. There was no place to hang wet items in my little room, so I strung up a plastic-coated line (taken from our lab) in the bathroom after the room was cleaned in the morning, making sure to remove it early next morning before anyone showed up. After 15 hours of hanging, the clothing was still damp, so I spread it out over hangers and rotated them through the "dryer," the shelf just above the in-wall refrigerator, which had warm air escaping from around it. The socks and underwear are now washed and reasonably clean, but not fluffed and tumble-dried. T-shirts will be the victims next week.

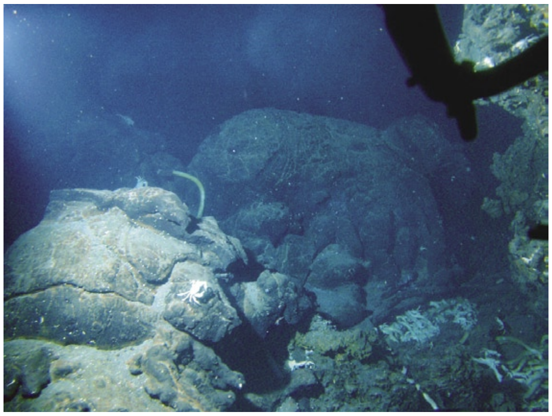
Monday October 6. When the *Keldysh* docked in Cabo today, we received a care package from Rohit that included a software upgrade for McDUVE. We tried this out just before supper and were blown away! The high-end sensitivity had increased by more than a thousandfold, and the gain controls were much more responsive. Pan is going to have a great time with this instrument on her dive.

Tuesday, October 7. At 4 a.m. we reached our new dive location, a 2,600-meter-deep site at 21N. Tomorrow is to be Pan's first dive, and the first working test of McDUVE.

Wednesday, October 8. Pan, Genya, and Ron Allum (on camera in Jim's absence) climbed into Mir 1 at 11 a.m. and were lowered into the water, followed shortly after by Stanford graduate student Kevin Hand, Mike Cameron, and Viktor in Mir 2. On the seafloor, they found some interesting biology and geology, but no hydrothermal activity. This was a disaster for the Russians, who were taking their guests down the next day—guests who had paid to see *active* vents. The Mirs drove round and round looking for active vents, and Pan's science-measurement agenda fell to pieces. After she had been in Mir 1 for almost 12 hours, unable to do very much except look out the small viewport now and then, she was finally allowed to turn McDUVE on and target it at a few rock surfaces and one rather nonplussed sea anemone. She also performed some water-column measurements before Mir's battery energy reserve became too low. Resurfacing around 1 a.m., Pan was rather tired and exasperated, but very pleased that the instrument had successfully detected both organic and mineralogical materials at 2,600 meters depth.

Right: Pan took this photo in Mir 1 as pilot Genya, on the right, and cameraman Ron Allum despaired of finding any active vents.

Saturday, October 11. After much poring over maps, and late-night phone calls with other oceanographers around the world, the Russians had managed to find an active vent site for their paying guests, which Pan and I visited today. We'd hoped to be together in one submersible, but in the end I was in Mir 1 with McDUVE, Ron, and Genya, and Pan was in Mir 2 with Mike Cameron and Viktor. As we headed down to 2,605 meters, I got the instrument up and running and measured the water-column characteristics at different depths. The water cooled from 23 to 1.8 ° C, and the inside of the passenger sphere felt like a pleasant winter's day. One significant problem of measuring water-column properties on the way down is that the Mir is still quite a bit warmer than the adjacent water, so that a thermal wave is generated that peels off the sides as the vehicle descends. Coming up, when the sphere is in good equilibrium with



At vent site 21N, pillow lava covered much of the seafloor.

To produce 15 seconds of the film took two and a half hours. Sure makes you wonder about the movie industry.

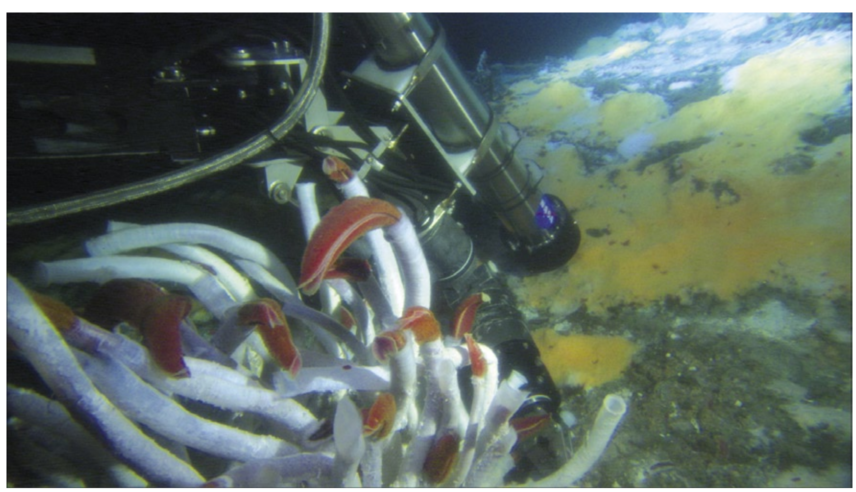
the water temperature, measurements can be made up to about 400 meters without affecting the water column. It helps that McDUVE extends away from Mir's body and measures water just outside the edge of this comet-tail-like thermal wave.

The scenery down here was very different from that at 9N, with a tumult of basalt-pillow lavas (that really do look like giant pillows) tossed about on the seafloor. We parked near a good chimney vent that had a large number of tubeworms (*Riftia* species), and I slowly scanned McDUVE across the chimney and onto the white exterior tubes and some of the live, bright-red worms sticking out of them. Do not fear, we are not hurting them. The laser pulse-intensity is reduced by 70 percent by the time the UV light crosses the 20 centimeters of seawater to the target, and the wavelength we use can only penetrate about 0.005 inches into the animal. It is safe even for humans, in spite of our aversion to anything to do with lasers, as our outer layer of dead skin cells stops the radiation.) As I scanned, I could see the intensities of the different fluorescence color bands going up and down on the screen of the control computer. I think we have some results!

Wednesday, October15. After returning to Cabo to pick up Jim and the rest of the film crew, the *Keldysh* set course for the overnight journey around the tip of Baja California into the Sea of Cortez to set up diving at the last location. This was some 50 miles off the coast of mainland Mexico, between Guaymas and the Baja peninsula, where the hydrothermal vents are found at about 2,000 meters depth.

Thursday, October 16. After lunch we got word that Jim wanted to film Pan and me showing the inside of McDUVE. We were to pull the instrument out of its titanium shell, inspect a connector or two, and then slide the shell back. We carried the heavy fluorimeter down three flights of stairs to the film studio in the lower bowels of the ship, and set it up with the ancillary props to make things look like our lab. After four rehearsals where we pulled McDUVE in and out of the shell, I said, "*Stop*—the action is putting too much strain on the internal structure." After that we did it in fake motions—again and again. To produce 15 seconds of the film took two and a half hours. Sure makes you wonder about the movie industry.

Saturday, October 18. Today, Pan (with McDUVE) and Jim Cameron are diving in Mir 1, this time piloted by Anatoly, and I'm in Mir 2 with Genya and astrobiologist Tori Hoehler from NASA Ames. I had not been in Mir 2 before; without the camera system it was going to be noticeably more spacious (if you can call three people and electron-



At dive site 21N, just southwest of Cabo San Lucas, we pointed McDUVE at tube worms and an orange-white biomat coating the rocks. Biomats are dense communities of bacterial species feeding off the vent-water minerals and each other.

Some vent chimneys at the Guaymas dive site were made of an unusually black, nonreflective material, right. Other rocks oozed a strange orange fluid, below.

ics racks in a six-foot sphere spacious). Because I was diving today, I had stopped most of my fluid intake at midnight (sounds like getting ready for a hospital operation) and breakfast at 7 a.m. was very light; some oatmeal, one grilled sausage link, and a tablespoon of scrambled eggs, no coffee or tea.

There was a briefing to review the dive activities, and then Mir 1 began its final prelaunch preparations. Anatoly, Jim, and Pan had their picture taken in front of Mir 1, and were airborne over the side at noon. Tori, Genya, and I had our picture taken in front of Mir 2, climbed inside, and were in the water just 24 minutes later.

On the bottom of the sea, the two Mirs worked together in an area about 300 meters in diameter, examining a number of structures and sediment and biomat beds. We saw no horrendous sea creatures, such as a giant squid, but we did see a spider crab that had a legspan of over 18 inches, although it is very hard to judge size and distance because of the mild distortion from the view ports and the refractive index change. A jellyfish floated in front of us for a minute or two, doing a sensuous breathing dance that results in propulsion through the water, but this was not a translucent white jellyfish, it was an umber orange, and very different from anything I had ever seen before.

There were also strange, mushroom-like structures, 5–8 meters high, emitting shimmering hot water in excess of 170 °C. On one of the flanges we found vents with small, pinnacled spires that were very black and nonreflective, even when illuminated by 3,000-plus watts of intense movie lights. We collected a small piece and took it back to the ship's lab; it was bone-charcoal black and ultra-finegrained, and had an albedo (reflectivity) as dark as the surface of Halley's comet, but probably a quite different composition.

In the last hour of the dive, our Mir left the area so that Pan could get dark measurements of the plume water without being bothered by our bright lights. We picked up some rock samples, took a water sample from a hot vent, and returned to the surface after six hours of bottom time. Pan came up about 75 minutes later. It had been a great dive set. After photographing, cataloguing, and storing our samples for the next two to three hours, we finally stumbled into our beds around 1:30 a.m. Tomorrow would be a dive day for the Russian scientists, and then we would head back to Guaymas and the end of our trip.

Monday, October 20. With *Keldysh* now docked in Guaymas, Pan and I started work on

Pan (left) and Lonne (right), in fire-retardant flight suits, pose with McDUVE before a dive to the Sea of Cortez vent sites near Guaymas.

packing our equipment. We had packed about 75 percent of it when word came from Jim that he wanted to film McDUVE mounted on the manipulator arm. We unpacked the instrument and cable and waited.

Tuesday, October 21. After lunch we were told they would be ready for us around 2 p.m. That became 4 p.m., then 9 p.m. At 11 p.m., I left instructions to come wake me when they were ready, and dozed lightly in my room with my clothes on. I awakened at 1:30 a.m., realized that this business was somewhat crazy, and went to bed for the night.

Wednesday, October 22. It is 1 p.m. They still have not shot the scene with our instrument. I quit.

Epilogue.

We were thrilled when we successfully used McDUVE at 21°N on the East Pacific Rise and in the Guaymas Basin. It operated beautifully. We acquired induced fluorescence data from the orange microbial mats blanketing the rocks near the vents, and saw optical signatures from the vents themselves that we are working to understand right now. Moreover, we believe we've contributed to a new paradigm in deep-ocean research—experiments controlled in real time in a manner that allows a quick response to changing conditions. This maximizes the scientific return from very expensive operations. A single Mir dive, for example, including the support ship, can cost as much as $30,000 for a single day. We'd like to continue this work in the deep ocean, and also plan to transform McDUVE into an instrument that can go down a deep, hot-water-drilled hole in Antarctica to a subglacial lake 3,500 meters below the ice, so we can explore the water and the sediment bed. We hope to find the remnants of organic molecules that will tell us more about what happens to living entities when subjected to long-duration dark, and very cold and icy environments. □

During his almost 39 years at JPL, planetary scientist Arthur Lonne Lane has "been" to seven of the nine planets, and has also worked on several earth-orbital missions. For the last eight years, he has been developing instruments to detect biosignatures, and tested predecessors of McDUVE at two other vent sites, Lo'ihi off Hawaii and a South Pacific seamount. He holds a BS in chemistry from Harvard and an MS and PhD in physical chemistry from the University of Illinois, though he did his research at Caltech when his supervisor moved here. After that, it was just a short hop across the Arroyo to start his career at JPL. He is currently project manager and investigator for the Deep Ocean Hydrothermal Vent Astrobiology Project and science investigator for the Astrobiology Research Group.

PICTURE CREDITS:
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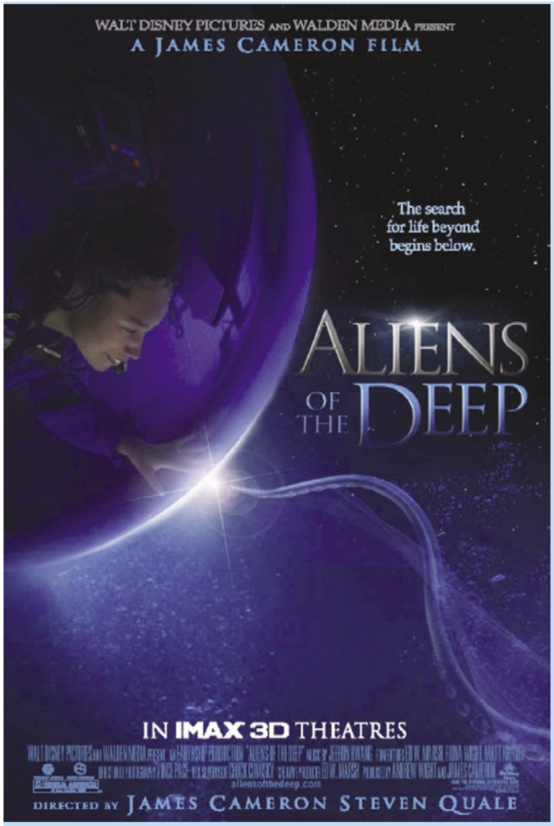


If you're just itching to be down among the hydrothermal vents yourself, and don't have a spare $30,000 or so to go with the Russians, you can get pretty close to the real thing by donning 3-D glasses at an IMAX cinema screening *Aliens of the Deep*. Pan is a leading member of the cast, and Lonne makes a cameo appearance, though you may see more of him in a longer, non-IMAX version being prepared.

A major aim of the movie is to inspire youngsters to become scientific explorers; for further encouragement, there's an Educator's Guide to download from the movie website, www.aliensofthedeep.com. There's also a National Geographic book, *"James Cameron's Aliens of the Deep: Voyages to the Strange World of the Deep Ocean"* by Joe MacInnis.


Photo by Akira Kinoshita

Cremona Revisited: The Science of Violin Making

by Andrew Hsieh

Itzhak Perlman in concert.

The lights dim, and a hush falls over the concert hall. The concertmaster rises, and as the orchestra tunes, the faint rustling of programs is heard in the background. Tonight's concert features one of the greatest living soloists performing with the orchestra, and the anticipation is palpable. The conductor appears and is duly acknowledged by the crowd; but he is not the one they are waiting to see. Finally, the soloist emerges, leaning on a pair of walking sticks, and takes his seat at center stage to thunderous applause.

It is the distinguished violinist Itzhak Perlman, and the instrument in his hands is one of the finest string instruments ever made: the "Soil" Stradivarius, crafted in 1714 by the Italian master Antonio Stradivari. Even before the first notes have been played, members of the audience are transfixed by the sight of the violin, its brilliant red varnish and the stunning "flame" pattern of its back catching the eye as they reflect the bright stage lights. The conductor raises his baton, and as the first notes reverberate through the hall, they complete the image of the renowned virtuoso and his legendary instrument.

Each violin, viola, cello, and bass is a masterpiece, simple lumber converted into a sublimely expressive musical instrument. Most were made long before the musicians playing them were born. Musicians and violin makers claim that a violin's sound improves with age, and therefore it is not entirely surprising that most musicians prefer older instruments.

The best-known string instruments, with only a few exceptions, are the work of either Antonio Stradivari or Giuseppe Guarneri, both active in Cremona, Italy, in the first half of the 18th century. Their violins were often passed down from virtuoso to virtuoso and sometimes named after famous past owners. Both Stradivari and Guarneri generated a sort of mystique about themselves by selling their instruments only to virtuosi or to extremely wealthy customers, and the quality of instruments such as those played by great soloists past and present has served to not only perpetuate but to increase the "Cremona mystique." The two men maintained an extraordinary level of secrecy throughout their lives, suggesting that they might never have revealed some of their techniques to the world. The possibility of such secret techniques existing continues to provoke vigorous debate and experimentation, even after hundreds of years.

A Brief History

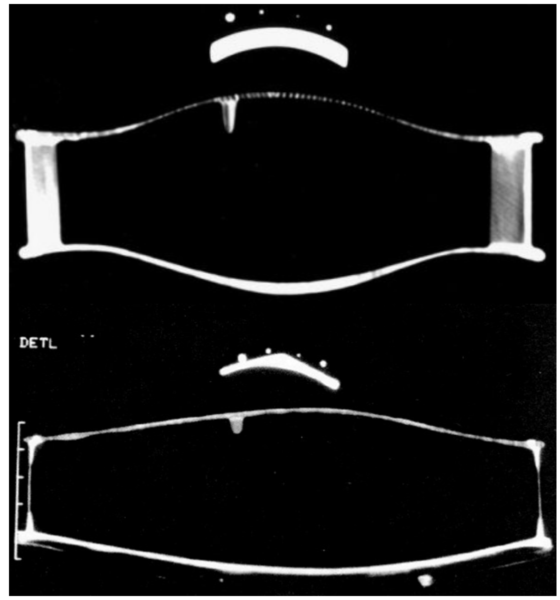
The violin family first appeared in northern Italy in the first half of the 16th century, and has changed little since the 1550s. Instruments made as early as 1560 are still in regular use today and are in most respects identical to their more recent counterparts.

The years from 1650 to 1750 were a golden age of violin making. Nicolo Amati (1596–1684), the last and greatest of the Amati line of violin makers, was almost single-handedly responsible for the emergence of the many famous masters of the era; his students included Antonio Stradivari (1644–1737) as well as Andrea Guarneri (ca. 1626–1698), grandfather of the better-known Bartolomeo Giuseppe Guarneri (1698–1744).

Antonio Stradivari and Giuseppe Guarneri departed significantly from previous designs, which had very highly-arched front and back plates, by building instruments with relatively flat bodies. These were better able to withstand high string tensions and had greater carrying power in large concert halls. Stradivari's violins were known for their brilliant tone color; Guarneri's for their full, dark character.

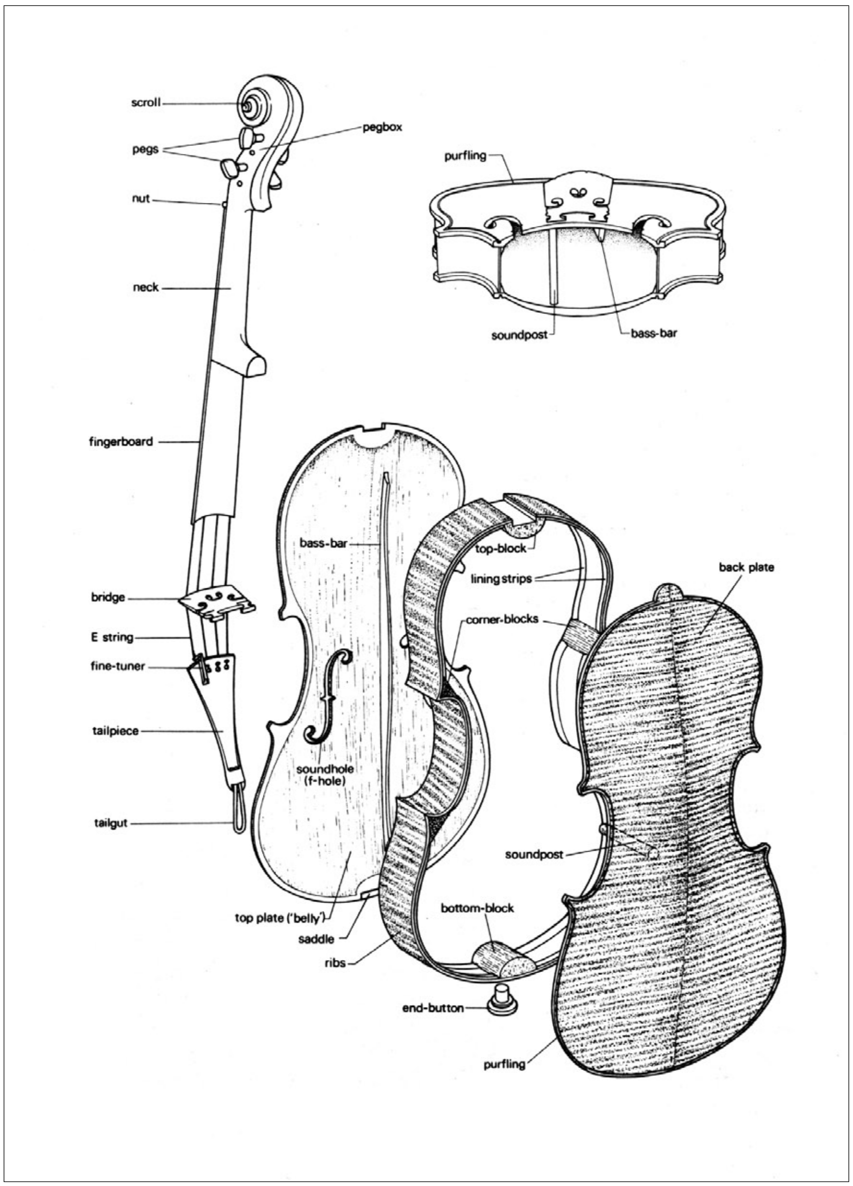
With the deaths of Stradivari in 1737 and Guarneri in 1744, the Cremonese school of violin making came to an abrupt end. Since then, their violins have been frequently copied. Some makers even built reputations for producing high-quality

Right: X-ray cross sections of a 1654 Amati violin (top) and a 1698 Stradivari violin (bottom), showing the more gentle slope of the front and back plates in Stradivari's instrument.



Images courtesy of Steven A. Sirr, M.D.

Below: The parts of a violin.



From David Boyden *et al.*, *The Violin Family* (New York: W. W. Norton & Co., 1989) p. 4.

replicas by painstakingly measuring every aspect of the old instruments. However, while the copyists could duplicate the appearance of the Cremonese violins, they could never duplicate the sound.

Building a Violin

The violin appears simple at first glance, but it is one of the most complex musical instruments, built from more than 70 separate pieces of wood that are shaped and assembled by hand. No two violins are exactly alike; a trained ear can distinguish between individual violins. Whether it is a centuries-old masterpiece or a mass-produced fiddle, each violin has its own unique "voice."

Many of the features of the violin that appear merely ornamental are highly functional. The low vaulting of the front and back plates is essential for strength and for amplification of sound. The narrow middle bout, or waist, allows the player more room to bow on the highest and lowest strings. The purfling—the decorative trim around the edges of the instrument—protects the body from cracking, but also changes the dynamics of vibration considerably. Cutting the groove in which the purfling is inlaid allows the plates to vibrate as if they were hinged rather than clamped at the edge.

The process of making a violin begins with the selection of materials. Choosing wood is an art in itself: it must be strong, flexible, and as dry as possible. Wood for violins is always cut during the cold dormant months, when the amount of sap in it is at a minimum, and "seasoned" for years under very dry conditions. The wood used in the best instruments is aged at least ten years, and sometimes as long as fifty years.

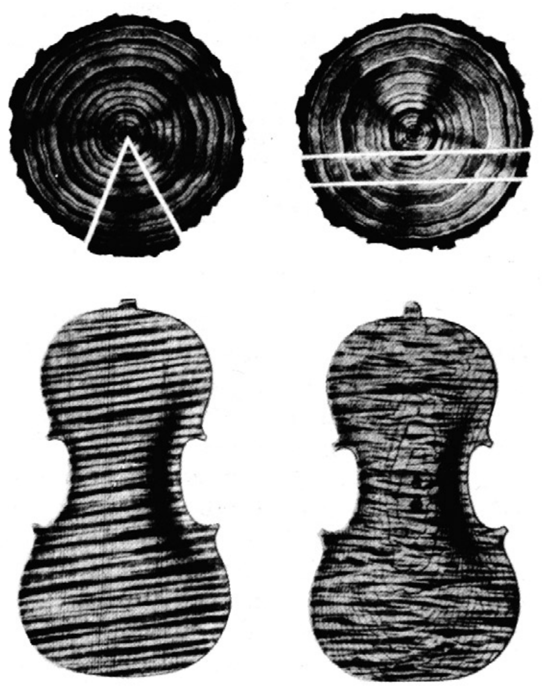
Equally important is the process of shaping the front and back plates. The front plate is made from a softwood, typically spruce, while the back plate is normally maple. The arched outer surfaces are carved rather than formed by bending. The arching gives the thin front plate increased resistance to the lateral force exerted by vibrating strings, and subtly alters the modes in which both plates vibrate. The violin maker carefully "tunes" the front and back plates, tapping the plates with the knuckles, listening for the characteristic "tap tones." The pitches of different harmonics are adjusted by scraping away material as necessary. Tuning the front and back plates is easily the most demanding part of making a violin, and takes years to master.

From Neville H. Fletcher and Thomas D. Rossing, *The Physics of Musical Instruments*, figure 3.13, p. 79.

IMAGE NOT LICENSED FOR WEB USE

Above: The resonant modes of a square plate with free edges. The X mode and the ring mode are the second and third ones, respectively, in the top row. The numbers below each mode are frequencies corresponding to the modes, relative to that of the first mode. Lines represent nodes, or places that remain stationary as the plate vibrates at a given frequency.

Below: Quarter-cut (left) and slab-cut (right) sections of a log, with the look of a violin back made from each. These are the only cuts of wood used in violins; the softwood front plate is traditionally quarter-cut while the hardwood back plate may be quarter-cut or slab-cut. In either case, the longitudinal axis is in the plane of the plate.



From David Boyden *et al.*, *The Violin Family* (New York: W. W. Norton & Co., 1989) p. 6.

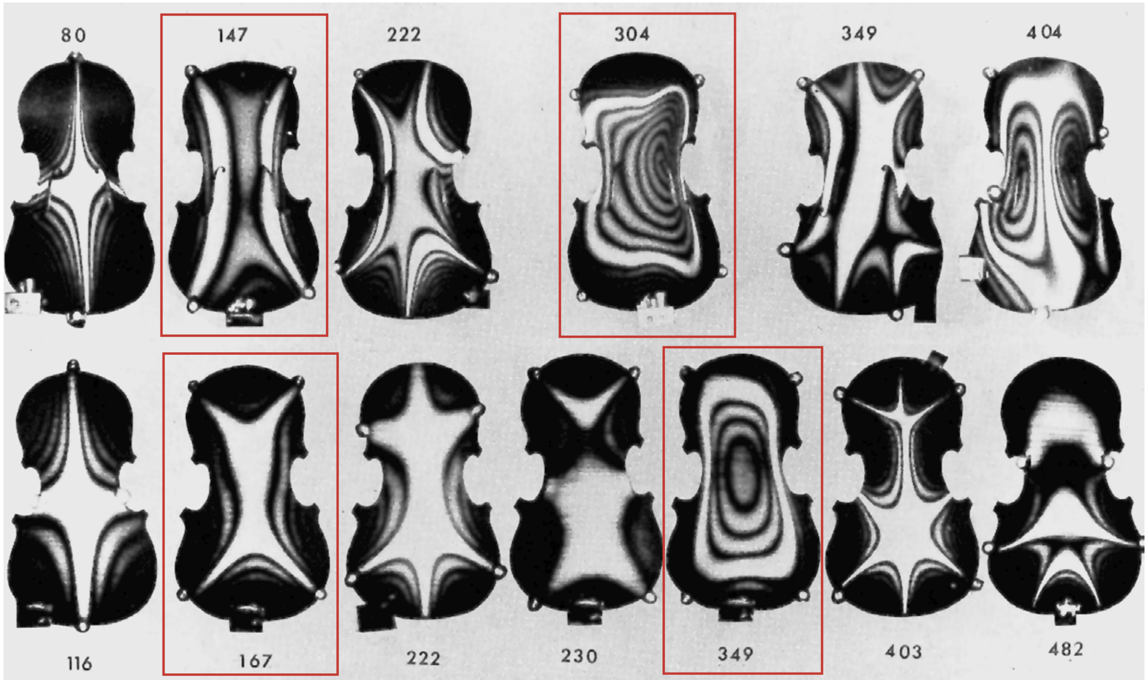
Violins and Sound

A vibrating string alone produces almost no sound, as it is too thin to sufficiently disturb the air. Therefore, it is not the string itself, but the body of the violin, that actually generates its sound. When a string vibrates, the bridge rocks back and forth at the same frequency. The soundpost immobilizes the front plate directly beneath the right foot of the bridge, so that the right foot remains stationary, and the front plate is driven rapidly up and down by the left foot's "pumping" motion. The bass bar, mounted lengthwise under the left foot of the bridge, reinforces the front plate and couples the upper and lower bouts so that they move together.

The body of the violin has a number of resonant frequencies, or natural vibrational frequencies, at which a weak stimulus can cause large vibrations. Forced vibration of the top plate produces some amplification at any frequency, but the amount of amplification at a given frequency depends on how well it corresponds to one or more of these resonant frequencies. The bridge transmits a whole set of harmonics from a vibrating string to the front plate, and each harmonic is amplified according to the resonance generated at that frequency. The violin's relative response levels to different frequencies create the instrument's unique timbre by preferentially amplifying some harmonics and damping others.

The resonant frequencies of the violin body as a whole depend most strongly on the resonant modes of the front and back plates. The plates themselves can be modeled most simply as two-dimensional panels, free to move at all points out to the edges. Just as a string vibrates in harmonics corresponding to standing waves on the string, a two-dimensional panel vibrates in specific resonant modes; the graphic above left shows the calculated resonant modes of a simulated square panel.

In violins, there is a further complication: wood has very different mechanical properties along different axes. Its mechanical properties are determined entirely by its cell structure. Wood is made up of long, thin cells with walls composed of the polymers cellulose, hemicellulose, and lignin. Cellulose, a carbohydrate that forms long straight



From C. M. Hutchins, *et al.*, "Clarification of Free Plate Tap Tones by Hologram Interferometry," *Catgut Acoustical Society Newsletter*, No. 16 (1971), p.15. Reprinted with permission of the Violin Society of America.

The vibrational modes of the front plate (top) and back plate (bottom) of an unassembled violin made by a modern master craftsman are revealed by laser interferometry. Nodal areas appear white. The X modes and ring modes of both plates are highlighted in red. The numbers are the frequencies at which the resonances occur.

chains, is the main structural component of wood. Cellulose chains usually form microfibrils, fibers consisting of groups of parallel chains held firmly together by hydrogen bonding. In wood, cellulose microfibrils lie parallel to one another in four layers, and spiral around the cell in its long direction, with different angles of spiraling in each layer. Lignin and hemicellulose, which form highly cross-linked structures, act as a "glue" that holds together the cellulose components and binds adjacent cells together. The longest dimension of each cell runs parallel to the growth of the tree trunk, in the longitudinal axis, and therefore wood has its greatest tensile strength in the longitudinal direction. As a result, wood plates must be elongated along the grain of the wood, in the direction of greatest tensile strength, in order to achieve the same types of resonant modes that are observed in an ideal square plate.

Many modern-day violin makers use visualizations of resonant modes to aid in tuning a violin's front and back plates. During construction, modal patterns in a plate can be seen by covering the surface of the plate with a fine sand and inducing mechanical vibrations at various frequencies. As the plate resonates, the sand moves about, except at the nodes, which remain stationary. The sand collects at the nodes or is bounced away, creating much the same patterns as shown above.

Two particularly strong modes are the second and fifth harmonics of the plate, often referred to as the "X mode" and the "ring mode" for the shapes of their nodal patterns. These harmonics are the main components of a plate's tap tone. Recently, a number of violin makers have recommended tuning each plate such that the ring mode sounds exactly an octave above the X mode, in order to mimic the efforts of early violin makers, who would have tuned the most prominent modes to exact musical intervals. While the theory is difficult to test, it seems highly plausible because tuning tap tones to musical intervals requires no specialized equipment and therefore could have been done by even the earliest violin makers. In addition, the idea parallels Renaissance ideals of mathematical perfection, which may well have guided the Italian violin makers of centuries past.

Lumber Redux: Another Look at Wood

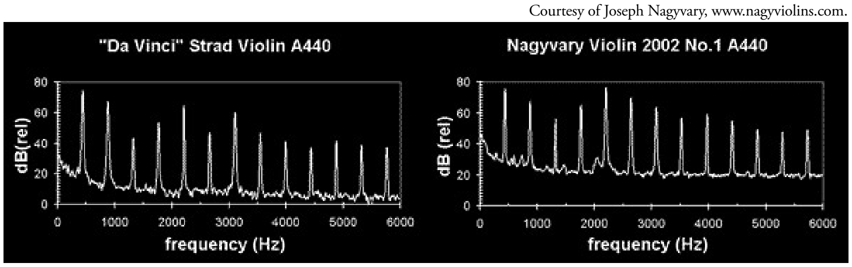
Do violins actually improve with age? The acoustical properties of the wood used in their construction certainly change with the passage of years.

Moisture in wood absorbs vibrational energy, converting it to heat energy by evaporation. Although the wood used in violins is already dry, minute changes in water content can have dramatic effects on violin acoustics: a 1 percent decrease in moisture content reduces damping by up to 3.5 percent. The long-term improvement of acoustical response depends mainly on the degradation of hemicellulose, the component of wood that adsorbs water most readily and degrades most dramatically over time. As hemicellulose degrades, the wood's maximum water content decreases. Even over very short periods, the sound of a frequently played violin may noticeably improve as small amounts of water evaporate from the wood.

Analyzing Cremona

Age, however, does nothing to explain the

Courtesy of Joseph Nagyvary, www.nagyviolins.com.



Above: The FFT spectra of the open (unfingered) A string on two violins, the 1725 Stradivari "Da Vinci" and a 2002 Joseph Nagyvary violin. (The A above middle C is tuned to 440 Hertz, a standard frequency also known as "international pitch.")

difference between Cremonese violins and their contemporaries. The recognized superiority of the Cremonese instruments must still be a result of unique acoustical properties.

One way to examine these properties is by performing a mathematical technique called a Fast Fourier Transform (FFT) on the waveforms that are generated when the violins are played. The sound waves produced by a musical instrument are the sum of the fundamental frequency of the note and all of its harmonics; the FFT breaks down a sound into its component harmonics and allows us to chart their relative strengths in what is known as an FFT spectrum.

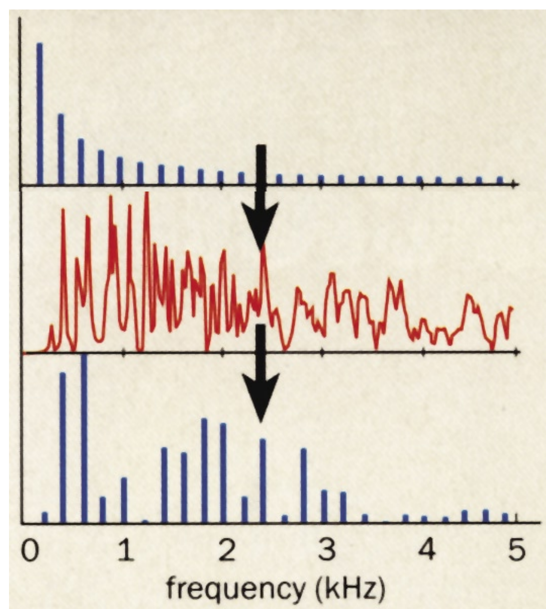
It is difficult to generate a steady waveform from a bowed string instrument, as the act of bowing the strings brings many unpredictable factors into play. Therefore, FFT spectra are never perfectly consistent; large variations can occur even in spectra produced by a single instrument. Such variations might be worked around by mechanically vibrating the bridge to simulate constant, perfectly consistent bowing. The resulting FFT spectrum is steady and can be used to create a response curve that represents the amount of amplification generated by the body at any given frequency, as shown at right. Peaks on the response curve indicate resonant frequencies of the violin's body, at which amplification is particularly high.

There are also easier ways to generate a response curve. Instead of simulating the full set of harmonics generated by the bowed string, one can produce the same results by vibrating the bridge at a range of pure frequencies, and measuring the resulting sound output in decibels. Ultimately, because body resonances are the main factor determining the tone quality of a violin, it is the response curves that provide the most insight into a violin's acoustical properties.

In 1985, German violin maker Heinrich Dünnwald compared the response curves of a group of Cremonese violins to two control groups, one of violins built by master violin makers and one of factory-made violins. The most striking contrast was seen at high frequencies. The Cremonese instruments showed a broad, strong maximum around 2500 Hertz (Hz), or vibrations per second, which is in the region of greatest human auditory sensitivity. There was a large reduction of response above 3000 Hz. Modern master-crafted instruments showed an overly strong response in the same range, which explains modern violins' widely-held reputation for shrillness; factory-made violins had a consistently dull response above 2000 Hz.

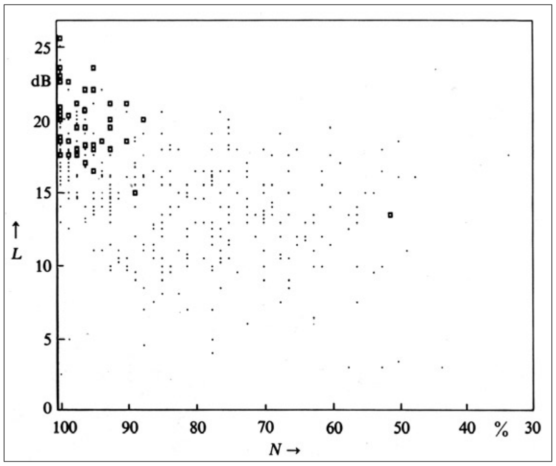
In a second experiment conducted the same year, Dünnwald found another characteristic trait of Cremonese violins: two of their response peaks are particularly strong. One peak, covering a fairly wide band located between 1300 Hz and 2500 Hz, was sufficiently strong that virtually any note played on the instrument had its strongest harmonic within that range. The other peak occurred at the air resonance frequency, the natural resonant frequency of the air inside the violin rather than of the violin body itself. Nearly every tested Cremonese violin showed a strong response at that frequency, as shown on the next page. In the vast majority of the other tested violins, both peaks were much weaker.

The Dünnwald experiments demonstrated conclusively that there is a clear acoustical difference between violins made by Stradivari and Guarneri,



Adapted from Colin Gough, "Science and the Stradivarius," *Physics World* (April 2000).

How a response curve corresponds to FFT measurements. The FFT of a vibrating string (top) decreases smoothly with increasing frequency. The violin's body (middle) amplifies harmonics that correspond to its resonant modes, while other harmonics are amplified very little. The sound we hear (bottom) thus has a very different FFT spectrum than does the string in isolation.



From H. Dünnwald, "Ein Verfahren zur objektiven Bestimmung der Klangqualität von Violinen," *Acustica*, Vol. 58, (1985) pp. 162-169.

Left: Dünnwald's second experiment. *L* is the relative strength of the air resonance frequency in decibels, and *N* is the percentage of possible notes for which the strongest harmonic is between 1300 Hz and 2500 Hz. Violins made by the old Cremonese masters are indicated by squares, and other violins are indicated by dots.

and contemporary violins. The characteristic Cremona sound appears to be the result of strong selective amplification of several key harmonics. The cause of this amplification remains an open question.

Varnish and Salt

For many years it was fashionable to study the varnish used by both Stradivari and Guarneri—the brilliant, reddish hue of their instruments suggested that their varnish was unique. The claim most commonly made by violin makers was that a secret recipe for varnish was the most important factor in tone quality. However, varnish is unlikely to improve the sound of a violin. Its only acoustical effect is to damp vibrations, and because its main function is to form a hard protective layer over the exterior of the instrument, it is highly implausible that any varnish could selectively damp very high frequencies. Furthermore, ultraviolet photography has revealed that most of Stradivari's and Guarneri's violins have lost much of their original varnish, and have been recoated in the last 150 years with modern varnishes. Since many modern violin makers believe that their violins sound better "in the white" than varnished, the best thing to do with varnish may simply be to use less of it.

The process of "stewing," or gently heating wood in a salt solution before drying, was also identified as a likely difference between the Cremonese school and the modern day. Analysis of wood shavings provides strong circumstantial evidence that Guarneri stewed his wood. The main effect of stewing is to substantially accelerate the degradation of hemicellulose, so the hemicellulose content of stewed wood should be far lower than is normal for its age. From comparison of growth rings to known climate data, we know that the wood in Guarneri's instruments cannot have been cut more than two decades before the instruments were made, yet the hemicellulose levels in the wood are what would be expected for wood three or four decades older.

But stewing was hardly a secret; on the contrary, it was a familiar process long before the 18th century. Evidence for it exists as early as 1580, when French chemist Bernard Palissy wrote: "Salt improves the voice of all sorts of musical instruments." The purposes usually stated for stewing were to prevent rot, to repel woodworm, and to stabilize water content. The last does not enhance acoustic response, but guards against cracking by preventing rapid changes in water content. Salt actually does this by hydrogen-bonding to water itself, slightly increasing the wood's water content and partially offsetting the effect of hemicellulose degradation.

The stewing theory has another flaw: there is no evidence that Stradivari stewed his wood. By the early 18th century the process was gradually passing out of standard practice. It has seen a resurgence in recent years, but still only a few violin makers practice it routinely.

The Second Coming of Stradivari?

If varnish and salt are not the answers, then Joseph Nagyvary, a biochemistry professor at Texas A&M University who moonlights as a violin maker, claims to be closer to knowing the secrets of the Cremonese masters. Recently he has gained notoriety in musical circles for making violins that show an amazing similarity to those of Stradivari himself. As a violin maker, Nagyvary was familiar with the extant literature on Cremonese violins; as a chemist, he gradually became convinced that physical characteristics alone could not adequately explain the Cremonese sound. He therefore hypothesized that Stradivari and Guarneri used some form of wood treatment that substantially altered the composition or structure of the wood itself. To

Photo by Kathleen Phillips, Texas A&M *AgNews*, August 2003.

Joseph Nagyvary applies varnish to a violin in his workshop in College Station, Texas.

test this hypothesis, he acquired and analyzed wood shavings from Stradivari instruments.

Nagyvary discovered that these instruments were made with wood containing extremely large quantities of embedded minerals, suggesting immersion in some mineral salt solution. However, he was unable to develop a wood treatment method that would cause sufficient penetration of minerals into the wood.

Eventually Nagyvary stumbled upon an unexpected answer to this problem. He currently constructs violins with timber salvaged from the bottom of Lake Superior. For over three centuries logs were floated to lumber mills across the lake chained together in large "rafts," and some became sufficiently waterlogged to break away and sink to the bottom. Decades of soaking have left the wood heavily impregnated with a variety of mineral residues which, as Nagyvary discovered, closely matched the mineral content of wood shavings from one Stradivari cello.

Nagyvary's revised theory is that Stradivari and Guarneri stored their wood in mineral-rich brackish water for years before beginning to dry it out. This storage allowed minerals to seep in and fill the empty space left as microbes digested hemicellulose in the wood. Nagyvary even suggests that 18th-century treatises calling for dry storage with no additional treatment may have been a deliberate deception aimed at obscuring the practices of the masters. The acoustical effect of embedded minerals is not yet well understood, but Nagyvary's experiments suggest that microscopic mineral crystals may modify resonant modes by stiffening wood in some directions and adding flexibility in others.

Baroque Tuning

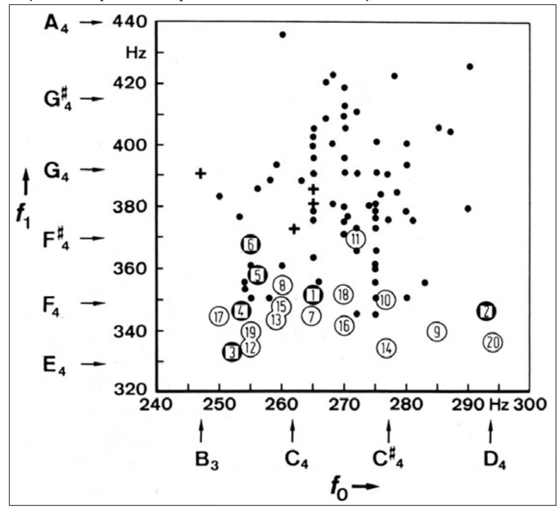
In addition to treating wood differently from modern practice, the Cremonese masters designed their instruments to fit specifications that distinguish them from their modern counterparts.

Most significantly, the tap tones of all early Italian violins are tuned distinctly lower than those of other violins. This in turn produces response peaks at lower frequencies. The difference is on the order of a half-step or a whole-step, which makes sense when one notes that Baroque orchestras commonly tuned to pitches that were approximately that far below modern standards. Violin makers may have begun to tune their tap tones to higher frequencies to match a late 18th-century rise in orchestral tuning pitch, affecting the violin's timbre in ways that they could not have predicted.

Coda

Although much has been discovered about the acoustics of violins in recent years, whether we have truly unlocked the secrets of Stradivari and

From J. Meyer, "The Tonal Quality of Violins," *The Journal of the Catgut Acoustical Society*, May 1984. Reprinted with permission of the Violin Society of America.



The distribution of the most prominent tap tones of 100 violins. f_0 is the air resonance; f_1 is the first body resonance. 17th- and 18th-century Italian instruments are marked with numbered circles; black circles indicate Stradivari violins.

Guarneri remains in question. Craftsmanship and design are likely as important to achieving high-quality sound as any purported secret recipe or technique, and there may be no substitute for three hundred years of graceful aging.

The present is an exciting time for violin makers and researchers alike. Acoustical analysis of Cremonese violins has, by revealing the specific patterns that define the Cremona sound itself, given violin makers a target to aim for. The exact way in which these patterns were achieved is still unclear, but new ways of looking at old instruments have generated plausible scientific explanations for many aspects of the art of violin making, as well as theories and avenues of research that could lead to further breakthroughs. Regardless of whether all the secrets of Stradivari and Guarneri are ever found, such technical advancements help contemporary violin makers fulfill every violin maker's ambition: to produce instruments that violinists might be proud to play three centuries from now. □

Andrew Hsieh (BS '04, biology) wrote this paper for the Core 1 science writing class. Hsieh plays both violin and viola, and is also active as a composer. He performed in both the Caltech chamber music program and the Occidental-Caltech Symphony Orchestra as an undergraduate. He is currently a member of the Division of Biology research staff and plans to go to medical school. Hsieh's faculty mentor for the paper was Jed Buchwald, the Dreyfuss Professor of History.

In the spring of 2004, the faculty modified the Core 1 requirement to emphasize technical writing for journals. A new course on science writing for the public, En 84, is now offered at the Hixon Writing Center.

Edward B. Lewis 1918 – 2004

Edward Lewis, the Morgan Professor of Biology, Emeritus, died July 21 after a long battle with cancer; he was 86. Lewis worked on the genetics of the *Drosophila* fly for almost 70 years, 61 of them at Caltech, and was engaged in active research until the final months of his illness. He also played a key role in the debate on nuclear testing in the '50s. Caltech president David Baltimore called him "one of the true masters of genetics, the bridge between the pioneers of *Drosophila* work—Morgan, Bridges and Sturtevant—and modern developmental biology."

Lewis was awarded the 1995 Nobel Prize in Physiology or Medicine for discovering a group of master control genes that orchestrate the development of a fly embryo's body parts, and for showing that these genes are strung along the chromosome in the same order, from head to tail, as the body parts that they control. These same genes, containing almost identical stretches of DNA, have since been found in all other animals, including humans: a strategy for development that gave rise to the first primitive marine animal over 550 million years ago had been preserved by all the invertebrates and vertebrates descended from it. Lewis, who worked on a group of genes called the bithorax complex, shared the Nobel Prize with Eric Wieschaus and Christiane Nüsslein-Volhard, who identified genes that work at an even earlier stage of development. Prior to his Nobel Prize, Lewis had received the Wolf Prize in Medicine in 1989 and the National Medal of Science in 1990, among many other honors.

Lewis championed the value of basic research for its own sake, and stressed that he hadn't set out to make the discoveries that led to his awards; he was simply trying to find out how genes worked, what they were made of, and how new genes could arise from old. By being allowed to do his research without having to justify its health benefits to funding bodies, he had ("by many circuitous routes") contributed toward the understanding of human congenital malformations.

He loved the abstraction of genetics, which "allows one to deduce many properties of genes without any knowledge of what they are made of." In fact, for the first 20 years of his research, genes were thought to be proteins—which turned out to be completely wrong. But it didn't affect his results, because "the laws of genetics have never depended upon knowing what the genes are chemically and would hold true even if they were made of green cheese."

The four-winged fly (normal flies have only two wings, the second pair having evolved into gyroscopic knobs called halteres) that became the visual icon of his work was one of the most striking bithorax mutants. But it was "just a stunt," Lewis said, "a byproduct of the theory we were testing." (A modest man who disliked self-aggrandizement, he always used "we," even when he had done all the work himself.) After working on four-winged flies, flies with stunted halteres, flies with legs in the wrong place, and many others for 32 years, he finally published, in 1978, "his miraculous paper," said longtime colleague Howard Lipshitz, "that laid out a paradigm for the genetic control of development." Lewis's work united three separate disciplines of biology—genetics, developmental embryology, and evolution—into one.

Born May 20, 1918, in Wilkes-Barre, Pennsylvania, where his father was a watchmaker, Lewis loved the wildlife that lived near the banks of the Susquehanna river, especially the insects, toads, turtles, and snakes. After reading about the work of Morgan and Bridges on *Drosophila* at Caltech, he spotted an ad in the back of *Science* for cultures of the flies at $1 each. Seventeen-year-old Lewis and schoolfriend Edward Novitski scraped up some money, ordered a few tubes, and spent their spare time in the high school biology lab breeding the tiny flies, sorting through their offspring with magnifying glasses, and analyzing the results. Lewis, a talented flutist, gained a music scholarship to Bucknell College, but transferred to the University of Minnesota (chosen for its low out-of-state tuition fee of $25) after a year. It was a lucky choice: genetics professor C. P. Oliver encouraged the undergrad to carry on with his *Drosophila* hobby at a desk in his lab. Lewis worked on a new mutant sent by Novitski (who also became a geneticist; PhD '42) from Purdue.

After earning a BA in biostatistics ('39) in just two years (a zoology degree would have taken a third, unaffordable, year), a recommendation from Oliver landed Lewis a teaching fellowship at Caltech as one of Sturtevant's graduate students. He discovered a way to tell if two recessive genes were on the same gene or on two different ones, the *cis-trans* test, an important new technique for genetic analysis that won him his PhD in 1942.

Lewis's love affair with *Drosophila* (he didn't like it referred to as a fruit fly) began in 1935 and continued through 1964, above, and 1996, right. He numbered his genetic crosses sequentially from the day he started his research, and ended at number 53,446.

He now had to enlist for war service, but president Robert Millikan guaranteed him an instructor's job afterward. Lewis took the Caltech-based U.S. Army Air Corps meteorology course (MS '43) and was sent to Hawaii and Okinawa as a weather forecaster. The year he came back to Caltech, 1946, was also the year he married Pamela Harrah, a Stanford graduate trained as a scientific illustrator. She was working in George Beadle's lab in Stanford that year, but Beadle was moving to Caltech and he wanted her with him to look after his *Drosophila* stock collection. Son Hugh Lewis, speaking at a memorial service last October, takes up the story: "One day [Beadle] looked at Pam and said, 'Pamela, how tall are you?' 'Five foot four,' she replied. And he said, 'Well, there's a nice young man at Caltech, and he's also kind of short (Lewis was about five foot two); his name's Ed Lewis. You could meet him, he'd fall in love, and you could get married.'" It worked.

Lewis published infrequently, often in obscure journals, and his papers were difficult to read, according to Lipshitz, whose book *Genes, Development and Cancer: The Life and Work of Edward B. Lewis* was published a few months before Lewis's death. "His publication rate would be considered atrocious by most grant review panels or academic promotions committees." Seymour Benzer, Boswell Professor of Neuroscience, Emeritus, once joked, "Ed is a maverick who could never survive in a normal institution." Lewis was also unusual in that he worked alone. "The number of postdocs he had in 60 years could be counted on one hand, and the number of graduate students was even less," Lipshitz wrote. "Ed continued to do science for himself his whole life."

Yet he wasn't antisocial. Speakers at the Caltech memorial service recalled him as friendly, collegiate, kind, and caring. Provost Paul Jennings remembered more than 40 years of lively lunchtime discussions with him at the Athenaeum faculty table (Lewis came into work very early, and left very late, but was a popular lunchtime regular.) Jennifer Caron (BS '03), whose senior thesis, "Biology and 'The Bomb'" (published in *E&S*, 2004, no. 2), was about his important role in highlighting the health risks of above-ground nuclear-bomb tests, recalled his patience and helpfulness, and how, when she visited his room on the top floor of Kerckhoff, he would "move a stack of papers, rearrange the journals and bottles of fruit flies, and offer a chair."

Lewis loved art, and was renowned for his Halloween costumes; he would come to parties as a painting, often a Magritte. Always a keen flute player, he arranged chamber music sessions with friends, took part in Caltech musicals, and fit in lessons from San Francisco opera flutist Patricia Farrell (who performed a short piece at the end of the memorial service) when in the Bay Area for the opera season.

The Lewis family pets weren't the furry kind, recalled Hugh. Desert tortoises roamed the backyard of the family home in San Marino, and octopuses lived in large tanks inside. He was one of the first to get them to breed in captivity.

Lewis became professor of biology in 1956, was named the Morgan Professor of Biology in 1966, and became an emeritus in 1988. With the advent of molecular biology in the '60s, bacteriophages and bacteria were in favor. Lewis, still working with flies, became an anachronism. But when David Hogness (BS '49, PhD '53), Welcome Bender (PhD '78), and others decided to clone a higher organism, they chose the bithorax complex of *Drosophila* because of Lewis's detailed knowledge of this area and his outstanding collection of mutants, which he generously lent them. When the positional cloning was complete, "the physical map of the bithorax complex corresponded perfectly with the genetic map," Lipshitz wrote, "validating over 35 years of Lewis's genetic results."

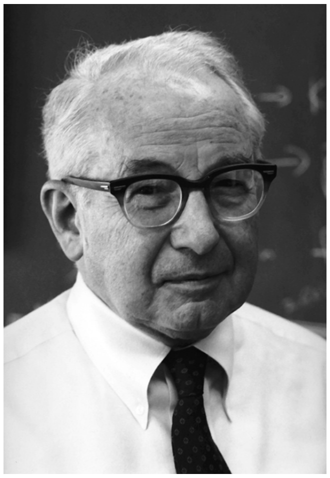
Worried about above-ground nuclear testing in the '50s, Lewis challenged the current dogma that exposure to low amounts of ionizing radiation didn't damage human tissues. As told in "Biology and 'The Bomb,'" he calculated the relationship between radiation doses and leukemia using publicly available data, and published the results in *Science* in 1957. His conclusion that even small amounts of radiation caused leukemia created such a stir that he was summoned to appear before a congressional joint committee on atomic energy. Despite the grilling they gave him, he continued to publish on radiation risks for another 20 years. "Ed has a permanent place in the history of radiation and chemical protection policy in the U.S.," James Crow, of the University of Wisconsin–Madison, said at the memorial service. "This is not the work he won the Nobel Prize for, but maybe as far as public policy is concerned, it might be the most important work he did."

Lewis is survived by his wife, Pamela, and two sons, Hugh, an attorney, and Keith, a biologist. A third son, Glenn, died in his early teens in a mountaineering accident.

"Ed did science because he loved it, rather than for fame and fortune," said Andrew Dowsett (BS '74), "and when it brought him fame anyway, one could only smile and think that sometimes, nice people *do* finish first." □—*BE*

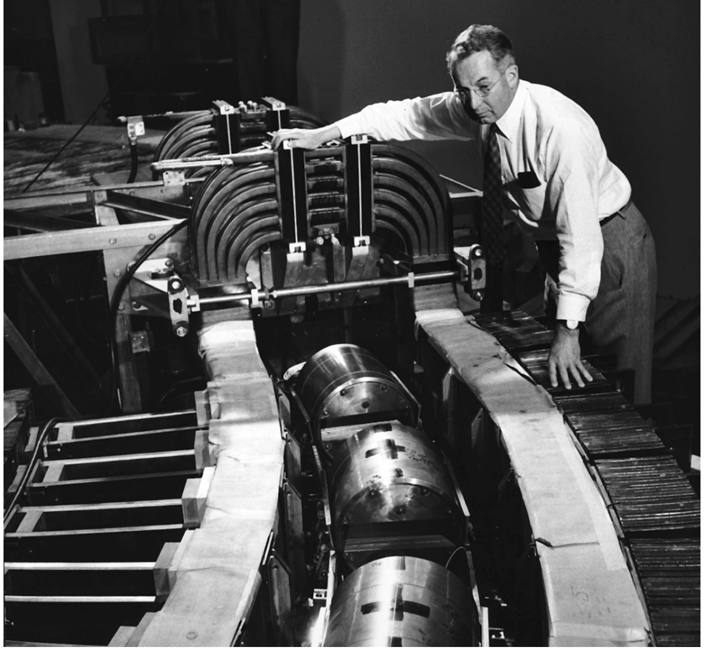
At the 1995 Nobel Prize celebrations in Stockholm, Ed and Pam were guests of King Carl XVI Gustaf of Sweden and Queen Silvia. Crown Princess Victoria is on the left.

Robert F. Bacher
1905 – 2004



Robert F. Bacher, Caltech's first provost, who had headed the experimental physics division of the Los Alamos Laboratory, died November 18 at the age of 99.

Bacher was born August 31, 1905, in Loudonville, Ohio, but grew up in Ann Arbor, Michigan, where he knew his later-to-be wife, Jean Dow, from childhood. He graduated from the University of Michigan in 1926, to which, after a year of graduate school at Harvard, he returned to earn his PhD in 1930, under Samuel Goudsmit, with a thesis on hyperfine structure in atomic spectra. He and Jean married right after graduation and embarked on a cross-country drive to Pasadena; it was Bacher's first encounter with Caltech—as a National Research Council Fellow. He didn't know much about what went on here, he said in his oral history (recorded by the Caltech Archives in 1981), but it had one of the larger graduate programs in physics at the time. And he admired Ira Bowen as the best spectroscopist in the country. During that year he attended Robert Oppenheimer's lectures, "but I must say, they were extremely difficult to understand." Nevertheless, they later became close friends and colleagues.



Bacher stands beside the magnet of the synchrotron in 1955. At that time the electron accelerator had a peak energy of about 300 MeV; Phase 2, which began operation in 1957 had a peak energy of just over a billion volts.

After another NRC year, at MIT, Bacher returned to the University of Michigan, then went to Columbia as an instructor in 1934, where he worked with I. I. Rabi. A year later he followed Hans Bethe to Cornell, where he started doing experimental work in nuclear physics with Bethe and left theoretical work behind. He was quickly promoted to full professor and director of the Laboratory of Nuclear Studies. Early on, he had felt that the United States needed to start doing war work, and when Lee DuBridge, head of the Radiation Lab working on radar at MIT, summoned him there in 1941, he went.

Then, late in 1942, Oppenheimer approached Bacher about a new lab for nuclear weapons work that was just starting up and the following spring asked him to join the Manhattan Project. Bacher declined initially, telling Oppenheimer that what he needed was engineers. Ultimately, when Oppenheimer made a commitment to hiring more engineers and made him head of the experimental physics division, Bacher signed on. From the beginning, Bacher was firmly opposed to making Los Alamos a military lab and persuaded Oppenheimer, who had agreed to take a commission as lieutenant colonel and had already ordered his uniforms, to keep it under civilian control, at least until they had enough fissionable material for a bomb.

When the project was reorganized in July 1944 to speed work on implosion, Bacher's experimental physics division was split, and he was put in charge of the G (for "gadget," the code name for the bomb) division. Bacher personally escorted the first bomb to the test site in July of 1945. In 1946 he was awarded the President's Medal for Merit for his work on the Manhattan Project.

Bacher returned to Cornell (he had taken a leave of absence during the war), hoping to get back to high-energy physics, but the bomb's aftermath continued to involve him. He felt strongly that there should be some sort of international control of atomic weapons and worked hard on negotiations with the Soviet Union. He admitted in his oral history that this was perhaps idealistic, but thought that getting this technology out in the open might have avoided the subsequent Cold War. When the Atomic Energy Commission was established, Bacher served as the only scientist among its members; he had tried to decline the post but took it on when he learned that there would be no scientist at all if he didn't accept. While a member of the AEC, he pushed for the development of nuclear submarines and breeder reactors for commercial power.

In the meantime, Lee DuBridge, now president of Caltech, offered him a position as chairman of the Division of Physics, Mathematics and Astronomy—or as just a professor, whichever he preferred. "The decision I came to was a fateful one and probably illustrates a major failing in my makeup," Bacher said in the oral history. "I saw what was needed in the division at Caltech and felt some real confidence that I could do a respectable job, so I agreed to take the division chairmanship—at least to get some new fields started and make some additions." What he saw as a "major failing" in his makeup was, in fact, a superb talent for envisioning the future and leading the Institute into it. After getting a commitment that the Institute would support a program in high-energy physics, both theoretical and experimental, Bacher arrived in 1949.

One of his first hires in high-energy physics was Robert Walker, whom he had known at Los Alamos and Cornell. (Walker died January 4; see page 41.) Another of Bacher's early recruits was Richard Feynman, who was reportedly feeling "unsettled" at Cornell; Bacher persuaded him to sign on at Caltech with a sabbatical year in Brazil in between. Feynman then settled in Pasadena in 1951 for the rest of his career. Now, with Feynman and Robert Christy, who had come in 1946, Bacher felt he had the two most outstanding theorists from Los Alamos. Then in 1955 he also hired Murray Gell-Mann.

On the experimental side, he presided over the construction of Caltech's electron synchrotron, one of the first high-energy particle accelerators in the country. Bacher was nominally director of the synchrotron, but Walker supervised much of the research. Although it wasn't shut down (after almost 20 years) until 1969, Bacher had come to the conclusion in the early '60s that if Caltech were going to continue in high-energy physics, "we'd better get started sending people away to work on some of the really big machines." Big Science had arrived, and Bacher was urging Caltech physics into it.

"He was a hands-on provost. He didn't just wait for things to happen; he was a man who got things done."

Next to Robert Millikan, Bacher was the person most important to the early growth of Caltech's reputation in physics and astronomy, says Christy, now the Institute Professor of Theoretical Physics, Emeritus. "He was responsible for building Caltech physics after the war and for making Caltech physics what it is today."

Bacher remained division chair until 1962. During that time he reformed the undergraduate curriculum to make it less rigid, broke up large classes, expanded the teaching staff, and lowered the faculty teaching load. Another field that he helped get started at Caltech was radio astronomy, playing a key role in founding the Owens Valley Radio Observatory in the mid '50s.

He continued to spend quite a bit of time on government work as advisor to the AEC and a member of President Eisenhower's Science Advisory Committee; he served as chairman of a Defense Department committee on nuclear problems and on numerous other committees. In 1958, he was a member of the U.S. delegation to the nuclear test ban negotiations. He was president of the American Physical Society in 1964 and of the International Union of Pure and Applied Physics from 1969 to 1972.

Jesse Greenstein congratulates Bacher on his retirement as provost in 1970. The two were key to starting radio astronomy at Caltech in the mid '50s, when Greenstein was professor of astronomy and Bacher, division chairman.

As Bacher was looking around for new challenges, DuBridge decided he needed someone to be responsible for academic coordination and planning. So, in 1962 Bacher became the Institute's first provost, welcoming the chance to learn about other Caltech divisions. He recruited and hired top social scientists and supported the establishment of graduate programs in the Division of the Humanities and Social Sciences.

"He was a hands-on provost. He didn't just wait for things to happen; he was a man who got things done," said Tom Tombrello, currently chair of Bacher's old division (and Kenan Professor and professor of physics). "He was a man of strong opinions, who knew what he wanted." But he also had a sense of humor and loved bad puns, said Tombrello. "You didn't laugh; you groaned."

Said Christy, who succeeded him as provost: "He was kind of particular about how things were done. He liked to have things done his way." As an example, Christy remembers, before he took over from Bacher as provost, how he insisted that Christy occupy the office next door for six months as a sort of understudy. Bacher wanted to be able to tell him how to do things.

Bacher retired as provost and vice president (incoming president Harold Brown had added the second title in 1969) on his 65th birthday, in 1970, but remained on the faculty exploring new interests in sources of energy. He became professor of physics, emeritus, in 1976. In the late '80s, the Bachers moved into a retirement community in Montecito, where he lived until his death.

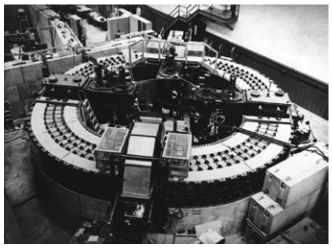
His wife, Jean, died in 1994.

In the synchrotron lab in 1952. From left: Bruce Rule, Robert Bacher, Robert Langmuir, and Robert Walker—the four men who built Caltech's first accelerator.

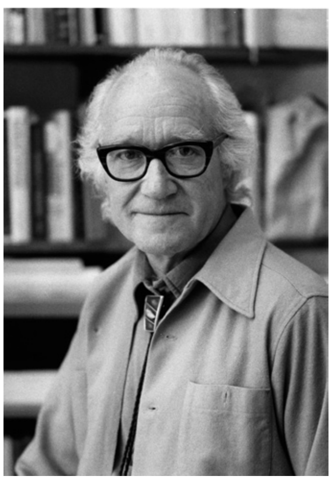
He is survived by their son, Andrew Dow Bacher, PhD '67; daughter, Martha Bacher Eaton; and two grandchildren.

A memorial service is being planned, but not the usual sort of memorial service. When Tombrello broached the idea to Bacher's family, Andrew Bacher (who happens to have been Tombrello's first graduate student) said his father wouldn't like the idea of a bunch of old guys talking about him, and wouldn't want to be there. According to Tombrello, he said his father liked *new* things, what was going to happen *next*. So, early next fall, the "memorial service" will be a celebration of Bacher's 100th birthday; topics for discussion will be "new things" that have their roots in what Bacher started. □—*JD*

Below: The synchrotron lived in the Optical Shop, where the 200-inch mirror for the Hale Telescope was ground. See page 39 for scale.



Robert L. Walker
1919 – 2005



Robert L. Walker, professor of physics, emeritus, died January 4 at his home in Tesuque near Santa Fe, New Mexico, where he had lived since his retirement in 1981. He was 85.

Born June 29, 1919, in St. Louis, Walker earned his BS from the University of Chicago in 1941. While a graduate student at Cornell, he was recruited for the Manhattan Project and spent the rest of the war years at the Metallurgical Laboratory of the University of Chicago and at Los Alamos, where he built pressure gauges to measure the size of explosions. After the war, he returned to Cornell as a student of Boyce McDaniel; they invented a pair spectrometer for measuring gamma-ray energies from light nuclei. He finished his PhD in 1948 and stayed on for postdoctoral research for a year before Robert Bacher (whom he knew from Los Alamos and Cornell) lured him to Caltech, as one of Bacher's first hires in an expanded program in high-energy physics (see page 39).

Walker's immediate task, along with Bruce Rule and Robert Langmuir, was to build a billion-volt electron synchrotron, the design of which had been funded by the Office of Naval Research and the Atomic Energy Commission. It was housed in what was then called the Optical Shop, where the 200-inch mirror for the Hale Telescope had been ground and polished before vacating the premises for Palomar Mountain two years earlier.

Walker supervised most of the work with magnetic spectrometers at the synchrotron until the machine was shut down in 1969, as more energetic accelerators became available elsewhere. For a number of years thereafter, he continued his research at Fermilab (Fermi National Accelerator Laboratory), outside Chicago.

According to Charles Peck, professor of physics, emeritus, who earned his doctorate under Walker, his collaborative research on the synchrotron helped lay the foundation work that led to what is now known as the Standard Model of elementary particle physics. His particular work involved pion photoproduction (in which a proton or neutron is bombarded with a high-energy photon, which produces a pi meson). His research was also useful to his longtime colleague Richard Feynman in his theoretical studies of the underlying mechanisms of particles, according to Peck.

"Bob was also a superb teacher," said Peck. For many years he taught Ph 129, "Mathematical Methods of Physics," and Ph 125, "Quantum Mechanics." He was reportedly the only experimentalist whom the theorists trusted to teach these courses. With Jon Mathews, he coauthored a textbook, *Mathematical Methods of Physics*, described in a review in the January 1965 issue of *E&S* as "a book that not only meets the didactic needs of the first-year graduate student, but also satisfies the practicing physicist who for some time has been hungry for a readable book on mathematical methods written for physicists by physicists."

He was made associate professor in 1953 and professor of physics in 1959. He was executive officer for physics from 1976 to 1981.

Walker retired quite suddenly in 1981. He loaded all his belongings in a U-Haul one day, said Peck, and he and his wife, Dorothy, took off for New Mexico. Peck wrote to Walker on the occasion: "There was no question among the naïve and eager young physics graduate students of 25 years ago about who our favorite prof was. We richly enjoyed your 'Walkerisms,' your occasionally wildly misspelled printing on the blackboard, and especially your subsequently oft-quoted line about something being 'well known—to those who know it well.' I am sure that we all have carried into our careers important lessons from your classroom. I know I have."

On the same occasion, Bacher, who noted that their paths had "run close together for nearly 40 years," wrote: "Without you, I doubt if we

Walker's project in the year 2000 was to build a fortepiano (an 18th-century forerunner of the modern piano). He took its design from a full-scale drawing in the Smithsonian Institution, believed to be of an instrument built about 1795 by Johan Ludewijk Dulcken. Walker's wife, Dottie, sits at the keyboard.

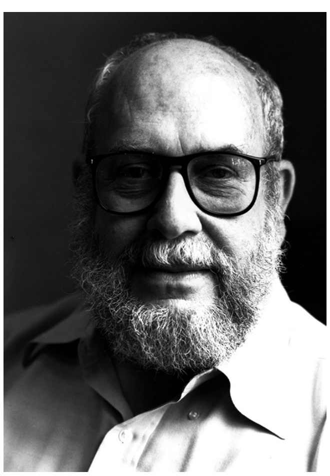
would have been successful in setting up a high energy physics program at Caltech. You made major contributions at every stage from the earliest ideas of what we would do to the present. These contributions were of wide variety from the initial plans of our synchrotron, to its construction and successful use for elucidating the first nucleon resonance, and to many subsequent photonucleon experiments." In listing Walker's "major contributions," Bacher wrote: "As I put them down I realize even more how impressive they are and how much we are in your debt."

In New Mexico, Walker turned to something completely different: he built harpsichords, which have been in great demand by professional musicians throughout the Southwest. Several years ago Walker tackled a fortepiano. It took him, he wrote, about 650 hours to build and another 200 hours "to cure its deficiencies." The "principal challenges were forming the bentside, taming the idiosyncrasies of the action, and figuring out how to convince the upper notes to make more musical sound and less clunk.

"Why would anyone want to make a fortepiano? Well, it's something different and it was fun."

Dorothy Walker died in 2003. They are survived by their two children, Robert Craig Walker and Jan Walker Roenisch. □—*JD*

Thomas K. Caughey 1927 – 2004



Thomas Kirk Caughey, the Hayman Professor of Mechanical Engineering, Emeritus, died Tuesday, December 7, in Pasadena. He was 77.

A native of Rutherglen, Scotland, Caughey earned bachelor of science degrees in mechanical and electrical engineering from Glasgow University, a master's degree from Cornell University, and a doctorate in engineering science from Caltech. He joined the faculty in 1953 as an instructor, and spent his entire career here. He was named the Hayman Professor in 1994, and in 1996 became the Hayman Professor Emeritus.

Caughey's research involved nonlinear differential equations, stability theory, stochastic processes, vibrations and acoustics dynamics, and classical physics. He was involved in a Sloan Foundation project on campus in the early 1970s to use the campus interactive computer facilities in teaching applied mathematics and engineering systems analysis.

He is survived by his wife, Jane; four children, Penelope, William, Catherine, and Christine; four grandchildren; and six great-grandchildren.

A memorial service is planned and will be covered in a subsequent issue of *E&S*. □

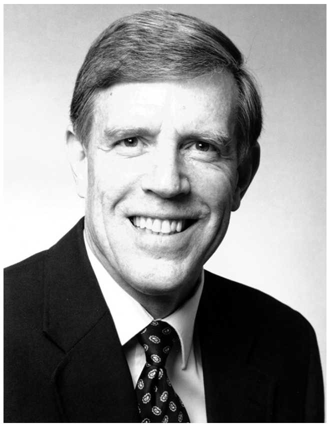
Iwan to Coordinate Tsunami, Quake Investigations

Wilfred Iwan, professor of applied mechanics, emeritus, and director of the Earthquake Engineering Laboratory, has been appointed by the Earthquake Engineering Research Institute to coordinate the tsunami and earthquake investigations that the EERI is conducting as part of its Learning from Earthquakes program. This effort includes more than three dozen investigators from universities, government agencies, and private firms carrying out field studies in the countries devastated by the December earthquake and tsunami in South Asia.

"There are many lessons to be learned from this extraordinary event," said Iwan. "These range from science and engineering to societal impact and public policy. We must improve our understanding of such events so that we can prevent such catastrophes from happening in the future."

Iwan will be working with leading seismologists, tsunami experts, civil and structural engineers, lifeline engineers, and social scientists to compile a comprehensive picture of the events and to extract lessons for research and practice in other countries at risk.

EERI is a multidisciplinary, national, nonprofit, technical society. Its Learning from Earthquakes program is more than 30 years old and is funded by the National Science Foundation. □



Wilfred Iwan

Honors and Awards

Richard Andersen, the Boswell Professor of Neuroscience, has been selected by the McKnight Endowment Fund for Neuroscience to receive a 2005 Neuroscience of Brain Disorders Award. According to the fund, "Andersen's laboratory has made progress in developing a 'brain-machine interface' to help people with severe paralysis." The award of $300,000 over three years, beginning in February 2005, will help Andersen test this device—a "'cognitive cortical prosthetic' that would 'read' the intentions of people with severe paralysis, enabling them to direct their movements"—with human patients.

Frances Arnold, the Dickinson Professor of Chemical Engineering and Biochemistry, has been elected to the Institute of Medicine (IOM) of the National Academy of Sciences. Candidates for membership are "nominated for their professional achievement and commitment to service," according to the institute, and, "with their election, members make a commitment to devote a significant amount of volunteer time as members of IOM committees, which engage in a broad range of studies on health policy issues."

Paul Asimow, assistant professor of geology and geochemistry, has been selected as the 2004 James B. Macelwane Medalist of the American Geophyscial Union, awarded for significant contributions to the geophysical sciences by an outstanding young scientist.

David Baltimore, president of Caltech and Nobel laureate, has been named by California state treasurer Phil Angelides to the Independent Citizens Oversight Committee, which will oversee the spending of $3 billion in state bond money approved by Proposition 71 for stem-cell research. The committee is made up of representatives of the five University of California campuses with medical schools, and of members appointed by the governor, lieutenant governor, treasurer, controller, senate president pro tempore, and speaker of the assembly.

Kaushik Bhattacharya, professor of mechanics and materials science, has received two honors. Named the 2004 recipient of the Young Investigator Medal from the Society of Engineering Science "in recognition of his contributions to engineering science in the areas of thin films, active materials and continuum mechanics," he was awarded the medal during the society's annual meeting in October at the University of Nebraska, Lincoln. He was also presented by the Applied Mechanics Division of the American Society of Mechanical Engineers with the 2004 Special Achievement Award for Young Investigators in Applied Mechanics, this at the 2004 International Mechanical Engineering Congress and R&D Exposition in November in Anaheim, California, "in recognition of his seminal contributions in identifying the critical crystallographic features that govern shape memory behavior in solids and thin films."

Andrew Blain, assistant professor of astronomy, has been awarded the Newton Lacy Pierce Prize in Astronomy for 2005 by the American Astronomical Society. Blain was cited for his outstanding contributions to submillimeter and far-infrared astronomy.

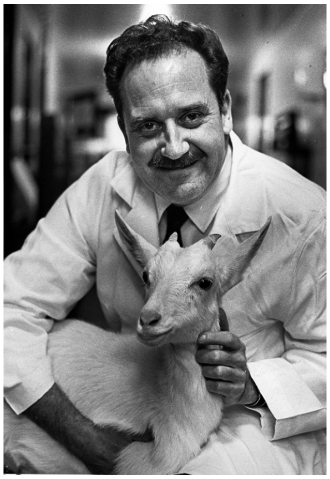
Yanbei Chen, postdoctoral scholar in theoretical astrophysics, has been selected to receive a Sofja Kovalevskaja Award, which is funded by Germany's Federal Ministry of Education and Research. The award sum of up to 1.2 million euros gives recipients "an opportunity to concentrate on high-level, innovative research work in Germany, virtually without administrative constraints, in order to promote the internationalization of research in Germany."

Charles Elachi, Caltech vice president, director of the Jet Propulsion Laboratory, and professor of electrical engineering and planetary science, "in recognition of outstanding dedication and service to the national security of the United States" has been chosen to receive the Bob Hope Distinguished Citizen Award for 2005. The award will be presented by the National Defense Industrial Association at a black-tie dinner scheduled to take place February 25. During his 30-year career at JPL, Elachi has "played the lead role in developing the field of spaceborne imaging radar from a small research area to a major field of scientific research and application."

Tom Hou, the Powell Professor of Applied and Computational Mathematics and executive officer for applied and computational mathematics, is the first recipient of the Morningside Gold Medal in Applied Mathematics. Awarded to outstanding mathematicians of Chinese descent under the age of 45, the Morningside Medals are intended to encourage the pursuit of mathematical truth. Hou was honored at the Third International Congress of Chinese Mathematicians "for his seminal research on applied partial differential equations, scientific computation and numerical analysis."

Shri Kulkarni, the MacArthur Professor of Astronomy and Planetary Science, has been chosen as this year's Marker Lecturer at Pennsylvania State University. He will give three lectures: on cosmic explosions ("Gamma-Ray Bursts and More"), space interferometry ("Planets and Parallaxes and More"), and millisecond pulsars ("Extreme Physics, Extreme Matter, and More").

Harald Pfeiffer, Sherman



The University of Wisconsin–Madison has endowed the Ray Owen Chair in Transplantation in its Surgery Department. Owen, a Caltech faculty member since 1947 and now a professor emeritus of biology, grew up on a Wisconsin dairy farm and took his PhD in genetics at UW in 1941. He stayed on as a faculty member, studying the inheritance patterns of blood groups in cattle. In the mid-1940s, he noticed that blood samples from non-identical twin cows contained cells of the other twin's type as well as its own. But in transfusions, mixing blood types can be fatal. Owen realized that by exchanging blood in the womb, each twin had somehow learned to live with the other's cells. This discovery of "immune tolerance" helped make organ transplants without tissue rejection possible.
At left, Owen and one of his "research assistants" pose for the camera in 1968.

Fairchild Postdoctoral Scholar in Caltech's numerical relativity group, has been selected to receive the American Physical Society's 2005 Nicholas Metropolis Award for Outstanding Doctoral Thesis Work in Computational Physics. "Established to recognize doctoral thesis research of outstanding quality and achievement in computational physics and to encourage effective written and oral presentation of research results," the award consists of $1,500 and a certificate, which will cite Pfeiffer for "his outstanding research on determining initial data for the dynamics of black holes."

John Preskill, the MacArthur Professor of Theoretical Physics, has been invited to deliver the prestigious Rouse Ball Lecture for 2005 at the University of Cambridge. He will speak on "Quantum Information."

Anneila Sargent, the Rosen Professor of Astronomy and director of the Owens Valley Radio Observatory, has been invited to be the 2005 Oort Professor at Leiden University, the Netherlands; she will give the Oort Lecture in April and then will visit for approximately a month in the summer.

Tapio Schneider, assistant professor of environmental science and engineering, has been honored with the first annual James R. Holton Award for Junior Atmospheric Scientists, receiving the prize on December 14 at the annual meeting of the American Geophysical Union in San Francisco. He was honored for "outstanding research contributions by a junior atmospheric scientist within three years of his PhD."

Kip Thorne, the Feynman Professor of Theoretical Physics, has been chosen to receive the 2005 Common Wealth Award in Science on April 23 in Wilmington, Delaware. According to the award letter, the selection committee was impressed not only by Thorne's reputation as an outstanding scientist, but also by his mentoring of younger colleagues. The committee, the letter continues, "speaks highly of your ability to take a very esoteric subject and make it understandable to even non-scientists. Your reputation as a professor is inspiring to see at a time when university students need encouragement to help further interest in scientific research for the sake of pure sciences." The award carries a cash prize of $50,000 and a sculptured metal trophy symbolic of the honor.

Nai-Chang Yeh, professor of physics, has been elected a fellow of the American Physical Society, with her citation reading: "For her contributions to the understanding of cuprate superconductors, vortex dynamics and phase transitions of extreme type-II superconductors, and physical properties of ferromagnetic perovskite oxides."

Kai Zinn, professor of biology, has been selected by the McKnight Endowment Fund for Neuroscience to receive a 2005 Neuroscience of Brain Disorders Award. The award will enable Zinn's research group to further evaluate Pumilio—an RNA-binding protein that represses protein translation—in yeast and fly systems. This work may have implications for studies of human brain function and dysfunction, since humans have a close relative of Pumilio that is expressed in the brain. The award will comprise $300,000 over three years, beginning in February 2005. □

Warren and Katharine Schlinger increased their pledge for a new laboratory building for chemistry and chemical engineering, boosting the campaign over the $1 billion level.

Milestone Reached

The Institute's "There's only one. Caltech" campaign has crossed the $1 billion mark in gifts and pledges! A campus-wide celebration filled Beckman Auditorium January 25 to mark this milestone on the way to the campaign goal of $1.4 billion.

"Only $390 million to go," said Wally Weisman, chairman of the Campaign Leadership Committee, at the event. Weisman announced that it was a gift from Warren and Katharine Schlinger that "catapulted us across the threshold." The Schlingers are longtime supporters of Caltech—Warren, BS '44, MS '46, PhD '49, earned his degrees in chemical engineering. They have increased their campaign pledge to provide lead funding for the new laboratory building for chemistry and chemical engineering.

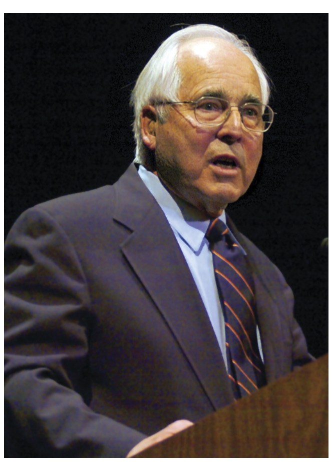
Anneila Sargent, the Rosen Professor of Astronomy and director of the Owens Valley Radio Observatory, spoke briefly on the campaign's effect on the faculty. "We're encouraged to dream" at Caltech, she said, and her own dream, CARMA (Combined Array for Research in Millimeter-Wave Astronomy), is being fulfilled with help from the Norris Foundation, the Gordon and Betty Moore Foundation, and the Associates.

Students also benefit from the campaign fundraising efforts, said Ben Golub, '07, an Axline Scholar, who spent his SURF (Summer Undergraduate Research Fellowship), funded by the Associates, on a project in pure mathematics, which he described as "very abstract." Golub drew an analogy of his position to that of Buddhist monks. To provide for their real-world needs, monks would carry a large bowl among the villagers for contributions of food. "I'm amazed and grateful that people have undertaken the care and feeding of abstract scholars," he said, in his own case leaving him free to focus on "curiosity instead of capital."

Weisman immediately joked to President David Baltimore that maybe they had missed a bet in the campaign—they should have been wandering through villages with a bowl.

Carl Larson, BS '52, is the SURF campaign chairman and a member of the Campaign Leadership Committee; he and his wife are also among Caltech's longtime supporters. But "we're not donors," said Larson, "we're investors." In return, he said "we are allowed to feel we're part of this great institution and tag along for some of the fun." He told the audience that, like a good investment, "you give us back more than we put in. Thank you."

The celebration was concluded by Baltimore, who described some of the other generous gifts, which, along with that of the Schlingers, have made the campaign a success: the Annenberg Foundation grant for Information Science and Technology, support from the Sherman Fairchild Foundation toward the new Cahill Center for Astronomy and Astrophysics, and gifts from Fred Kavli and the Kavli Foundation for nanoscience. "We've set our sights on the most challenging and fundamental questions we can ask of nature and ourselves," Baltimore said. □



Carl Larson, BS '52, invests in Caltech.

For more information about the campaign, please contact:

California Institute of Technology
Development and Alumni Relations
Mail Code 5-32
Pasadena, California 91125
Phone: 1-877-CALTECH
http://www.one.caltech.edu

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California Institute of Technology
Pasadena, California 91125

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