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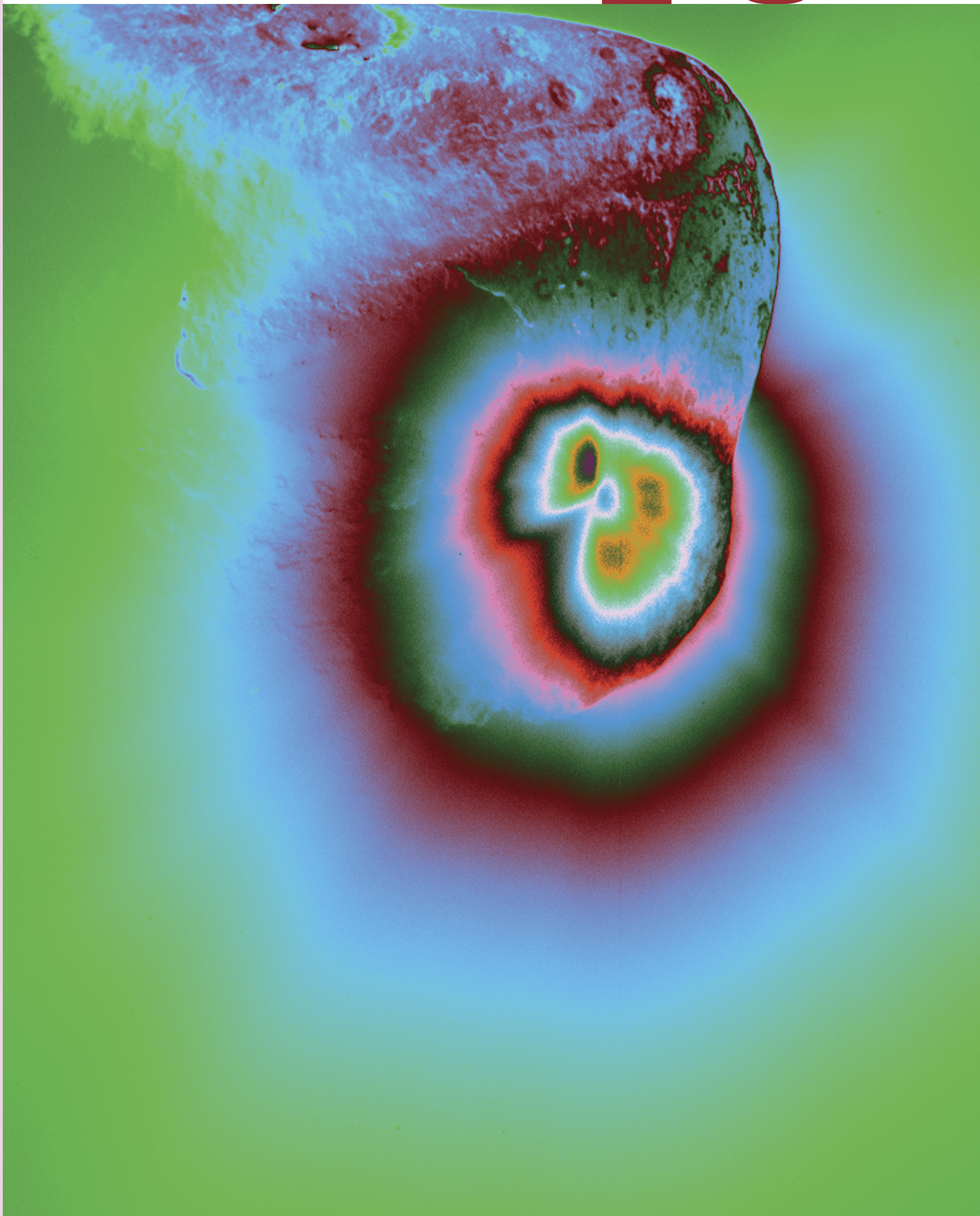
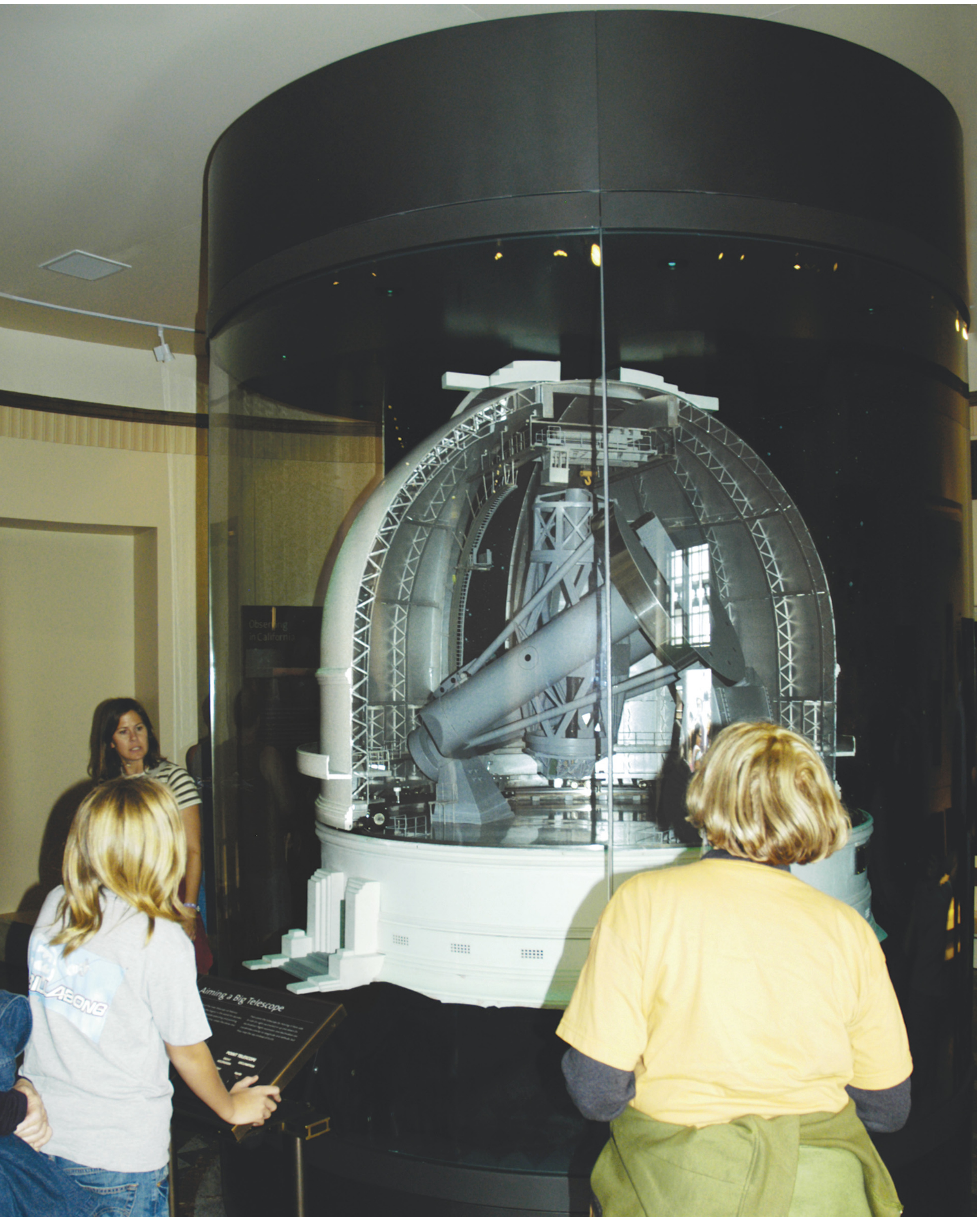


IN THIS ISSUE



Griffith Observatory, one of Los Angeles's best-known landmarks and the most visited public observatory in the United States, is open again after a nearly five-year refurbishment and expansion. Kids can once again play with this scale model of Palomar Observatory's 200-inch Hale Telescope, rotating the dome and aiming the telescope. The model is part of the new "Observing in California" exhibit, which highlights the role of California (and Caltech) astronomy "in inventing the modern universe" says Deputy Director Mark Pine. But Caltech's biggest contribution—at least in terms of square footage—is the Big Picture, in which data from the Palomar-Quest Sky Survey, taken at the 48-inch Samuel Oschin Telescope, was transformed by Caltech astronomers and computer scientists into an eye-popping panorama of glorious galaxies. See the story on page 20.

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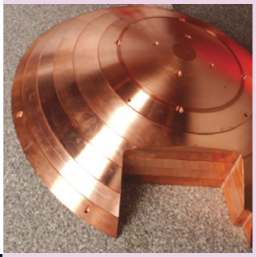

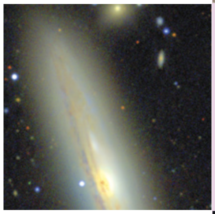

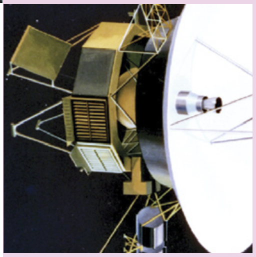

On the cover: Comet Tempel 1 as seen some six minutes after being whacked upside the head with 300 kilograms of copper by JPL's Deep Impact mission. The mother ship took this shot at a range of 868.58 kilometers. The colors represent the brightness of each pixel, with the brightest areas resulting from the impact's dust plume. Image courtesy of Alan Delamare and the Deep Impact science team. To find out how one hits a 10-kilometer ice cube from hundreds of millions of kilometers away, see the story on page 10.

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Funeral for a Planet

JPL's Varoujan Gorjian (BS '92), who works on the Spitzer Space Telescope team, cut quite a figure as the red planet.

Their heads hung low, accompanied by black-clad mourners and a jazz band, eight planets marched in a New Orleans–style funeral procession for Pluto in the 30th annual Pasadena Doo Dah Parade. They were joined by more than 1,500 parade participants, among which were the Marching Lumberjacks, guru Yogi Ramesh, Raelian devotees, the Zorthian nymph snake sisters, and the Men of Leisure and Their Synchronized Napping Team, who stopped every now and then to recline. Marching Lumberjack Karolyn Wyneken, who drove 700 miles from Humboldt County for the event, exclaimed, "Wow, that is awesome! That is so good, and necessary," upon seeing the open casket with its papier-mâché Pluto.

One of the mourners, Caltech Image Processing and Analysis Center staff engineer Kaly Rengarajan, saw the event as a way to educate the public. "The very idea of Pluto being demoted is so exciting. We're trying to refine what we knew before. I'm so glad people are being made aware!" she raved.

Saturn, played by JPL postdoc Angelle Tanner and accompanied by her many rings, organized the march and voiced the sentiments of most of her fellow planets when she noted, "Most astronomers don't think Pluto should be a planet, but we all miss it." Some planets, however, felt strong-armed into participation—as trumpet-playing Earth (Samantha Lawler, BS '05) noted, Saturn was "writing my recommendation letters."

Uranus (astronomy postdoc Nicholas Law) seemed to bear a grudge, sporting a T-shirt that proclaimed, "Pluto had it coming." And mourner Zane Crawford, a JPL visiting graduate student from the University of Colorado who drummed the funeral march, didn't hide his contempt. "Pluto did have it coming, seriously," he said.

Ironically, Mercury (JPL postdoc Joe Carson), winged messenger to the gods, was late. But when he showed up, he was all sympathy, perhaps because now he is the smallest planet in the solar system and fears his turn is next. After all, Mercury is only about twice the size of Pluto. "To be honest, I felt bad for Pluto," he said about the planetary excommunication. "My little cousin started crying when she found out Pluto got demoted."

Even Caltech Professor of Planetary Astronomy Mike Brown showed up, and brought along his daughter Lilah to play the fledgling Eris. “The dwarf planet was originally supposed to be named after her, so it’s appropriate,” said Brown. No cosmic scuffles arose, and everyone strove to maintain peace, for Pluto’s sake. While some memorial services were held in Washington, D.C., days after Pluto’s ejection from planetary circles on August 24, 2006, none came close to this procession. Thirty thousand onlookers gathered in the balmy weather under clear skies. And the planets were all in alignment. □—*EN*

Saturn helps a tardy Mercury with his wings.

Pass the Toothpicks, Please

When it comes to digestive ability, termites have few rivals—try noshing on a two-by-four sometime. But each termite in turn depends on the 200 or so microbial species that call its digestive tract home and are found nowhere else in nature. Despite several successful attempts, the majority of these gut bugs have never been cultivated in the laboratory, so figuring out which microbe does what remains an open question. Now a group led by Caltech researchers is untangling this complex web of relationships using sophisticated “labs on a chip” that can look at a termite’s intestinal ecosystem cell by cell.

The traditional approach to this problem involves removing the gut contents of individual termites, smashing the microbial cells, extracting and pooling their DNA en masse, and analyzing the genes found in the randomized mash. Assigning relationships between any two genes or to the organisms from which they are derived is complicated at best, and often just not possible. Says Associate Professor of Environmental Microbiology Jared Leadbetter, “It was like studying the contents of several hundred books after having torn off their covers, ripped up all the pages into small pieces, and jumbled them together into a big pile. We would find sentences and paragraphs that we found extremely interesting and important, but then we were left frustrated. It was very difficult to determine what was in the rest of the book.”

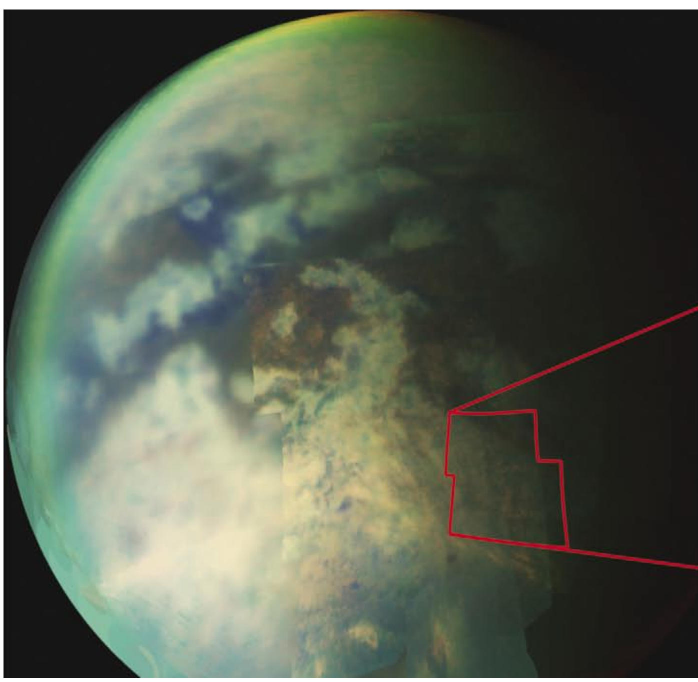
The new approach uses microfluidic devices into which more than 1,000 individual cells can be distributed into separate chambers before analysis, so that each can be studied as an individual. “With this technique, we’re suddenly able to read portions of the books without having first torn off their covers,” says Leadbetter. “We are still reading with a narrow penlight, but when we identify an interesting sentence, we can quickly find the title and author, and even move on to examine the other pages. This approach can lead to a better understanding of the many microbial processes that underlie the environments in which we all live.”

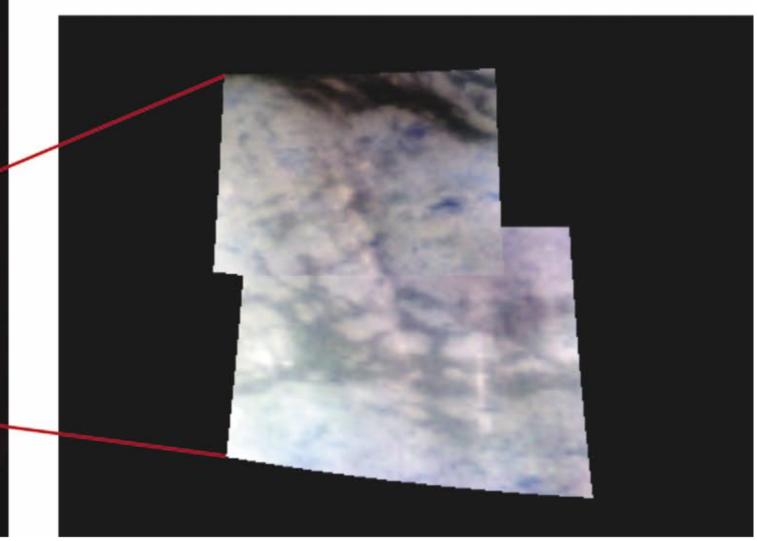
In this particular instance, the researchers found that in the California dampwood termite (*Zootermopsis nevadensis*) a family of bacteria called spirochetes are responsible for a key step in the process of digesting wood—homoacetogenesis, which makes the acetate molecules that are the termite’s chief energy source. (As a side note, these acetate-producing microbes consume hydrogen gas, for which they compete with other gut bacteria that make methane—a potent greenhouse gas—thereby keeping many termite species from emitting as much methane as they otherwise would.) Termites are extremely abundant and active in many tropical ecosystems. Says Leadbetter, “There are 2,600 different species of termites, and it is estimated that there are at least a million billion individual termites on Earth. It is thought that they emit two and four percent of the global carbon dioxide and methane budget, respectively. And by extrapolation from numerous studies of a few dozen termite species, we think that there could be millions of novel microbial species found only in the hindguts of termites.” The work could also illuminate ways for humans to convert plant biomass into useful products, such as transforming low-value lignocellulose (that's straw and cornstalks to you) into biofuels.

The paper appeared in the December 1 issue of *Science*, with Elizabeth Ottesen, a Caltech grad student in biology, as the lead author. The coauthors are Jong Wook Hong, an assistant professor of materials engineering at Auburn University; Stephen Quake, professor of bioengineering at Stanford; and Leadbetter. □—*RT*

There's Methane in Them Thar Hills

JPL's Cassini orbiter around Saturn got another look at its methane-clouded moon, Titan, on October 25. These closest-ever shots from the Visual and Infrared Mapping Spectrometer have a maximum resolution of 400 meters per pixel—about the size of the JPL campus, excluding parking lots—and in the image below left are overlaid on previous VIMS data. The close-up below right reveals a mountain range about 150 kilometers long and 1.5 kilometers high. This mini-Sierra Nevada has "snow"-clad summits (possibly of frozen methane) and appears to have been formed when subsurface material welled up in cracks between diverging tectonic plates, much as the mid-ocean ridges formed on Earth. "These mountains are probably hard as rock, made of icy materials, and are coated with different layers of organics," says Larry Soderblom (PhD '70), a Cassini interdisciplinary scientist with the U.S. Geological Survey in Flagstaff, Arizona. The mountain range had been seen in previous radar-mapping passes, but its signature had been difficult to interpret. In the infrared, however, the shadow it casts is clearly visible. □





Urrrp!

A giant black hole dipping into the cosmic cookie jar has been caught red-handed—the first time astronomers have seen a black hole eat a star from the first to nearly the final bites. The glutton was nailed by the ultraviolet space telescope known as the Galaxy Evolution Explorer, or GALEX—a NASA Small Explorer mission headquartered at Caltech. (See *E&S*, 2004, No. 2.) "This type of event is very rare, so we are lucky to study the entire process from beginning to end," says Caltech postdoc Suvi Gezari, the lead author of the paper in the December 10 issue of *Astrophysical Journal Letters*.

For perhaps thousands of years, the black hole rested quietly deep inside an unnamed elliptical galaxy. But then a star ventured a little too close and was torn to shreds—a black hole's gravity is so strong that even light cannot escape it. Part of the shredded star swirled around the black hole, then began to plunge into it, triggering the bright ultraviolet flare that GALEX saw. The spacecraft continues to watch as the black hole finishes the remaining crumbs of its midnight snack, observations that will ultimately provide a better understanding of how black holes evolve within their host galaxies. NASA's Chandra X-ray Observatory and the Canada France Hawaii Telescope and the Keck Observatory, both in Hawaii, have also helped chronicle the event in multiple wavelengths over two years.

In the early 1990s, three other dormant black holes were suspected of having eaten stars when the joint German-American-British Röntgen X-ray satellite picked up X-ray flares from their host galaxies. Astronomers had to wait until a decade later for Chandra and the European Space Agency's XMM-Newton X-ray observatory to confirm those findings, and show that the X rays had faded dramatically—a sign that stars were swallowed.

Active black holes are always feeding, creating glowing disks of material around themselves that are easy to see. But the black hole hiding in the heart of a typical galaxy may only snare an unsuspecting star once every 10,000 years. "Now that we know we can observe these events with ultraviolet light," says Gezari, "we've got a new tool for finding more." This black hole is thought to be tens of millions times as massive as our sun, and its host galaxy is located four billion light-years away in the constellation Boötes. □—*WC*

Sea-Urchin Genome Sequenced

A group of 240 researchers from an international consortium of more than 70 institutions has announced the sequencing of the male California purple sea urchin. The project was led by Erica Sodergren and George Weinstock, a husband-and-wife team at the Baylor College of Medicine-Human Genome Sequencing Center (BCM-HGSC), along with Richard Gibbs, director of the BCM-HGSC, and Caltech's Eric Davidson, the Chandler Professor of Cell Biology, and Andrew Cameron, a senior research associate in biology. The purple sea urchin's genome has been studied intensely for years at Caltech, and the organism is a workhorse of developmental and biomedical research. Davidson and Cameron coordinated the sequencing effort, and Caltech's Kerckhoff Marine Laboratory provided all the sea urchins required for the project.

Reported in the November 10 issue of *Science*, the high-quality "draft" sequence covers more than 90 percent of the sea-urchin genome. The genome contains more than 814 million letters, spelling out 23,300 genes, nearly 10,000 of which have already been scrutinized by the consortium. In addition to the primary results in *Science*, 41 companion manuscripts will appear in *Science* and in a special December 1 issue of *Developmental Biology*.

More than 30 years ago, Davidson and Roy Britten, a distingushed senior research associate at the marine lab, began to use the sea urchin as an experimental animal and decided to develop it as a model system in the then-emerging field of molecular biology. As a result, "Britten and Davidson offered a comprehensive theory of gene regulation in higher organisms, and the sea urchin has been the premier model for testing these predictions," says Gibbs. "The complete sequence is now available to further these studies."

Sea urchins are echinoderms—Greek for spiny skin—a phylum of marine animals that originated over 540 million years ago and includes starfish, brittle stars, sea lilies, and sea cucumbers. The purple sea urchin is a recent arrival, however, emerging in the North Pacific some 15–20 million years ago. Sea urchins and humans share a common ancestor that gave rise to the deuterostomes, the superphylum that includes the echinoderms and the chordates, essentially animals with a spinal cord.

The sea urchin is the first nonchordate deuterostome to be sequenced. (Insects, nematodes, and other such creatures that have been sequenced lie outside the deuterostome superphylum.) "Each genome that we sequence brings new surprises. This analysis shows that sea urchins share substantially more genes and biological pathways with humans than previously suspected," says Francis S. Collins, director of the National Human Genome Research Institute. "The sea urchin fills a large evolutionary gap in sequenced genomes," says Weinstock, codirector of Baylor's Human Genome Sequencing Center, which did the sequencing work. "It allows us to see what went on after the ancestral split that gave rise to humans and insects."

Comparing the sea-urchin to the human gene list shows which human genes are likely to be recent innovations. It also shows which human genes are evolving rapidly in response to natural selection. This will make it possible one day to know the history of every human gene—and build a picture of what the extinct ancestors that gave rise to animals ranging from worms to humans looked like.

Sea urchins sure don't look like people, but our embryonic development displays many basic similarities, an important shared property of deuterostomes. This makes the sea urchin, with its many transparent embryos and easily isolated eggs and sperm, a valuable model organism. Animal development occurs through a complex network of genes, and sea urchins provide a rapid and efficient means of manipulating that network, allowing researchers to figure out which genes turn other genes on and off. Consequently, the sea urchin is among the best understood developmental systems among animal models. Now, with the genome sequence in hand, this process can be studied exhaustively.

Because of its evolutionary position, the sea-urchin genome is a sample of unknown biological territory, the early exploration of which is already bearing fruit. The sea urchin has most of the same gene families as people, but the gene families are often larger in humans. One unexpected exception to this rule is the immune system.

Humans have innate and acquired immune systems. Innate immunity is the set of proteins that are “hard wired” to detect unique molecules within bacteria, such as their cell walls, and to signal that there is an intruder. Acquired immunity is the province of cells that “learn” to recognize specific invaders and then create customized antibodies to fight them. The sea urchin has some acquired immune system genes, but its innate immune branch is greatly expanded—10 to 20 times as many genes as in humans. This rich repertoire of sea urchin proteins could turn out to provide new reagents in the fight against infectious diseases.

And the sea urchin has no eyes and ears, at least as we know them, yet it has genes for sensory proteins that are involved in human vision and hearing. Some of the visual sensory proteins are localized within an appendage known as the tube foot, and likely function in sensory processes there. “The sea urchin reminds us of the underlying unity of all life on earth,” notes Baylor’s Erica Sodergren. “It is a similar set of genes and proteins being reused in different ways, in different numbers, and at different times in the life cycle to create the diversity of living forms.”

The National Human Genome Research Institute of the National Institutes of Health provided most of the funding for the sequencing and annotation. ☐—*RT*

Red, Hot, and Gold

The ancient Greeks used finely ground gold to color glass, which paradoxically turned it a rich ruby red. They didn’t know it, says Caltech staff scientist David Boyd, but they were using nanoparticles. Since then, many people have exploited the odd optical properties of nanoparticles. Now Boyd and his colleagues are taking advantage of their equally odd thermal ones in a technique called “plasmon-assisted chemical vapor deposition” that adds a powerful new tool to the methods available for making microdevices.

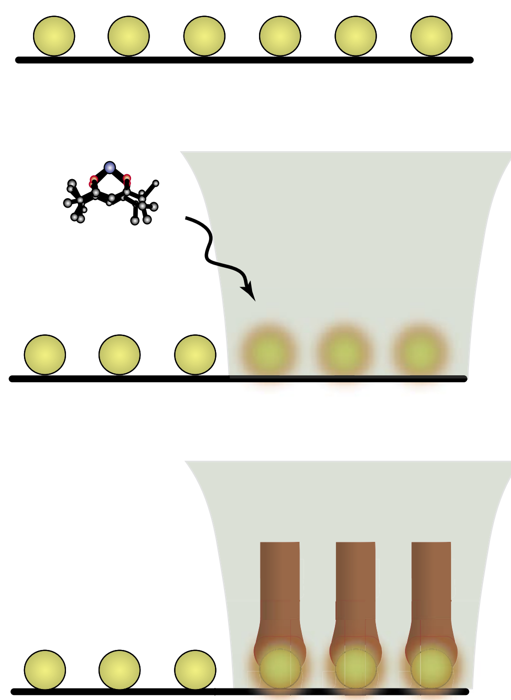
In the November issue of *Nano Letters*, Boyd and colleagues report that the process can be used to create a variety of nanostructures. The underlying material, or substrate, as it is called, is coated with gold nanoparticles and placed in a vacuum chamber that is then filled with a carrier gas containing a precursor of the material to be deposited. A low-power laser whose wavelength matches a natural resonance in the gold particles is focused onto a small spot about one micron in diameter, or less than a hundredth the diameter of a human hair, which quickly heats up by several hundred degrees—hot enough so that the particles decompose the precursor molecules in the vapor, forming microscopic deposits. Since this does not happen at nearby cool particles outside the laser spot, structures form only where the laser shines, allowing one to “draw” patterns by moving the laser across the substrate.

The key is the surprisingly low thermal conductivity at the tiny scales involved, explains Boyd. The gold nanoparticles absorb energy from the laser very efficiently, but do not conduct the heat away to their surroundings very well. They thus can be heated to much higher temperatures than one would expect.

The process requires a laser about as powerful as a green laser pointer, says David Goodwin, professor of mechanical engineering and applied physics and a coauthor of the paper. The ability to write micron-scale or smaller structures directly, without the need for conventional lithographic patterning and etching, while also keeping the substrate cool outside the laser spot, opens up new possibilities for the types of structures that could easily be fabricated.

The researchers grew lead oxide “wires” as small as a few tens of nanometers in diameter on a glass substrate, and predict that even smaller structures are possible. The team has also deposited titanium oxide and cerium oxide. “Anything that can be deposited as a film by conventional means can probably be deposited with this technique,” Boyd says.

The paper’s other authors are Leslie Greengard, of New York University’s Courant Institute of Mathematical Sciences; Mark Brongersma of Stanford University, a former Caltech postdoc; and Mohamed Y. El-Naggar (MS ’02), who has completed all the requirements for his Caltech PhD and is now a postdoc at the University of Southern California. ☐—*RT*



Top: Gold particles are laid down on the substrate. Middle: A pinpoint laser illuminates some of the particles, heating them, while a precursor molecule (the crablike thing) drifts by. Bottom: The hot particles break down the precursor molecule on contact, causing deposits to form on top of themselves.

Test-Tube Logic

Computers and liquids don't mix, as many a careless coffee drinker has discovered. But a breakthrough by Caltech researchers could result in logic circuits that literally work in a test tube—or even in the human body. Made of DNA, these circuits work in salt water—an environment similar to that within living cells—which could lead to a biochemical microcontroller, of sorts, for cells and other complex chemical systems. The lead author of the paper describing this work, which appeared in the December 8 issue of *Science*, is Georg Seelig, a postdoctoral scholar in Erik Winfree's lab. "Digital logic and water usually don't mix, but these circuits work in water because they are based on chemistry, not electronics," explains Winfree (PhD '98), an associate professor of computer science and computation and neural systems and recipient of a MacArthur genius grant.

Rather than encoding signals in high and low voltages, the circuits encode signals in high and low concentrations of short DNA molecules. The logic gates that process the information are carefully folded complexes of two or more additional short DNA strands. When a gate encounters the right input molecules, it releases its output molecule. This output molecule in turn can help trigger a downstream gate, so the circuit operates like a cascade of dominoes in which each falling domino topples the next one. But unlike dominoes and transistors, these components have no fixed positions and cannot simply be connected by wires. Instead, the molecules bump into each other at random, relying on the specificity of their designed interactions to ensure that only the right signals trigger the right gates.

"We were able to construct gates to perform all the fundamental binary logic operations—AND, OR, and NOT," explains Seelig. "These are the building blocks for constructing arbitrarily complex logic circuits." The largest circuit the group has made so far processes six inputs with 12 gates in a cascade five layers deep. While this is not large by Silicon Valley standards, Winfree says that it demonstrates several important design principles. "Biochemical circuits have been built previously, both in test tubes and in cells," Winfree says. "But these circuits rely solely on the properties of DNA base-pairing. No enzymes are required to make them work."

"The idea is not to replace electronic computers for solving math problems," Winfree says. "Compared to modern electronic circuits, these are painstakingly slow and exceedingly simple. But they could be useful for the fast-growing discipline of synthetic biology, and could help enable a new generation of technologies for embedding 'intelligence' in chemical systems for biomedical applications and bionanotechnology." Such circuits could be used, for example, to detect specific cellular abnormalities.

The other authors of the paper are David Soloveichik and Dave Zhang, both grad students in computation and neural systems. □—*RT*

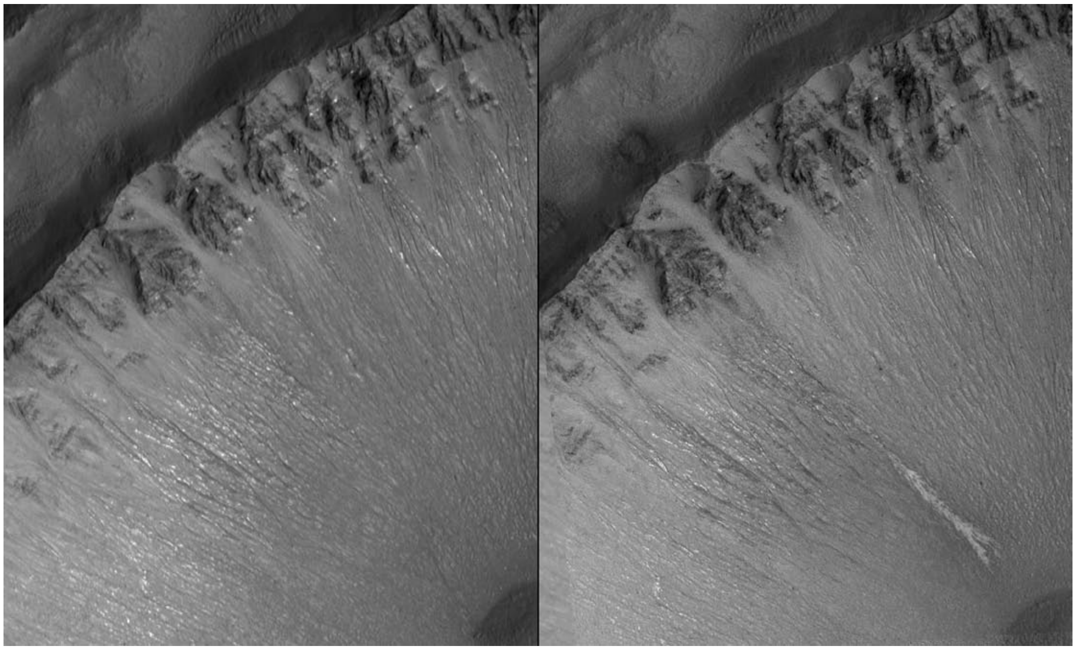
Mars Global Surveyor—Lost, But Not Forgotten

On November 21, NASA announced that Mars Global Surveyor's operating career was likely over. The news came almost three weeks after the last signal was received from the 10-year-old spacecraft, better known as MGS. One possibility is that the spacecraft lost the power to communicate because it could no longer pivot its solar panel to collect enough sunlight to recharge its batteries. Efforts are still under way to regain contact by taking photos of the spacecraft from the Mars Reconnaissance Orbiter. Knowledge of the detailed orientation of MGS may permit JPL to regain radio contact and reestablish control of the spacecraft. Arden Albee, MGS project scientist, former chief scientist at JPL, and Caltech professor of geology and planetary science, emeritus, says the odds are against recovering it, but that it will endure for many years in its orbit at 400 kilometers above the surface of Mars.

Our story really begins with the loss of the Mars Observer in 1993, a year after launch, as it entered Mars orbit. MGS in a sense rose from the ashes of the Observer, as it was assembled quickly from spare Observer parts. The Surveyor was half the size and mass of its forebear, but carried much of the same equipment—narrow- and wide-angle cameras, a thermal-emission spectrometer, magnetometers with an electron reflectometer, a laser altimeter, and a radio system with an ultrastable oscillator.

MGS was launched two days after the 1996 presidential election. Ten months later it pulled into an elliptical orbit around Mars. While pioneering the technique called aerobraking, in which the spacecraft would dip into and out of the Mars atmosphere repeatedly in order to slow down and reach a circular orbit, a solar-panel hinge was damaged. This incident meant the spacecraft needed to brake more slowly to reduce pressure on the panel and avoid further damage, and may have contributed to MGS's ultimate loss. MGS remained in an elliptical orbit, decelerating slowly, for one Mars year (two Earth years).

This delay yielded unexpected bonuses. It had long been thought that Mars had at best a very weak magnetic field, suggesting that, unlike Earth, Mars did not have an actively convecting nickel-iron core. The eventual circular orbit would measure such a field, if it existed. But the elliptical orbit dipped under Mars's ionosphere and revealed remnant magnetism



Far left: This Mars Global Surveyor image of an anonymous crater wall near 38.7 degrees south latitude, 263.3 degrees west longitude in the Centauri Montes region was taken on August 30, 1999. Left: Another image of the same spot taken on September 10, 2005 shows a fresh, bright deposit whose downslope end branches out like fingers of water would around obstacles. If the flow was, in fact, water, it would amount to some five to 10 swimming pools' worth, says Edgett.

in the oldest parts of the crust, suggesting that early in its history Mars had an internal dynamo resembling that of our own planet.

MGS also gathered detailed information about the Martian atmosphere during its delayed descent. The circular orbit that MGS was meant to enter was aligned so that the local surface time below the spacecraft was always 2 p.m. (2 a.m. on the night side), a compromise between the optimal lighting times for camera photography and spectral imagery. Rather than the 2 a.m./2 p.m. measurements MGS would have been restricted to in a circular orbit, the local time changed continuously in the elliptical orbit. During the prolonged aerobraking process, the Martian atmosphere was determined to vary greatly with altitude, and this information guided MGS—as well as later spacecraft—during entry into its ultimate orbiting altitude of 378 kilometers above Mars's surface.

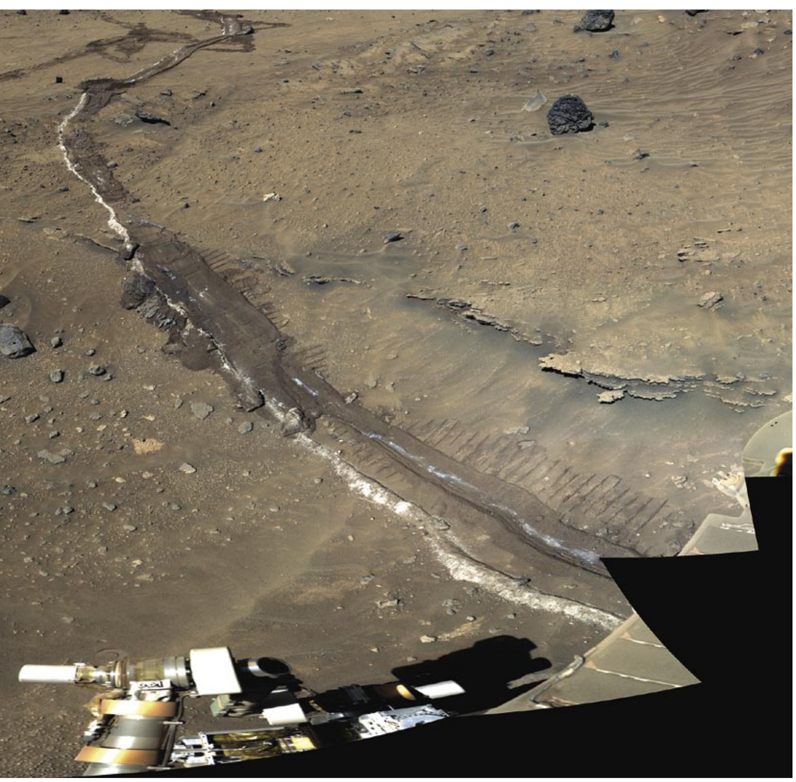
The MGS photos, which number over 240,000, have provided exciting insights into the Martian surface, suggesting a past in which water flowed through gullies and ancient river deltas. The discovery of the water-associated mineral hematite near the Martian equator guided the selection of the landing site for the Mars Exploration Rover Opportunity. Atmospheric measurements allowed MGS to report the "weather" to other incoming spacecraft. Repeated observations and measurements over five Martian years have revealed the changing surface of a planet nearly 60 million kilometers away—for a while we even had better global topographic coverage of Mars than we had of Earth. "Surveyor changed the planet into a known object," Albee says. "Second-grade kids read about Mars as if it were Earth because of the information that came from Surveyor."

We now know that weather systems blow from west to east on Mars just as they do on Earth, and that Mars has a winter during which it snows dry ice at the poles, followed by a summer during which the ice retreats. In its final days, MGS cemented its fame as a comparison of new and old photos showed a fresh, gully-like feature in the side of a formerly smooth crater. The lack of topographic relief of the gully suggests it arose from recently flowing water rather than a landslide. According to Michael Malin (PhD '76), president of Malin Space Science Systems, the sediments deposited along the gully were diverted around obstacles and ended in finger-like branches, just as would happen to water-laid sediments on Earth. Ken Edgett, a Malin staff scientist, was quoted in the *Los Angeles Times* as saying, "You have all heard of a smoking gun; this is a squirting gun." The possibility of liquid water on Mars has boosted the hopes of many who believe life does exist on other planets.

MGS reached many milestones in its lengthy career. The first came after 28 days of data reception provided the first systematic global portrait of Mars. It satisfied all its mission objectives after one Mars year in orbit. Measured by these standards, MGS has far outlived the dreams of the space scientists who designed it and sent it on its way. And now, 10 years later, during which the spacecraft and all its instruments operated nonstop for 24 hours a day, seven days a week, MGS has finally entered a deep sleep, perhaps someday to be reawakened by a radio "kiss" from Earth. □—*EN*

Meanwhile, on the Martian surface, Spirit is on the move again as the days of spring lengthen. The rover had spent the winter strategically parked on a low ridge in order to get maximum solar power for its instruments, which performed a thorough study of its surroundings. Many mysteries remain, however, including the nature of the light material lying just beneath the surface that was exposed by the rover's wheels (below) en route to its winter quarters.

And on the opposite side of the planet, JPL controllers are looking for a route to get Opportunity, Spirit's twin, to the bottom of Victoria Crater.



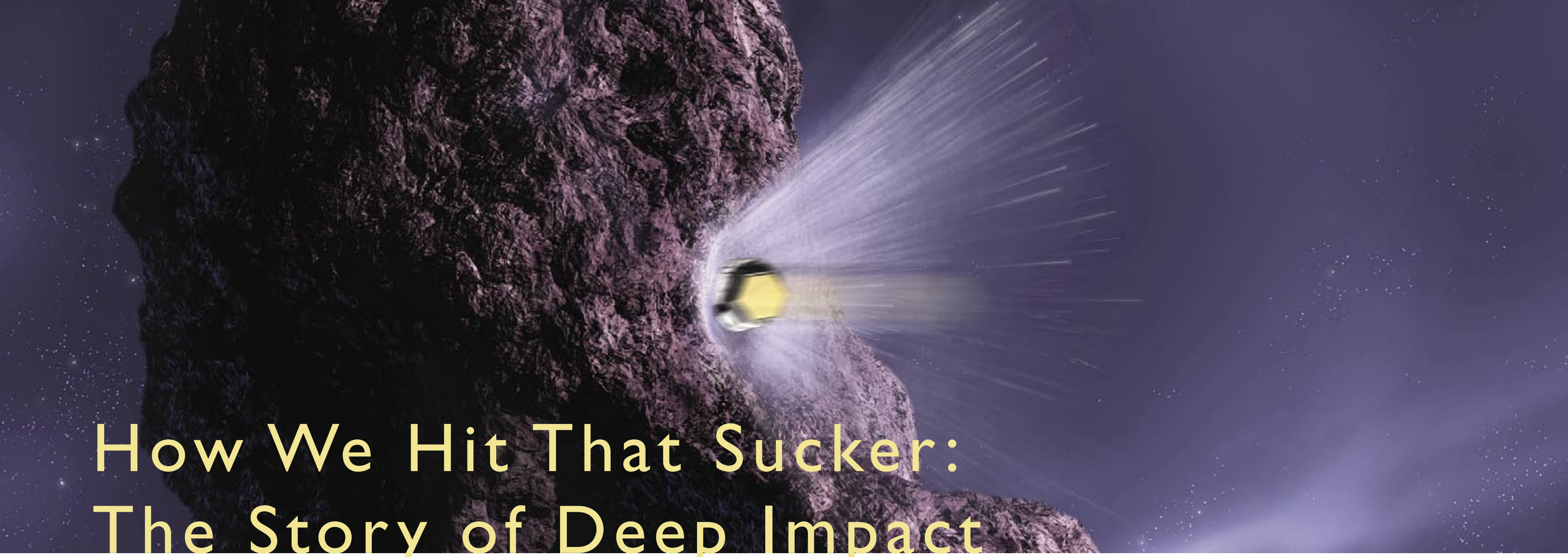
Brain, Heal Thyself

Caltech neuroscientists have found a way to stimulate the growth of neural stem cells in the adult brain up to sixfold—cells that might then be used to repair it. According to Paul Patterson, the Biaggini Professor of Biological Sciences, future work may find ways to direct these stem cells—which have the ability to turn into other types of brain cells as they mature—to replace cells that die in disorders such as Parkinson's and Alzheimer's diseases and multiple sclerosis. "Basically, what my colleague Sylvian Bauer did was take a protein called leukemia inhibitory factor, or LIF, and inject it into the brains of adult mice," Patterson explains. "The results show that you can stimulate the subventricular zone to produce a much larger pool of adult neural stem cells." (Bauer, the lead author of the paper describing the work that appeared in the November 15 issue of the *Journal of Neuroscience*, was a postdoc in Patterson's lab at the time.)

"The brains of patients with neurodegenerative diseases show evidence that their neural stem cells do attempt to replace dying cells," says Patterson. "However, their contribution is very limited. Our approach may overcome this, and using one's own cells avoids the problems of the brain rejecting the transplanted cells." The next step is to see if these cells can be directed to replace cells in mice with brains that are damaged in ways similar to those of humans with Parkinson's, Alzheimer's, and multiple sclerosis.

This development in no way renders the use of embryonic stem cells obsolete, or argues against further research with embryonic stem cells, Patterson says. Embryonic stem cells have the potential to become any cell in the body, whereas this process uses adult neural stem cells for brain disorders only. □—*RT*

PICTURE CREDITS: 2, 3 — Bob Paz; 4 — NASA/JPL/U. of Arizona; 8 — NASA/JPL/MSSS; 8–9 — NASA/JPL-Caltech/Cornell



How We Hit That Sucker: The Story of Deep Impact

by William M. Owen Jr.

"It's a big bullet with a small bullet hitting a comet. So Dr. Owen, how did *they hit that sucker?" – Le Val Lund*

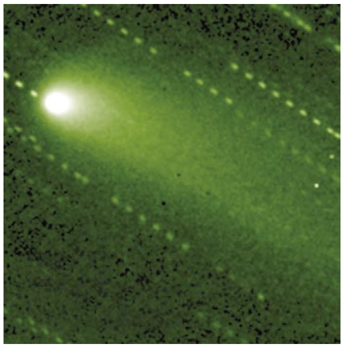
"You want to do WHAT??!!"

In a fit of irrational exuberance on the Fourth of July 2005, our project manager Rick Grammier yelled out, "We hit that sucker!"

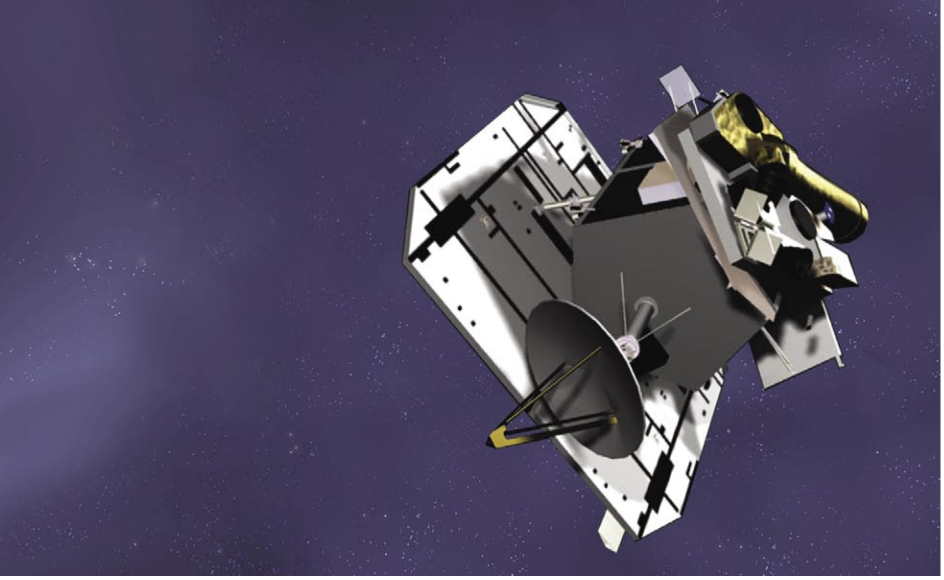
How do we make a hit like that? To paraphrase the bridgekeeper in *Monty Python and the Holy Grail*, we just had to answer these questions three: First, what was our quest, or where did we want to go? That falls under the general heading of mission design. Second, where in space were we, and where was our target? That's orbit determination, which is where I fit into the scheme. And what could we do about getting to our target? That's maneuver analysis.

Before we get into how Deep Impact did it, we need a little bit of background. As always at the start of a mission, we begin with the science objectives. In our case, the requirements were, "We want to hit a comet." At JPL, the reaction was, "You want to do WHAT??!!" The principal investigator, Michael A'Hearn at the University of Maryland, planned this mission to improve our knowledge of key properties of a comet's nucleus by means of a massive impact at high velocity. In other words, he wanted to make a crater in order to directly assess the interior properties of a comet and figure out what it is made of. Every time a comet sails past the sun, it loses a little bit of material, which is what makes its tail. But if we could dig a hole deep enough, we would excavate to a pristine level that hasn't been perturbed the way the surface has. The underlying material preserves the primordial ingredients from which the planets of our solar system condensed some 4.5 billion years ago.

Our target was Comet 9P, otherwise known as Tempel 1. The P means periodic and the nine means it's the ninth periodic comet discovered. Comet 1P is Halley, which was the first discovered to be periodic. Tempel 1 was the first of four periodic comets discovered by astronomer Ernst Wilhelm Leberecht Tempel during a scan of the sky on April 3, 1867. All periodic comets, and there are 182 known, have orbital periods of less than 200 years. Tempel 1 has an orbital period of less than six years, and although gravitational influence from Jupiter threw off its orbit and led to its "disappearance" between 1879 and 1967, since 1978 it has been viewed from Earth, like clockwork, every 5.5 years. It's not bright enough to be seen by the naked eye—Tempel 1 has an apparent magnitude,



Comet Tempel 1 on August 21, 2000. The color is false: the areas that appear green are actually the darkest, and the bright cloud is sunlight reflected off of dust grains in the comet's tail. This picture, which captures about 175,000 kilometers of sky at the distance of the comet, is a composite of 19 separate images taken as the comet moves across the sky, so background stars appear as dotted lines. North is at the top and east is to the left. The images were taken by J. Pittichová and K. Meech at the University of Hawaii's 2.2-meter telescope on Mauna Kea.



or brightness, of 11, and the magnitude of the dimmest stars we can see without a telescope is six. But it's predictable and easy to get to.

When you look at a comet, you see mostly the fuzzy head, or coma. Not all comets have tails, and periodic comets are generally faint and don't have much of a tail. Tempel 1's coma is thousands of kilometers across and a bit asymmetric, which might suggest difficulties in finding a good impact site. To make this mission even more challenging, we needed to hit the nucleus, or the hard core of the comet, inside the coma. And, as David Levy once said, "Comets are like cats. They have tails, and they do precisely what they want."

We were aiming for a cometary nucleus whose dimensions were estimated to be 14 × 4 kilometers. Which is pretty crazy, because if we miss the target by 500 meters, it could all be over.

This was not the first time a spacecraft had launched something on a collision course with a planetary object. Galileo carried a probe to Jupiter in 1995. Cassini dropped the Huygens probe onto Saturn's moon, Titan, in early 2005. But Jupiter is the largest planet in the solar system, and Titan is bigger than Mercury. We were aiming for a cometary nucleus whose dimensions were estimated by the Hubble and Spitzer space telescopes to be 14 × 4 kilometers. Which is pretty crazy, because if we missed the target by 500 meters it could all have been over. And our spacecraft reached its position just one day before impact, while in other missions the spacecraft arrived weeks or months ahead of time. But I'm getting ahead of myself.

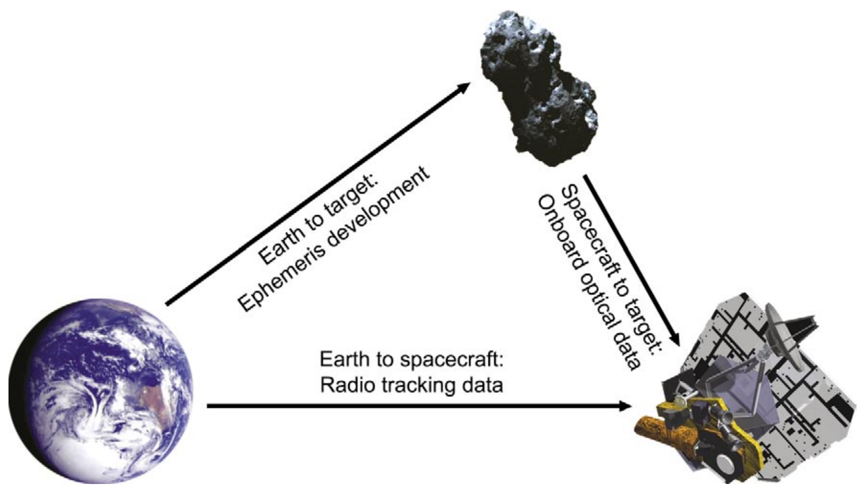
Designing a Mission

A space mission begins with trajectory design, which includes orbit determination and maneuver analysis. Trajectory design answers the question, "How do we get there?" The comet's nucleus is just a few kilometers across, so our flight path has to be known to something better than a couple of kilometers if we want to have a prayer of hitting it. So we've got accuracy requirements, and in order to achieve them we've got to have enough data coming in. That drives all the schedules for radio data, for onboard camera capability to gather optical data, for maneuver capability (including errors!), and all the other operations necessary for a successful mission. And it's all got to fit in the schedule and the budget, and, we hope, not work our people too darn hard.

To integrate a trajectory, or in other words determine where in the solar system our spacecraft is, all we need to do is a plain old numerical integration of the Newtonian formula $F = ma$ (force equals mass times acceleration)—just figure out the gravitational accelerations of each solar system object, right? Well, Newton doesn't work here anymore. We rely on general relativity to accurately calculate the gravitational forces. These not only affect the spacecraft, they deflect all electromagnetic radiation in space, including the radio signals we use to command and communicate with the spacecraft. Don't let anybody ever tell you that Einstein was wrong or general relativity has not been proved. At JPL we demonstrate it daily.

But gravity is not the only thing that affects the spacecraft. Maneuvers do, obviously. As does the solar wind, which is the stream of charged particles emitted in all directions from the sun. Also solar pressure, just the light from the sun, affects the motion of spacecraft; this was discovered by surprise by Echo, a 1960s NASA project that deployed an inflatable passive communications satellite in the form of an aluminum-covered Mylar balloon. Outgassing and other mass losses to the spacecraft are also critical to calculating its path.

The navigation triangle, each side of which is measured in a different manner and must be constantly updated in order to reach the target. Side one: Earth to the spacecraft. Side two: Earth to the target, comet Tempel 1. Side three: The spacecraft to the target.



The Navigation Triangle

A simplified trajectory can be thought of as a navigation triangle, which in our case will consist of Earth, the spacecraft, and the comet, our "target du jour." The triangle has three sides, each measured in a different manner. For the distance from Earth to the spacecraft, side one, we use radio tracking data, of which there are three different types. The first type of data is range, or how far away the spacecraft is from Earth. The spacecraft receives a signal and turns it back around, and, using the speed of light and the travel time of the signal, we calculate the distance it traveled. The second is Doppler, which is the change in frequency of the signal due to the effects of the spacecraft's movement. We know what the frequency of the signal is going up, and then we measure it coming down, and the difference between the two frequencies—the Doppler shift—tells us how fast the spacecraft is receding (or approaching) along our line of sight. And the last one is called ΔDOR, or the delta difference of one-way range. It is essentially very-long-baseline interferometry. Two widely separated antennas look at the spacecraft and determine the difference in the distance that each measures. Then they turn away from the spacecraft in unison and look at a well-known object nearby, like a quasar. They do this over and over, going back and forth, back and forth, providing the information to cancel out all sorts of systematic errors and biases that are difficult to calibrate out, and ultimately yielding the precise angular position of the spacecraft. When it works it works really well, but sometimes it's hard to pull off because it takes two tracking stations working in sync with each other on two different continents.

Of course these things have their subtleties. Errors in range can arise from phase delays as the signal travels through Earth's ionosphere and troposphere. We can calibrate these out a little bit. As for Doppler, the difficulty with it is that the antennas are on Earth, and Earth rotates, so the antennas are moving as the Earth spins. This means that the antenna has its own velocity, which gets impressed upon the signal, resulting in a little sine wave on top of the signal. But, luckily, that sine wave gives you the position of the spacecraft in the sky. The sine wave phase tells you the right ascension, which, like longitude on Earth, gives the east-west position, only measured in increments of hours from zero to 24. And the wave's amplitude yields the declination, which is the same as latitude on Earth, from –90˚ S to +90˚ N. So we take Doppler measurements, which are radial velocity measurements, and wind up being able to infer position. Who'd a thunk it?

Navigation triangle, side two, is from Earth to the target, and this is the province of our ephemeris group—the scientists in charge of determining the future positions of solar-system objects. These are the JPL people whose names you might read in the paper, like Don Yeomans, Paul Chodas, and Steve Chesley, because they save us from killer asteroids. They get the orbit of whatever it is that our spaceship is going to fly by, whether it's a comet or a planet or an asteroid or a satellite. In the case of Deep Impact we needed the orbit for our comet, Tempel 1, which was determined initially by optical astrometry from ground observatories and improved when new observations came in.

Finally, the position of the spacecraft relative to the target, side three, is determined through optical navigation, using photos taken from cameras aboard the spacecraft. That's where I come in. These cameras take pictures of whatever they are facing, with stars in the background. Thanks to the European Space Agency's Hipparcos mission, which between 1989 and 1993 pinpointed the positions of more than 100,000 stars, and a lot of other work being done in stellar astronomy, we have good star catalogs now, and we know quite well where these stars are. We didn't used to, and in those times we contracted with Lick Observatory, up in San Jose, to take big photographic plates of the night sky. Then I would go up to Lick and survey the plates, picking out stars with a joystick and a little button that said "push" to record their positions on the plate. After a while, the "push" became engrained on my thumb. Luckily, those days are over.

So our onboard cameras take a photo of whatever target we are seeking against a background of stars, and from there it's fairly simple to figure out the direction the cameras were facing when they took the pictures. We can't get information on the distance of the spacecraft from the target with this method, but we can infer the right ascension and the declination of the target from the relative positions of stars photographed in a sequence.

Having measured the three sides of the navigation triangle, we put all three different data types together to get the position of the spacecraft—and, of course, they don't match. So we have to move on to higher math, with calculations that include about 100 parameters. We take each new solution as the starting condition and calculate again, and again, and again, until the difference between one solution and the next is sufficiently small. The final answer is subjective, because we are dealing with three disparate data sets—ground-based astrometry, radiometric, and spacecraft optical—and the relative weights assigned to the three data sets determines the answer. It becomes a question of knowing how to weight the data, so we try different things and see what holds together.

The result is another trajectory file, just like the one that went in but with different numbers, based on the spacecraft's initial position and velocity, the orbits of planets and satellites, solar pressure, maneuvers, and anything else that can affect the trajectory of the spacecraft. We're left with a whopping covariance matrix, several hundred elements on a side, showing how well we think we know the solution. For Deep Impact, we actually had good reason not to believe our solution. For starters, we knew that ground-based observations of the center of the comet's light were biased. Results from small, mostly amateur observatories were different from those of the large professional observatories, because the brightest part of the coma is offset sunward from the nucleus. We fully expected to see the same effect in the optical navigation images. So we knew there were systematic errors, but we couldn't model them, and we didn't know how big they were. But we also knew that the systematic errors would fade away as we got closer to our target and could observe it more closely.

This digitized sky survey, now accessible via the Internet, shows the type of photo astronomers once used to determine the positions of stars. These star positions would aid in navigation through space.

http://archive/stsci.edu

The *B* Plane

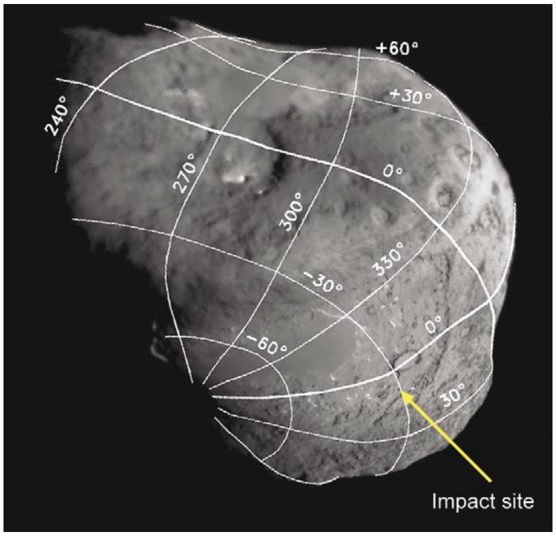
No space science coming out of JPL is complete without mentioning the *B* plane. If you ever took a course in particle physics, you might remember that *B* is the "miss distance," between something traveling by and the thing it was supposed to hit. The same *B* is considered here. We pretend that our comet is massless, which means that it has no gravitational pull on the spacecraft, which then travels in a straight line. Then we draw a plane perpendicular to the flight path and going through the target. The *B* vector goes from the center of the target to the point where the spacecraft goes splat! Right through the *B* plane.

That is just an idealization, to illustrate the operation conceptually. What we really do is transform the position and the velocity of the spacecraft relative to the comet, at some agreed-upon time, into Keplerian orbital elements, which are the parameters needed to uniquely specify an orbit. This world is made of circles and ellipses, and in this case we want to consider a hyperbola because the spacecraft is flying past the comet at a speed faster than escape velocity—it is not going back. And a hyperbola, if you can remember back to analytic geometry, has two asymptotes, one incoming and one outgoing. The *B* plane is perpendicular to the incoming asymptote, and the *B* vector is the miss distance of the incoming asymptote.

Now we know, from the optical determination team, the point on the *B* plane to which our spacecraft is headed. And we know the target in the *B* plane that we *want* it to hit, and these two don't match. So we need to move, or maneuver, the spacecraft, and we have a whole new set of equations for maneuver analysis. To a first approximation, space is big. It takes a long time to get from point A to point B. When a spacecraft fires its thrusters, it's like somebody with a

Comet Tempel 1 was overlain with a coordinate grid in order to map surface features like craters, one of which served to define the comet's prime meridian. The impact site was chosen because it would be sunlit and visible from the spacecraft.

NASA/U. of Maryland/Cornell/Peter Thomas & Tony Farnham



giant croquet mallet went POW! And the velocity is instantaneously changed. The change looks like an impulse, an abrupt change in the momentum of the spacecraft produced by the forward thrust: Force times time equals mass times change in velocity, or ΔV (delta vee) in the business.

We start by changing the velocity in one direction, let's say by adding one meter per second in the *x* direction. Where does the spacecraft go in the *B* plane, and when is its new closest approach to the target? Now we add one meter per second in the *y* direction, and then we do it a third time, a meter per second in the *z* direction. For each of the three changes in velocity, there is a numerical partial derivative for where the spacecraft will go. In fact, we already know where it's going because the orbit determination solution of the navigation triangle has told us, and we know where we want it to go. These pieces of information form three equations with three unknowns, which, when solved simultaneously, yield the three components of the ΔV that will remove the error, or match the spacecraft's trajectory to the target.

Except, unfortunately, the thrust is not *really* an impulse, so we have to do a numerical integration even for the brief moment the thrusters are on. And, of course, the problem is not linear, so the 3 × 3 set of linear equations will give you close to the right answer, but not quite, and the calculations have to be repeated until the right solution is found.

That concludes Navigation 101, which is all background and not the information you were hoping to get out of this article, so let's move on to Deep Impact.

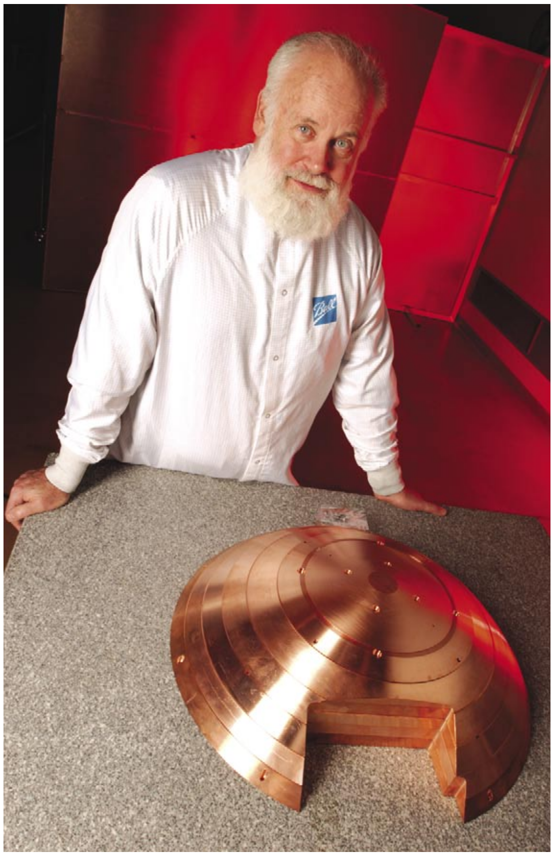
Seeing white, red, and blue

The fact that we wanted pictures of the impact from beginning to end meant that we needed two spacecraft—one to hit the comet and the other to hang back and take pictures of it. Remember how the Tribbles of the *Star Trek* universe were born pregnant? Well, Deep Impact was launched pregnant. There was one flight system, to use the nomenclature, but it was really two spacecraft joined at the hip, or somewhere else.

The mother ship is called the "flyby" and it is a basic spacecraft, with propulsion systems, telemetry systems, data storage systems, instrumentation, and an autonomous navigation system. It also carries a couple of telescopes, which are useful for optical navigation. One is the Medium-Resolution Imager (MRI), and it has about the same resolution as Voyager's camera. The other is the High-Resolution Imager (HRI), with a resolution that is close to that of the Hubble's. A big antenna beams signals back to Earth. And there's also a solar array, which not only provides power, but doubles as a shield. Each of the two panels is 2.7 × 1.5 meters, with a honeycombed core and exterior made of graphite fiber, and weighs less than 11 kilograms. When it passed the comet postimpact, the spacecraft would be shielded by these solar panels. You can see on this page what the mother ship looked like in the clean room.

The mother ship, nicknamed the "flyby," hovers near the impactor spacecraft, which houses the copper disk shown on the next page. The two were joined on April 7, 2004, at Ball Aerospace and Technologies Corp. in Boulder, CO, and shipped to Cape Canaveral, FL, for the January launch.

Michael A'Hearn, principal investigator for Deep Impact, poses near the 300-kilogram copper disk that will smash into comet Tempel 1.



Then there was the impactor, which was 300 kilograms of copper. Why copper? Because comets have no copper, so that if instruments monitoring the ejecta saw spectral lines indicating copper, then we would know it was from the impactor, not from the comet. The impactor was not just a dumb hunk of copper—it would have its own telemetry, its own propulsion system, and a sophisticated autonomous navigation system that would help it home in on the target. It would also carry a duplicate of the mother ship's MRI, which we called the Impactor Target Sensor, to figure out where Tempel 1 was and to see how the comet was moving.

I've heard the project described as a bullet launching a bullet to hit a bullet. It's hard enough to hit a comet, and we wanted to hit it in a place where it was lit so that the mother ship could take pictures of the resulting crater. No problem—things hardly ever go wrong, right?

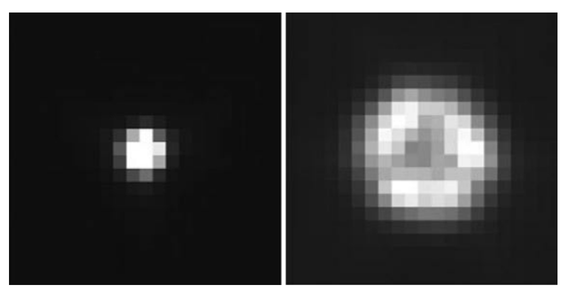
The key challenge fell to the solar-system dynamics group, to give us the best orbit they could that would bring the impactor to the bright side of the comet. But the brightness of a comet, and the location of the nucleus inside the gas- and dust-bearing coma, isn't necessarily that well predicted, so we needed to be prepared for any uncertainties that could lead us off target. We ran simulation after simulation and study after study on the impactor's autonomous navigation system. How well would it perform if the comet turned out to be dustier than we expect? Or if the nucleus had a weird shape and most of it was in shadow when we observed it? We tried to answer these "what-ifs" under extreme conditions, knowing that if the system worked well in these simulations it would do very well under more benign conditions. If our trajectory worked in the worst possible case, we started feeling a little bit good.

We launched January 12, 2005, with a specific energy of 10.9 km^2/s^2, the optimal energy needed to send the spacecraft on a path that would intersect the comet's orbit six months later. Tempel 1 follows a slowly changing elliptical orbit that would bring it closest to the sun (its perihelion) and to its peak of activity on July 5. This was also, luckily, when the comet would be easiest to reach as it crossed the plane of Earth's orbit.

We planned for impact on July 4, 2005, a date set by celestial mechanics rather than the folks back in 1776. But of course we took advantage of it. Project management bought red, white, and blue polo shirts. The boxes arrived a week before the Fourth of July, and instead of what we expected, we got red shirts, white shirts, and blue shirts. Well, life gives you lemons, so the best lemonade we could make out of that one was to give the colored shirts to the team members who might be on TV. So the impactor crew got red shirts and the mother ship crew got blue shirts. And the white shirts, which don't look too good on TV, went to those of us who worked behind the scenes.

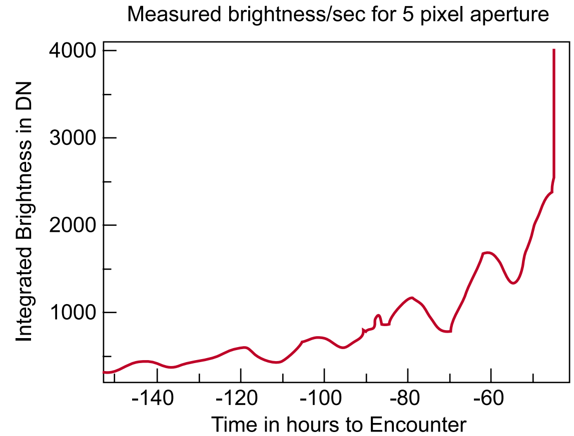
Bad News, Good News

Back to the mission. The mother ship was traveling one million kilometers per day toward the comet, and two days after launch it sent its first star-alignment pictures. The first photos from the impactor's camera followed a week later. We wanted to make sure these cameras were working, but more importantly we wanted to check the alignment of each camera with respect to the spacecraft.



The first photos sent by cameras aboard the mother ship bore good and bad news. At left, a typical star image taken by the Medium-Resolution Imager (MRI). On the right, the High-Resolution Imager (HRI) was too out of focus to be useful during the mission. Loss of the HRI required a retooling of the entire navigation strategy.

As the spacecraft neared the comet, it measured the brightness of both the nucleus and the coma. This graph shows the brightness of the nucleus growing steadily toward encounter time, with a sharp increase just before encounter. The sharp blip just left of E-80 hours is a cometary outburst, and the large-scale peaks show the rotation period of the elongated nucleus is 41.85 hours.

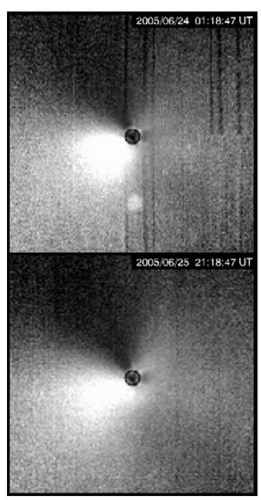


The first picture from the MRI looked like a typical star image. But the first picture from the mother ship's HRI was *way* out of focus. This camera had five times the magnification of the MRI and was the one we hoped to use both for navigation and to take high-resolution images of the comet. Because of the weight, the camera was launched without a focus motor, so the only way to have changed the focus would have been to heat the camera by exposing it to enough sunlight to burn off accumulated moisture and change the focal plane. Well, the heat shrank the camera, and this did change the resolution, but not by much.

But we were prepared, because among the contingency studies before launch was, "What if the HRI fails?" So we switched to Plan B and the MRI. This meant losing a factor of five in resolution, requiring a retooling of the whole maneuver strategy. If a pixel on the HRI was 20 kilometers, it would be 100 kilometers on the MRI, and our knowledge of the location of the comet's nucleus would be similarly compromised. The information we would have gotten five days out we now would get only one day out. There was consequently much more uncertainty in the trajectory of the spacecraft relative to the comet that dictated each maneuver.

The optical navigation team needed to set a route to the nucleus, but the nucleus is surrounded by the coma, this bright cloud of diffuse material whose brightness is offset toward the sun by an unknown amount. The nucleus, being a solid object, has a brightness that varies as $1/R^2$, with R being the distance from it to the observer. But the coma is not solid, it is optically thin—you can see through it—so its brightness varies as $1/R$ instead. So we were observing two different behaviors of light, and when complications like the changing geometry of light in space were added, it became very difficult to tease out light from the nucleus versus light from the coma. But we did a pretty good job at it. On this page, you can see the light from the nucleus getting gradually brighter and brighter until it takes off just before encounter. In the last week we got a pretty good light curve.

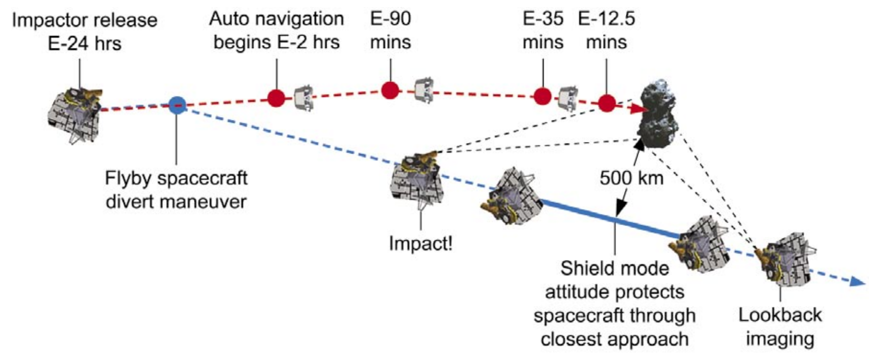
Every time we processed an image, we applied six different techniques. The one that turned out to work the best involved measuring the brightness of each pixel in a 3 × 3 box of pixels. We then fit a Gaussian distribution curve centered on the brightest measured pixel, and the center of the best-fit curve was taken to be the location of the nucleus. In the last week of the mission, the differences between the brightness of each pixel and the average brightness showed that we had found the target to within two tenths of a pixel. So we pretty well nailed that sucker.



NASA/U. of Maryland/Tony Farnham

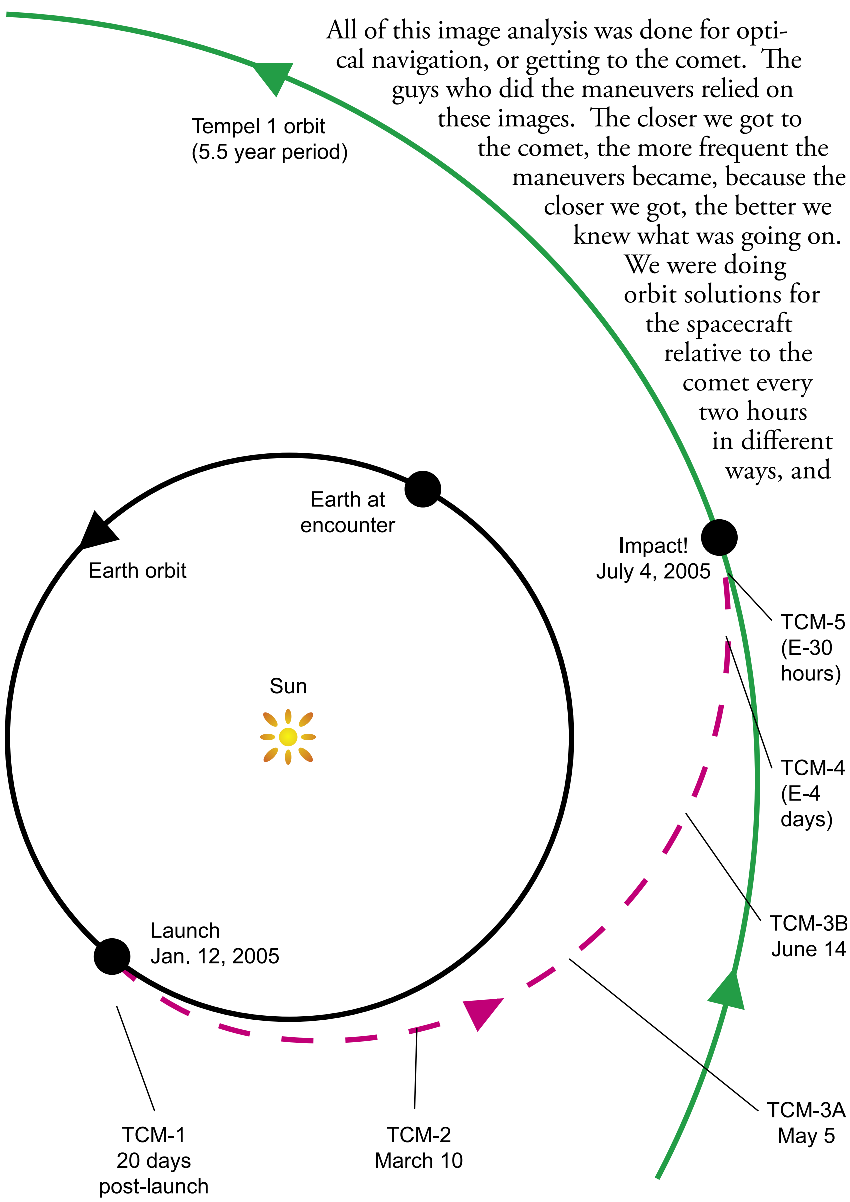
Several unexpected outbursts were detected as Deep Impact neared its target. These two, in images taken 44 hours apart, probably originated from the same location on the nucleus. The field of view is about 1,800 kilometers in the top image and 1,500 kilometers in the bottom one.

Encounter day began with the mother ship releasing the impactor at E-24 hours. The mother ship then moved a little to the side and slowed down to avoid potential collision. It continued to take photos until it reached its closest approach to the comet, 500 kilometers away, whereupon it went into "shield mode," turning its solar panels toward the debris flying from the impact. It then turned back to take postimpact photos. The Mauna Kea observatories were in darkness to best record the impact.



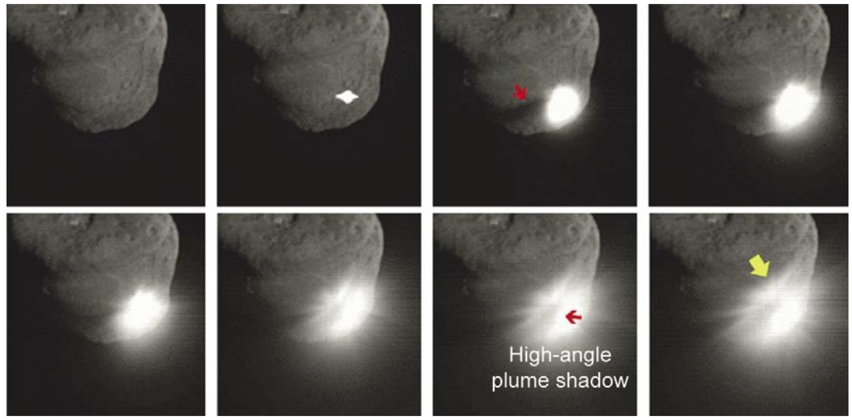
Impact!

All of this image analysis was done for optical navigation, or getting to the comet. The guys who did the maneuvers relied on these images. The closer we got to the comet, the more frequent the maneuvers became, because the closer we got, the better we knew what was going on. We were doing orbit solutions for the spacecraft relative to the comet every two hours in different ways, and using a lot of different assumptions to determine the trajectory change maneuvers (TCMs) that would bring the mother ship into position just before it released the impactor. The good thing is they all kind of, more or less, sort of agreed. The TCM 11 days before impact had brought us on a trajectory that was 34 kilometers off course in the horizontal direction. TCM-5, the final maneuver, was six hours before the release of the impactor, and it was our last chance to change the incoming trajectory. The optical data that had come in during the intervening 10 days helped immensely, and no matter what we tried, our solutions always landed within a box two kilometers wide by four kilometers high, centered on the four-kilometer-wide nucleus. We were confident that we were within two kilometers or so of our designated impact site.



Orbits of Earth, Tempel 1, and the spacecraft during the five-and-a-half month mission. Trajectory Change Maneuvers (TCMs) brought the spacecraft into impact trajectory, and the first came 20 days after launch. They increased in frequency until the last one, at Encounter-minus-30 hours, just six hours before release of the impactor. Deep Impact was planned for July 4, 2005, which coincided with the closest approach of Tempel 1 to the sun.

This sequence of images depicts the development of the ejecta plume when Deep Impact's impactor collided with comet Tempel 1 at 1:52 a.m. eastern time, July 4. Brightness peaked three to four seconds after impact. The red arrows point to shadows cast by the opaque ejecta, and the yellow arrow in the last image indicates the "zone of avoidance," where relatively little ejecta flew because of the oblique angle of impact. The eight images, taken by the mother ship, were spaced 0.84 seconds apart.

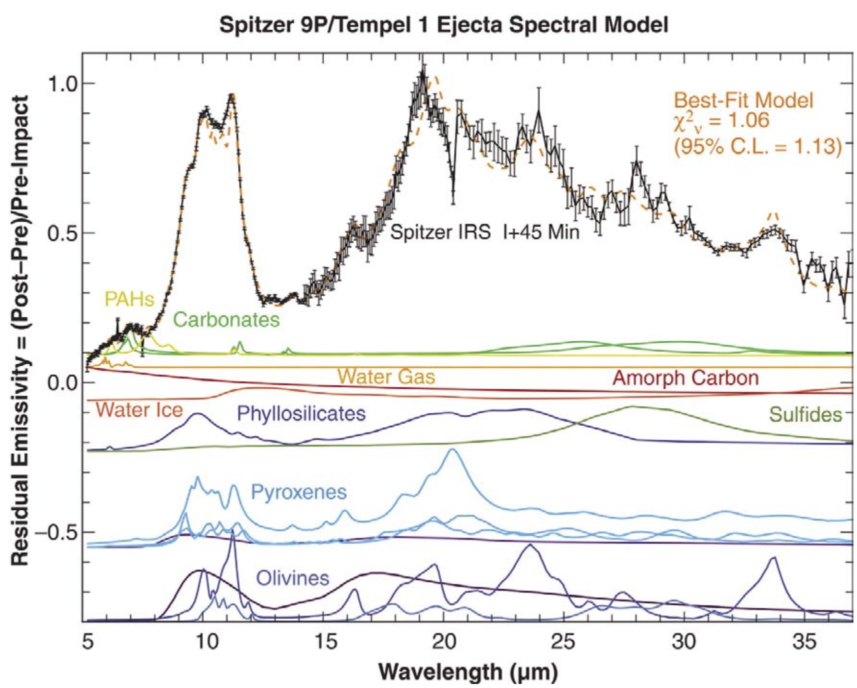


M. F. A'Hearn et al., *Science*, vol. 310, no. 258, p. 258-264, 2005; reprinted with permission of AAAS.

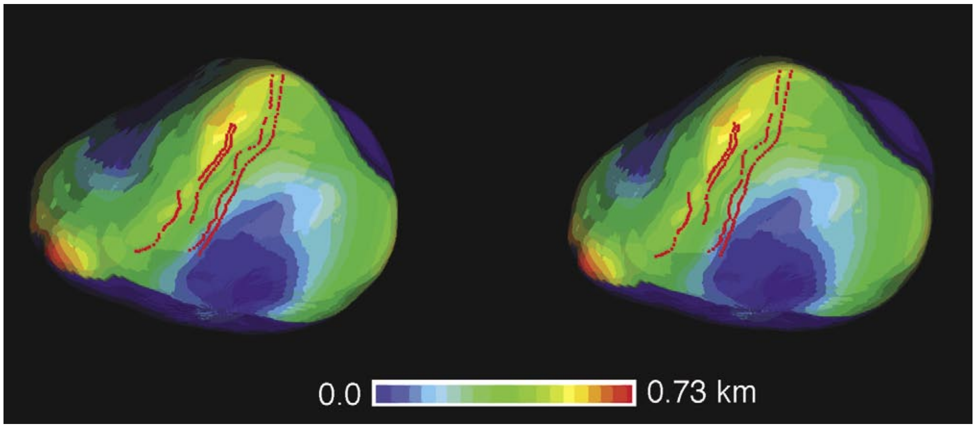
Finally, five and a half months after launch (it was a quick mission!), we reached Encounter-minus-one: one day before encounter with Tempel 1. The impactor was to be released 24 hours out. Now, when engineers say 24 hours out, they mean 24 hours, 00 minutes, 00 seconds. Point 00. At this point the whole flight system was on an impact trajectory, so that if we released the impactor and the mother ship stayed the course, it too would get smashed. So there was a postrelease maneuver planned—a little thrust in one direction to slow it down, a little slide to the left, and the mother ship takes a zigzag path. It didn't take much of a change in speed to accomplish this: the mother ship's speed relative to the comet slowed by only 100 meters per second, to about 10.2 kilometers per second. In this way, we could take nice pictures of the impactor flying toward the comet. The mother ship continued taking pictures until 800 seconds after impact, when the comet got really close, about 500 kilometers away. This was close enough to the coma that we were worried about flying particles, so to protect its instruments, the mother ship went into shield mode, where it turned its solar panels toward the comet. Once it was safely past the coma, the mother ship turned again to take look-back pictures.

Meanwhile, the impactor and comet were flying at each other at a relative speed of 10.3 kilometers per second (that's 26,000 miles per hour!). Now, one of the things we were told was not to get too excited—just because the telemetry from the impactor stopped, that didn't necessarily mean it hit the comet. It could have had some other

Silicates dominate the post-impact emissivity spectrum for the Tempel 1 ejecta. The dust composition, shown in black with the orange dashed line as the best fit, was determined by subtracting the post-impact spectrum from the pre-impact spectrum and dividing the result by the pre-impact spectrum. The colored lines show the individual consituents, and were generated from optical constants of each.



C. M. Lisse et al., *Science*, vol. 313, no. 635, 2006; reprinted with permission of AAAS.



Stereo view of the shape model of Tempel 1's nucleus, keyed for gravitational heights, with red lines tracing linear outcrops. When viewed at the proper distance, the image should appear three-dimensional.

problem instead. So we were told to wait for the scientists to say "Yeah, it hit." But then we started getting pictures back of a glow from the comet, so we all got excited anyway. I happened to be on the stairs going from the navigation area down to the science area, so I missed it. When I got down there everybody was cheering and jumping up and down and hugging each other. The glow from the impact lasted for several hours, and nearly every telescope in the world was trained on Tempel 1 for the event.

Even with the unfocused HRI, we got back 97 percent of the pictures that we wanted. The MRI covered about 25 percent of the nucleus. And the high-resolution images weren't garbage: they were deconvolved later and yielded coverage of 30 percent of the nucleus at a resolution of less than 10 meters per pixel. These images show the comet's surface materials vary quite a lot, and that geologic processes refined the comet during its 4.5-billion-year history. Unfortunately, the debris from the impact cloud obscured the crater, but a proposed second mission to Tempel 1 could take pictures of it.

Sky and Telescope couldn't resist the inevitable pun, "A smashing success." Deep Impact released 19 gigajoules of kinetic energy, which sounds like a lot, but it did not change the course of the comet. It did give us some of the science we wanted—the comet's local gravitational field and the average density of its nucleus, 600 kilograms per cubic meter, were estimated from the ejecta. Spectra from the debris cloud, which reached about 500 meters above the comet's surface, showed water, methanol, methane, methyl cyanide, carbon monoxide, carbon dioxide, and formaldehyde.

The mother ship's trajectory will now bring it back to Earth, where a gravity assist will send it off to another comet. As for the impactor, well, as one of our spacecraft operators put in the log, "On eBay: One impactor, used only once. Some assembly required." □

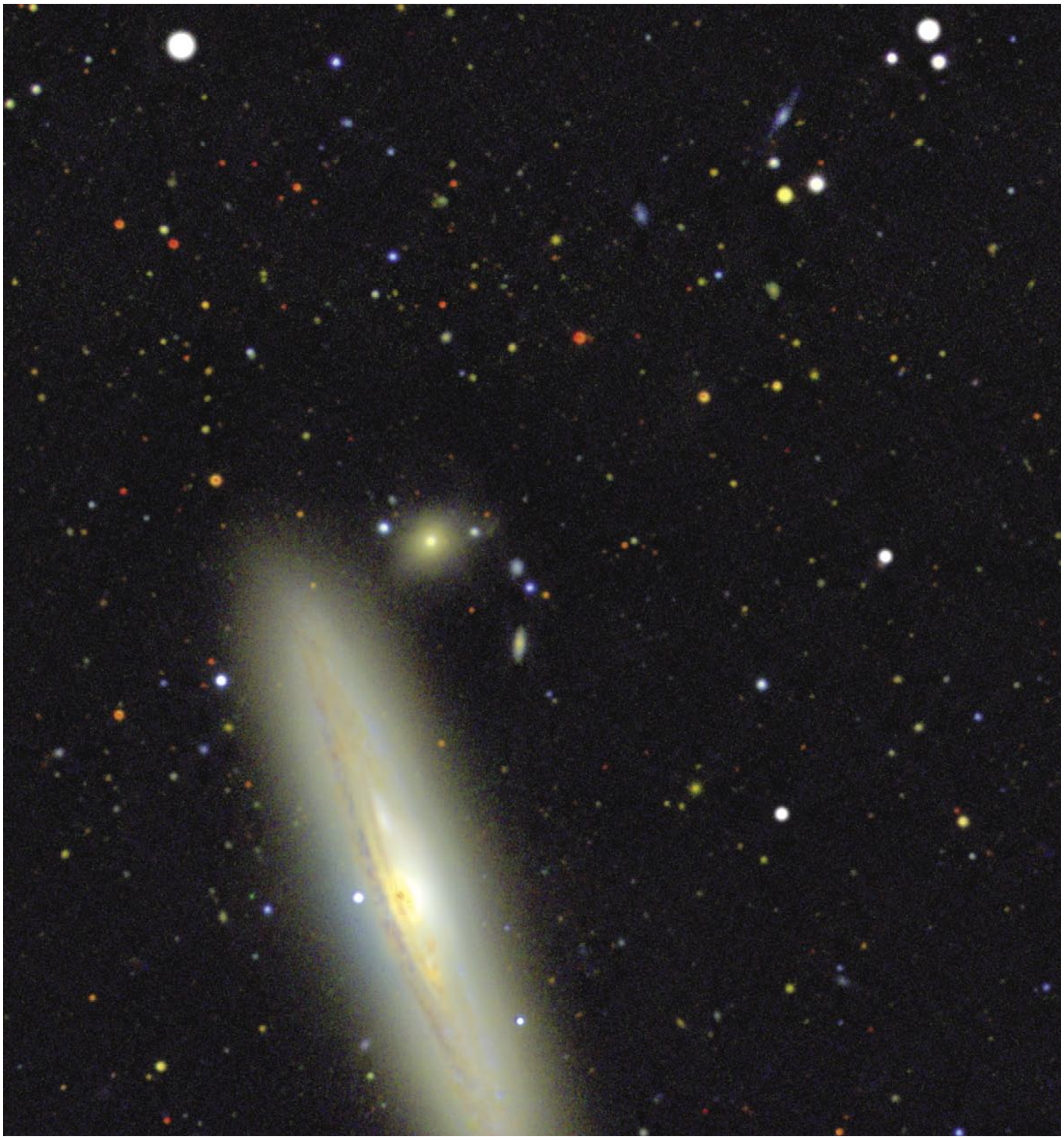
Bill Owen is a principal member of the technical staff at the Jet Propulsion Laboratory, and he was the principal engineer of the Optical Navigation Group for Deep Impact. He also served a short stint as principal navigator for Deep Impact, in July 2005. He got his bachelor's in astronomy at Caltech in 1976, and after spending a year as a church organist he joined the JPL staff. He worked there until 1986, when he took a leave of absence to get his doctorate in astronomy at the University of Florida. His JPL goodbye picnic was cancelled when an armed robber hid out at the lab and all employees were evacuated. He returned to JPL nonetheless, and was working there again when he finished his PhD in 1990. Among his recent activities, Owen was on the search for the incommunicado Mars Global Surveyor (see Random Walk, p. 7).

This article was adapted by Elisabeth Nadin from Owen's Seminar Day talk last May.

PICTURE CREDITS: 10–11, 16 — NASA/U. of Maryland; 10 — Karen Meech, U. of Hawaii; 12 — Doug Cummings; 14, 15 — Ball Aerospace; 17 —Raymond Frauenholz, JPL

Picture This

by Douglas L. Smith



On a hilltop near the Hollywood sign stands Griffith Observatory, which director Ed Krupp calls "the hood ornament of Los Angeles." The property of the city's Department of Recreation and Parks, this art-deco masterpiece has Caltech all over it—the building is significantly derived from drawings by Russell Porter, a Caltech staff member who also helped design the telescopes, buildings, and grounds at Palomar Observatory. Now it has Caltech all under it as well, in the form of a 152-foot-wide, 20-foot-tall astronomical image—the largest ever made—called, appropriately enough, the Big Picture. Take the elevator down to the mezzanine of the cavernous new Gunther Depths of Space exhibit hall, and there before you is the heart of the Virgo cluster of galaxies as seen by Palomar's 48-inch Samuel Oschin Telescope. Printed at the limit of the telescope's resolution, this panorama fills the hall's opposite wall; as seen in the night sky, holding your index finger horizontally a foot in front of your face would cover it—a point driven home by a life-sized bronze Einstein doing just that. Put another way, it's about four times taller and 30 times wider than the full moon.

The mural includes objects down to about 23rd magnitude. Unlike earthquakes, the higher the astronomical magnitude, the dimmer the star. Says Professor of Astronomy S. George Djorgovski, "The human eye sees to sixth magnitude, so this is on the order of six million times fainter than somebody with perfect vision would see at a perfectly dark site on a perfect night. And it's infinitely fainter than an average person would see on an average night in Pasadena. On the other hand, the Hubble Space Telescope can see down to maybe 29th magnitude, which is about 250 times fainter than that." Dotting the wall are some half-million stars from our own galaxy; nearly a million other galaxies, most of which are barely perceptible blobs; a thousand or so quasars; hundreds of asteroids; and at least one comet. "Essentially every little speck bigger than a single pixel is a real object. They range from a hundred million miles away—solar-system stuff passing nearby—back almost to the beginning of time itself. A few light-minutes to 12 billion light-years."

That's the mind-boggling part. The eye-popping part is the couple hundred nice, big, photogenic galaxies—several of them are more than a foot across, and the giant elliptical M 87 is four feet wide—rendered in lush, loving, *National Geographic* color on three rows of 38 porcelain enamel panels.

The Depths of Space exhibit is part of a nearly five year, $93 million renovation of the most visited public observatory in the United States. Because of the building's landmark appearance, the 40,000 square feet of new exhibit space, obligatory gift shop, and a Wolfgang Puck eatery (named the Café at the End of the Universe) had to go underground. Says Mark Pine, Griffith Observatory's deputy director and the program manager for the exhibit program, "I think it's cool that, in a building, underneath the lawn, people can look at something through a telescope. They're looking at a representation of the sky from 65 feet away." Several small telescopes, about as powerful as the coin-op binoculars you find in national parks, look out at the Big Picture from the mezzanine rail. Some are aimed at particular points of interest, while others swivel freely so that visitors can explore the wall for themselves. Descending from the mezzanine to the exhibit floor, anybody wanting a closer look can walk right up and touch the sky, as it were. Which is a big part of the reason why porcelain instead of the more traditional paper or posterboard was the medium of choice—nose- and fingerprints wipe right off.

"It's not an artwork," says Pine, "and it's not intended to be beautiful, even though it is both. It is an accurate rendition of scientific data." "It was very important to them to have a real data set and not an artist's impression," says Djorgovski. "They wanted a single, continuous, digital sky

Opposite: The Big Picture at Griffith Observatory includes the edge-on spiral galaxy NGC 4216, seen here at one-quarter of the size that it appears on the wall.

The Samuel Oschin Telescope at Caltech's Palomar Observatory took the Big Picture over 20 nights in "drift scan mode," with the telescope locked down and the sky wheeling overhead.

image from *real data*. And it didn't take them very long to figure out that Sky Surveys 'R' Us, and so they came to us." Says Pine, "Our exhibit designers, C&G Partners, formulated the idea of the Big Picture as a way of creating an immersive experience. Our premise was to have monumental things. We didn't want to give people the same experience that they could have sitting in front of their computer."

Krupp and Djorgovski quickly chose the Virgo cluster "because it is the nearest major cluster of galaxies," says Pine. "It's our immediate neighborhood, in the cosmic sense. It's both spectacular and relevant." Says Djorgovski, "We wanted Markarian's Chain of galaxies to be the centerpiece, to quickly draw your attention. And M 87, with its black hole and the jet of matter coming from it, we positioned at child's-eye level."

This tiny piece of celestial real estate covers roughly 100,000 times the acreage of the Hubble

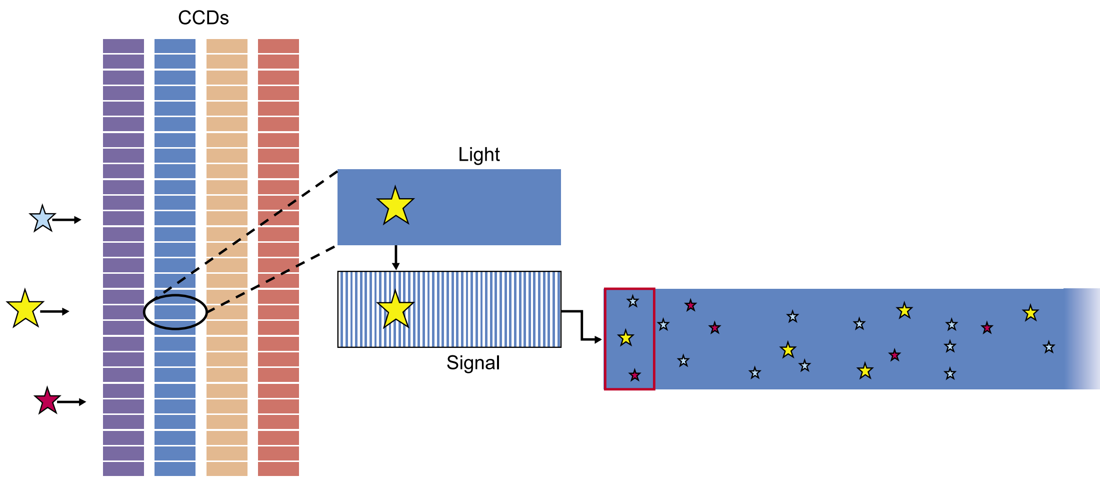
Printed at the limit of the telescope's resolution, this panorama fills the hall's opposite wall; as seen in the night sky, holding your index finger horizontally a foot in front of your face would cover it—a point driven home by a life-sized bronze Einstein doing just that.

Space Telescope's famous Deep Field image, which contains some 3,000 galaxies going out to 12.7 billion light-years. Says Djorgovski, "The big guns like Hubble or Keck have a very narrow field of view, and they bore really deep. A panoramic sky survey is more like a census, just to see what's out there." The two types of imaging work hand-in-glove—astronomers sift through the survey data to select interesting objects or places for a closer look. At survey depths, the Deep Field is an apparently blank patch of sky, so the idea was to look as far back as possible to see what might be seen—a census in time rather than area.

Sky Surveys 'R' Us

Palomar Observatory got into the sky-survey business in 1936, when Associate Professor of Theoretical Physics Fritz Zwicky began scanning the sky for supernovas with an 18-inch Schmidt telescope. The newly invented Schmidt design was a radical one that emphasized breadth, rather than depth, of field—a wide-angle lens instead of a telephoto. The 18-incher revealed whole classes of new objects, including dwarf galaxies, and a staggering number of galactic clusters—one of the first strong pieces of evidence that the universe is "lumpy," in a cosmic sense. It became obvious that a complete inventory of everything as far as a decent-sized telescope could see would be an invaluable astronomical tool, and George Ellery Hale extracted $450,000 from the Rockefeller Foundation to build a 48-inch Schmidt—the largest of its type in the world at the time—to go along with the $6 million they had already given to build the 200-inch telescope that now bears his name. With a field of view nearly three thousand times that of the Hale, said an *E&S* article in June 1948, "this then places the Schmidt in the position of acting more or less as a 'scout' for the 200-inch—a sort of astronomical bird dog."

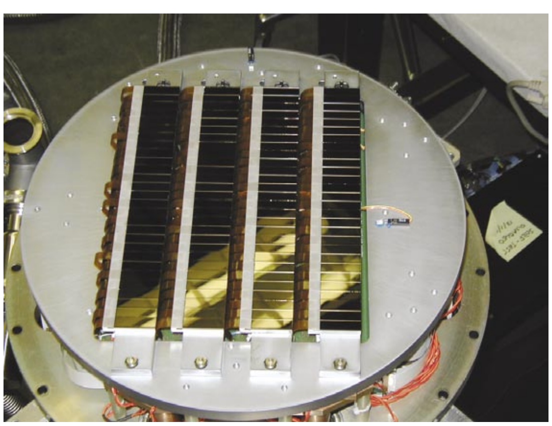
The first Palomar Observatory Sky Survey, later known as POSS I, began in 1949. By the time it wound down in the late 1950s, POSS I had covered nearly two-thirds of the celestial sphere and included everything down to about 20th magnitude. Says Djorgovski, "It had a tremendous impact. There had been other surveys, of sorts, but there was no detailed, extensive, widely available sky atlas reaching out to such a depth before. It was as if you were to publish a comprehensive road atlas of the United States for the first time. It was



In a drift scan, stars and galaxies drift across the four columns of CCDs, each with a different-colored filter. The computer reads the signal off each CCD at the rate of forward travel. The result is a long, thin image that Djorgovski calls "fettuccini on the sky."

the road map of northern-hemisphere astronomy for decades."

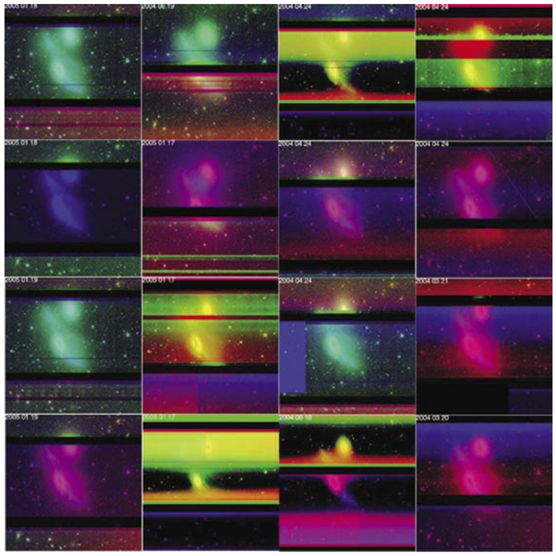
With POSS I completed, the 48-inch was used for several special-purpose surveys, including Zwicky's continuing hunt for supernovas and a survey to catalog guide stars for the Hubble. It was renamed the Samuel Oschin Telescope in 1987, while deep in the middle of POSS II—the world's last major photographic sky survey. POSS II wrapped up in 2000, at the dawn of the digital age. The Charge-Coupled Device (CCD), which now makes cell-phone cameras possible, had been pioneered for astronomical uses at Palomar a quarter of a century earlier. So Caltech's Jet Propulsion Lab, which builds interplanetary explorers for NASA, fitted the Oschin with a state-of-the-art digital camera named "Three-Shooter." "It was simply three CCDs in a row," says Djorgovski. "That wasted most of the focal plane, because you couldn't afford to pave it with detectors." Things have changed—the QUEST (Quasar Equatorial Survey Team) camera currently affixed to the telescope has 112 CCDs in four rows of 28; that's a 161-megapixel camera, if you do the math. The QUEST camera was built by Yale physics professor Charles Baltay's lab, and the Palomar-QUEST Sky Survey, sponsored by the National Science Foundation, gets about 45 percent of the Oschin's observing time. (JPL, which refurbished the telescope and built its computer-controlled pointing and tracking systems, gets 40 percent of the telescope's time for the Near-Earth Asteroid Tracking project; Yale gets 40 percent; and Caltech gets 20 percent—the Yale time and Djorgovski's share of the Caltech time go toward the survey.) If POSS I was a road atlas, Palomar-QUEST is the GPS in your SUV.



Yale's QUEST camera was among the largest astronomical CCD cameras in the world when it was built.

Recalls Roy Williams (PhD '83), a member of the professional staff at Caltech's Center for Advanced Computing Research (CACR), which does all the data processing for the Palomar-QUEST survey at Caltech, "Griffith Observatory called and said, 'we want to make this huge great image,' and George said 'We can do that with Palomar-QUEST.' I would have assumed that they would have used one of the old photographic surveys. You could make a fabulous job of that. But George had confidence." Trouble was, the QUEST survey had been designed to catalog sources, not make pretty pictures of them. The survey had been going for about a year and a half, and had already logged several terabytes of data. While the astronomers had agreed that it would be nice to have visuals at some point, "images were too computationally intensive," says grad student Milan Bogosavljevic, "because we pass across each piece of the sky so many times."

The data-reduction software had been designed to perform a sequence of operations. It scanned each camera frame, removed the various instrumental artifacts, and masked out any bad regions; extracted all the sources and measured their properties, such as brightness, size, and shape, which would help sort them into galaxies, quasars, and so forth later; determined their coordinates; entered them into a database; and cross-matched them against anything previously seen at those coordi-



Sixteen raw scans (left) from 16 different observations of the interacting galaxy pair NGC 4435 and NGC 4438. Says Williams, "The stately galaxies [below left] are what comes out of data cleaning and coaddition. The software is what converts the pigs' ears into the silk purse."

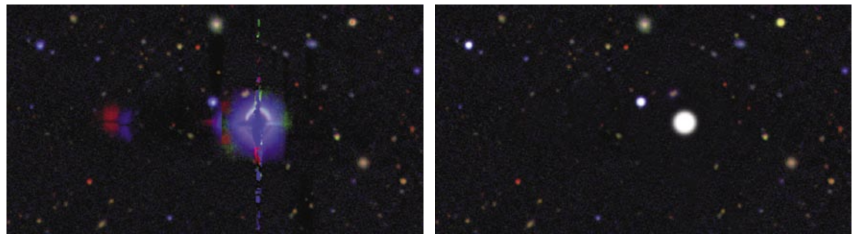
nates. Says Bogosavljevic, "We were still feeling out how to deal with this huge amount of data ourselves. We were forced to speed up the development of tools to find our way around our own data, because for this job we had to access it in a different manner." Until then, the frames had been logged sequentially in order of exposure, so postdoc Ashish Mahabal (now a staff scientist) created a sorting database organized by celestial coordinates.

The Cosmic Beauty Pageant

The Big Picture concept meetings were in early 2001, but it was July 2004 by the time the money had been raised and the contracts to build the exhibits were let. In the meantime, a new kid had arrived on the block—the Sloan Digital Sky Survey, which uses a 98-inch telescope with a 120-megapixel camera on Apache Point, New Mexico. So Pine emceed a beauty contest—both teams were asked to prepare four-foot-square renderings of M 87 and NGC 4216, the aforementioned elliptical and an edge-on spiral galaxy respectively. Both have a large brightness range, and each is a distinct color. M 87, being made mostly of mature stars, is yellowish-red, while NGC 4216 is ablaze with the blue light of hot, young stars. The teams had a couple of weeks of frantic data processing to put their best shot forward, and in a blind judging—perhaps not the mot juste for this very visual competition—a panel consisting of half a dozen people, including exhibit scientist Bruce Bohannan, an astronomer recently retired from the Kitt Peak National Observatory; Krupp (who has a PhD in astronomy from UCLA); and Mathew Malkan (PhD '83), an astronomy professor at UCLA, chose Caltech's pictures. Says Pine, "The Sloan data set is a fantastic data set. So it's not like we chose the good one and didn't choose the other one. We had the luxury of choosing between two great data sets."

"Frantic" really doesn't do justice to the effort that went into the renderings. Says Djorgovski, "It's actually much more demanding to produce a pretty picture than a scientific data set. Our programs recognize bad pixels and simply don't use them." For one thing, because the camera was designed to soak up every available photon, any bright star in the field of view saturated the CCDs. This spilled over into the adjoining pixels, leaving trails across the image. Says Williams, "When you're looking for faint sources, you don't care about the bleed trails. The bright stars are just pollution." But here's where CCDs beat the socks off of photographic plates—you can, with clever software, merge any number of frames into one image. So the gaps were filled with data from other scans of the same region. Says Williams, "By carefully removing the bad areas and saving all the saveable areas, it's possible to get the best of all the scans, rather than the worst of everything. If you add fifteen good images and one bad one, you end

Once the software has done its best, human eyes finish the job. Below left is a bright star and the artifacts caused by its internal reflections within the telescope's optical train. Below right is the same star after Maxfield's ministrations in Photoshop.



up with a bad image."

So much for the technological end. The human eye reigned in the all-important issue of color. The QUEST camera has four filters—near-ultraviolet, which honeybees can see but we can't; blue; "near red," which is a sort of orangey-red, and "far red," which is actually in the near-infrared, just beyond our vision. So to approximate a space tourist's view using the standard red-green-blue format of computer monitors, the ultraviolet data was ignored, the blue remained blue, the near-red stood in for green, and the far-red was nudged back a bit to our red. Says Williams, "It's an *exaggerated* color. But it is the *right* color, if that means anything. I was doing quite a bit of the colorizing, and I remember George saying to me once, 'Just remember, there are no green stars.' If you get the balance wrong, you output green stars, and you have to go back and try again."

The final touch-ups were made in Photoshop by Leslie Maxfield (BS '95), who works at Caltech's Digital Media Center and also happens to be Djorgovski's wife. She went through the images pixel by pixel and removed any remaining bleed trails, all the airplane lights that were too dim to be caught by the processing software, and internal camera reflections, which look sort of like those trails of bright circles emanating from the sun that you see in vacation snapshots. She also checked the alignments. "In some of the early versions I'd see little cloverleaf stars here and there," she says. "They'd have a red lobe, a blue lobe, and a green one. So I'd have to go back and tell them, 'Hey, the astrometry's not right. You'd better run that one again." She also did the final color corrections, and the Digital Media Center printed the posters.

The raw data is unprepossessing—bright blobs intermixed with lights from passing airplanes, bleed trails, camera noise, and the occasional cosmic-ray hit.

Adrift in a Sea of Pixels

Having gotten the nod by combining some eight exposures each of a couple of galaxies, the team looked at the Virgo cluster in earnest over a span of 20 nights between March 2004 and April 2005. This produced an average of a dozen or so passes over every pixel of the Big Picture. The raw data is unprepossessing—bright blobs intermixed with bleed trails, camera noise, lights from passing airplanes, and the occasional cosmic-ray hit. Streaks of all persuasions are removed by a computer running a "median filter," which removes things with sharp edges. Now the slight blurring caused by the atmosphere for once becomes an asset, because even bright stars have fuzzy boundaries. So the filter takes small groups of adjacent pixels, finds their median brightness, and rejects all the pixels in the group that are considerably brighter or dimmer than that median value. "We had an average of about 16 passes over this huge area of sky, about 200 gigabytes of pixels, and we had to do this to every pixel," says Bogosavljevic. "Normally you don't have to process such an amount of data in such detail. If you had one image you could do it on your own PC just fine. If you have a million, it's a problem."

But the biggest challenge was even more basic. Photographic sky surveys are "point-and-stare"—you aim the telescope at a certain spot, and as the earth rotates the telescope tracks its target's westward progress. This slow, methodical approach eventually allows you to tile the heavens in a mosaic of overlapping plates within which the position of every pinprick of light is precisely known. But in order to see as much of the sky as you can as quickly as possible, the Palomar-QUEST and Sloan

Comet P/Tsuchinshan as seen on two successive nights—once as a pair of fuzzballs directly above this caption, and again as a similar pair of fuzzballs below and to the left of the galaxies on the opposite page—again, at one-quarter the size of the Big Picture.

surveys operate in "drift-scan mode," in which the telescope is locked down as the sky wheels overhead. The QUEST camera is oriented so that its columns of four CCDs, each with a different color filter, are parallel to the direction of drift, and in the space of about 15 minutes the photons from a single star march from one edge of the array to the other. Over the course of a night's observing, a ribbon-like image emerges that Djorgovski calls "fettuccini on the sky."

The computations to bundle the pixels back into their stationary sources are reasonably straightforward, but try to wallpaper the celestial dome, and you'll quickly discover that the strips are warped. Earth plows along in its orbit, and incoming photons change their angles ever so slightly from each strip's beginning to its end. This is called "differential aberration," says Djorgovski, who compares it to driving a car in the rain—the drops look like they're coming toward you. "We know how to account for it, but we have to do it in a way that we normally don't bother with for pictures of small pieces of sky." When you're creating a catalog, all you have to do to move the stars back into their proper positions is tweak their coordinates. But to make the Big Picture, all the pixels had to be scrunched up and over, as it were, one hair's breadth at a time along each ribbon's length.

The final alignments were double-checked by comparing the astrometry—the measured positions—with a catalog maintained by the United States Navy. In a throwback to the days of sextants and dead reckoning, "the U.S. Naval Observatory has the world's best position catalog, at its depth of field, of the entire sky," says Williams. "They have so many stars that even in a small image you can find 30 that are covered. And since we know approximately where we are to begin with, we can check the astrometry automatically by pattern-recognition software."

But while stars and galaxies are fixed, some things do move. Thus, in the middle row of porcelain panels, near the top of the twelfth one from the left, are two images of Comet P/Tsuchinshan—a fuzzy, predominantly blue ball a few inches away from its equally fuzzy, but mostly green twin, captured in two scans made about an hour and a half apart. (To further complicate the color-balancing problem, you don't necessarily always have every color in every scan.) Then, some three and a half feet farther down to the right, there it is again—another pair of images captured in two passes the following night. Says Djorgovski, "We thought about reassembling the comet, but we said, 'No. This tells a story. This is real data.'" Ditto for the asteroids, which Maxfield called "stoplights" because each one appears as a green, a red, and a blue dot lined up nose to nose.

The computational heavy lifting was done on a cluster of 16 Intel Itanium 2 processors donated to CACR by Hewlett-Packard. Bogosavljevic had created a data-processing "pipeline" for the beauty contest. "I wrote an ugly mixture of several programming languages, stitching together some standard filtering procedures. We had to figure out the best way to make the pictures pretty in the first place, so we were changing the code as we went along." Adds Djorgovski, "Nearly everything we did for the pipeline would have to have been done for the survey in any case. But many of the things we ended up needing we did not anticipate, and some things we thought we would need we decided to give up on, all as a product of the experience gained as we were pushing along."

The code was awkward, and not easily expandable to run on many processors at once, so grad student Ciro Donalek adapted it for supercomputer use. Says Mahabal, "IRAF, which is one of the software packages, can sometimes be a bit moody. If that happens in a large pipeline and you don't know what's going wrong, that's not a good thing." IRAF, which stands for Image Reduction and Analysis Facility, is written in an obscure language called SPP. This is fine if you don't have to tinker with it, and you usually don't—"IRAF covers almost all the standard things you would need in your daily astronomical-image-dealing life," says Bogosavljevic. But IRAF turned dyspeptic when force-fed. If it ran into a picture it couldn't digest, it belched up a cryptic error number and died. "If you want to do something to images number 1 to 30,000, and it dies on image 2,985, it's tedious to keep restarting it saying, 'OK, now run from 2,986 to 30,000,' and then having it die again somewhere else. What you want is a code that will run the 30,000 images and then tell you nicely, 'I could not do 2,985 and 24,576.' For a while, the code was instructed to send an e-mail to all of us every time something would crash. Seems kind of funny, getting an e-mail asking for help from a computer." Donalek wound up writing counterparts for many of IRAF's processes in C, which is the vernacular of high-end computing, and he and Mahabal figured out how to make the pipeline spit out unpalatable images rather than gagging on them.

The team spent six months refining the pipeline. Says Bogosavljevic, "We never ran the entire data set, just a small piece, and we'd see an error and go back. Ciro is a good programmer, and he optimized his codes so it became faster as we went along. But even so, it would have taken a week to run the entire Big Picture data set." Adds Mahabal, "Sometimes an algorithm would do what we wanted it to do, but then we would find out something else that we should also do." "There was a lot of, 'Oh, Ciro's made a new blah-de-blah filter.

Let's run it all again!'" chuckles Williams. "That happened all the time. All the time!" The effort has paid off big time for the survey as a whole. The pipeline now runs three to five times faster than it did originally—fast enough to process the incoming data in real time.

But even with all this computational firepower, the Big Picture's final cleanup still had to be done by hand. "[Observatory director] Ed Krupp decided how big and fuzzy he wanted the foreground stars to be," says Maxfield. "Bright stars are bigger and bleed more, so I had to bring them back to size." Maxfield processed the first half of the Big Picture with Simona Cianciulli, Ciro's wife, working long into the night while Djorgovski watched the kids. "I think I discovered podcasts during that time," she laughs. Then, realizing that they weren't going to make deadline, Maxfield recruited Radica Bogosavljevic, Milan's wife, as well. The trio spent the next six weeks pixel by pixel, panel by panel, making the last cosmetic adjustments and checking the alignments. Galaxies, and even stars, frequently spilled over from one panel onto the adjoining one, and the match had to be flawless in both color and alignment.

Griffith Observatory director Ed Krupp inspects panels depicting the Markarian Chain on the factory floor at Winsor Fireform.

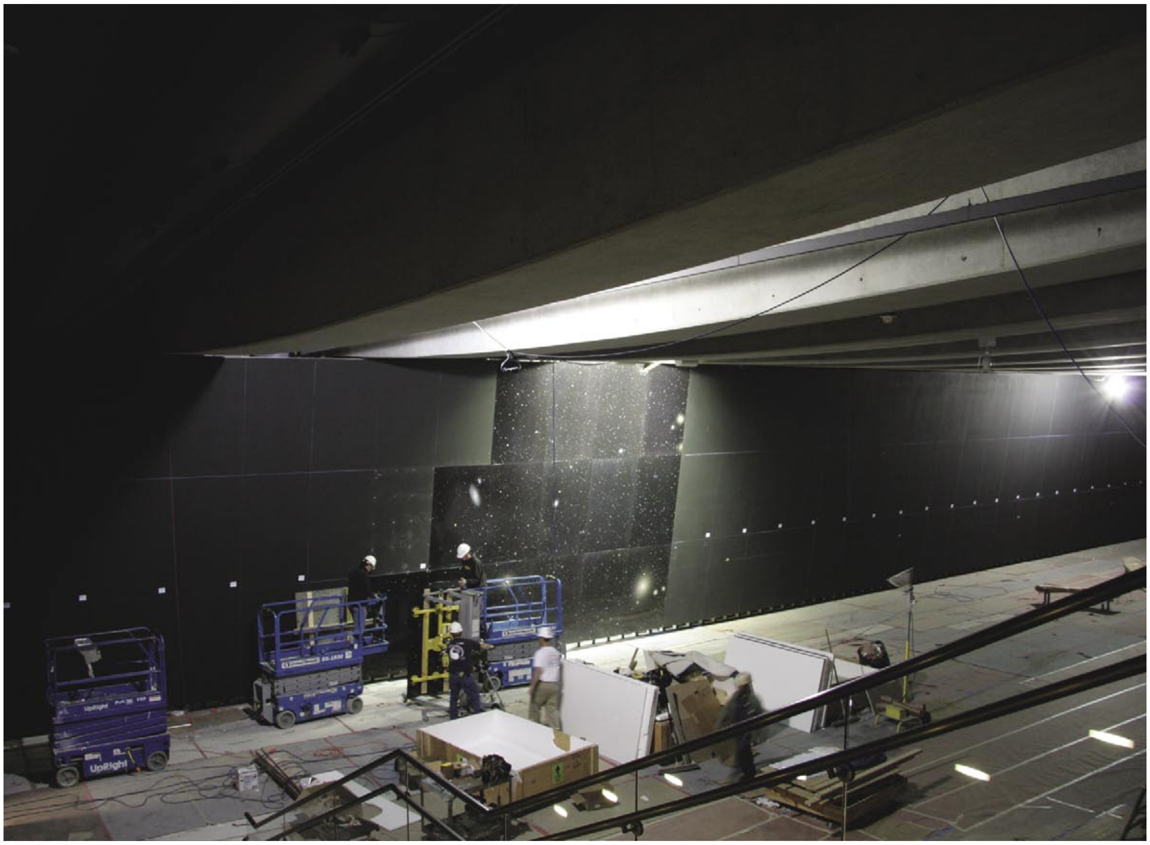
Fire When Ready

All 114 of the six-foot, eight-inch by four-foot panels were manufactured by Winsor Fireform of Tumwater, Washington, whose usual line of work is making somewhat smaller weatherproof signs and public art. If you've been to the White House, the Grand Canyon, Times Square, or any of a number of major metropolitan zoos, you've seen their work; they've also been a prime producer of interpretive displays for the National Park Service for more than two decades.

The production process is conceptually similar to printing the color pictures in this magazine. Each steel-backed panel gets a pure-white porcelain base coat to which are applied successive layers of enamel—pigmented glass, essentially—the mineral equivalents of cyan, magenta, yellow, and black inks. "We have a black base coat we could have used," says Bryan Stockdale, Winsor's president, "but there was so much white all over the image that it just wasn't a good idea. White is such a faint color that we would have had to apply two layers of it, both in perfect dot-on-dot registration with each other."

There may be a lot of white in the image, but there's even more black, and getting the black right was, if you'll pardon the expression, a black art. Among other issues, there's a tradeoff between getting the black of space as black as possible without making faint objects disappear. This was especially true for elliptical galaxies, which are basically giant fuzzballs of stars—bright at the core and fading off into nothingness in all directions. Make the black too black, and these galaxies shrink alarmingly. It took half a year of testing to get it right.

The black had to be absolutely uniform from



The galaxies begin to go up on the wall. M 87 is at lower right, and the spiral galaxy above the worker on the scissors lift is M 90.

panel to panel, because the plan called for the mural's central portion and focal point, Markarian's Chain, to be done first as proof of concept, followed by the left-hand side and then the right. Keeping the colors consistent over a six-month production run was an unprecedented feat, says Stockdale. Besides finding the proper mineral mixes, the length of each firing is calculated based on panel size, the number of firings still to come, and such arcana as the ambient humidity—Tumwater is on the shores of Puget Sound, which may be the rainfall capital of the continental United States. There are seven firings per panel: the "ground coat," which is a sort of primer that adheres to steel, and is basically that off-black substance you see on the underside of enamel sinks; the base coat; the four pigment coats; and a final clear coat to seal everything on and protect the finish. "The first firing is at over 1470 degrees Fahrenheit," says Stockdale, "and each firing after has to be done at a successively lower temperature. You don't want the underlying layers to go molten again, but you still have to melt the layer you're firing. The colors shift—the color you put in is not the color you get out, depending on the dwell time—and our experience tells us how to compensate for that, but you can't actually see the result until after the final firing."

A lot of frequent-flyer miles were logged over the summer of 2005, as test panels were fired and the color balance worked out. Exhibit scientist Bruce Bohannan was the best traveled, winging from the New York exhibit designers to Pasadena to meet with the Caltech and Griffith folks and to Tumwater to consult with Winsor, providing the crucial link between high concept, science, and appearance. The 10 panels featuring much of Markarian's Chain were approved in October 2005, and production began in earnest thereafter. Even so, Bohannan and Camille Lombardo, executive director of Friends Of The Observatory—two pairs of eyes with very different points of view—made regular pilgrimages to the factory to approve every single panel before it was shipped south.

And there were mechanical challenges: the panels had to hang perfectly flat in the kiln, but they expanded by an inch or more in each direction during firing. Drilling holes for hooks was not an option, so special jigs needed to be built to support the panels, a feat complicated by the fact that the porcelain is curved around the edges of the underlying steel to keep it from rusting. Says Pine, "We looked at making flush edges, which would have essentially required them to cut the porcelain and expose the steel. It would have looked more seamless, but it would have compromised durability." Protected as they are, the panels should last hundreds of years.

To top it off, the mural slopes out over its viewers at a 10-degree angle, in order to minimize glare from the ceiling lights. But the porcelain alone

The upper panels were installed using a lift equipped with those suction cups you normally see in bank-heist movies when a plate-glass window needs to be cut.

weighs nearly four tons, which is an awful lot of teacups. "It's not like a normal exhibit," says Pine. "Most exhibits are like refrigerators. You bring them into your home, you unbox them, you plug them in, and boom—welcome to your exhibit. This one not so much. It had to be reviewed by the city's Department of Building and Safety to make sure that it met all code requirements for earthquake safety, fire safety, all those kinds of things." Maltbie, Inc., the exhibit fabricators, had built an angled steel frame, bolted into the cement wall and floor, that supports a wood-and-drywall skin to which each panel is attached by four rows of five two-inch threaded studs and a good slather of industrial-strength adhesive. The studs were welded to the steel backsides of the panels before their first firings, making them "like porcupines," says Stockdale. "They were very hard to move around the shop. And the studs all had to be kept perfectly straight, so they'd line up with the holes in the wood." The company wound up backing the panels with two-and-a-half-inch-thick Styrofoam slabs. These were stacked, club-sandwich-style, in lots of a dozen in heavily reinforced three-quarter-inch plywood crates for the journey south. "You could almost build a condo out of the amount of wood we shipped down there," Stockdale laughs. The panels were trucked south as they were approved, and the last panel went up on the wall on April 26, 2006.

"It was a huge, huge undertaking," says Pine. "No one had ever done anything like this before. There's no reference book to go to and say, 'Hey, how do you build a gigantic porcelain wall?' It's not a miracle though, because miracles are things you can't explain. A lot of people worked very, very, very hard to make this happen." Stockdale agrees. "When you take on a job like this, which is literally one of a kind, you don't know at the start how you're actually going to do some of it. You're dealing with problems you've never had to consider before, even though you've done tens of thousands

The Winsor Fireform crew. Back row, from left: Tony Elhardt, Jon Colt, Avet Waldrop, Chris Heiting, Nelson Dan, Bryan Stockdale, Josh Kessel, Brandle Strand, Jerry Forrester. Front row: Diane Chamberlain, Leslie Tikka (production manager), Tom Rose, Nathan Ereth, Randy McAllister, Rachel McAuley, Patrick Horsfal. Missing: Joan Fulton, Virginia Viehmann.

of panels. You just have to rely on your team to rise to the challenge."

The Big Picture "is a testament to observational astronomy," says Pine. "And I can think of no better place for it than this place, which is oriented to sharing observational astronomy with the public. People don't look up any more. Especially in L.A.. You know, the sky here is something of an endangered species. But if we can get people to walk out of the building, and look up at the night sky, then the observatory has done its job." □—*DS*

PICTURE CREDITS: 23 — Doug Cummings; 20, 23, 24, 25, 26–27, 31 — Palomar-QUEST Survey Team; 22 — Scott Kardel; 28, 31 — Winsor Fireform; 29, 30 — Anthony Cook, Griffith Observatory

Griffith Observatory is open to the public from noon to 10:00 p.m. on Tuesdays through Fridays, and from 10:00 a.m. to 10:00 p.m. on Saturdays and Sundays. Reservations are required. Visit www.GriffithObservatory.org for more information and to make a shuttle reservation. (Tickets are also available at 1-888-695-0888.) There is no parking at the observatory; hikers and cyclists may brave the winding road to it, but the rest of us can catch the shuttle at the L.A. Zoo in Griffith Park or at Orange Court on the west side of the Hollywood and Highland entertainment complex in Hollywood.

More information on the Big Picture, including an interactive tour of it, can be found at bigpicture.caltech.edu. □

The Caltech team (and a couple of ringers) behind the Big Picture. Back row, from left: Simona Cianciulli; Ciro Donalek; CACR staff scientist Matthew Graham, who helped develop the database; Milan Bogosavljevic; CACR staff scientist Andrew Drake, who works on the new pipeline; Radica Bogosavljevic; Leslie Maxfield; Yale grad student Anne Bauer, who helped with the data acquisition; Roy Williams; George Djorgovski; Charles Baltay, whose lab built the camera; and Ashish Mahabal. Missing is Yale research scientist David Rabinowitz, who is best known to *E&S* readers as a codiscoverer of Eris, Sedna, and other dwarf planets in collaboration with Caltech Professor of Planetary Astronomy Mike Brown.

Planetary Exploration in Extremis

By Peter J. Westwick

Excerpted from Into the Black: JPL and the American Space Program, 1976–2004, *by Peter J. Westwick, Yale University Press, 2006. Reproduced by permission.*

Even as the Voyager spacecraft completed their triumphant encounters with Saturn, Professor of Planetary Science Bruce Murray, then the director of the Jet Propulsion Laboratory, was waging a fierce campaign to save Voyager, the rest of the lab's flight projects, and perhaps the lab itself from extinction. The crisis in planetary exploration reached its peak in 1981, but it was germinating when Murray arrived in 1976 and first blossomed the following summer, impelling lab managers and Caltech trustees into the political arena. Paradoxically, the public enthusiasm for solar system exploration was not translating into Congressional support: as NASA's deputy administrator, Hans Mark, said at a National Academy of Sciences colloquium, "[The] problem is that Americans don't vote *on [the] basis of the space science program achievements."*

There were several reasons for this: the slackening of the space race after the Apollo missions to the moon and the emergence of more pressing national priorities; continued contention between the human and robotic space programs, exacerbated by the space shuttle; increasing competition within NASA's space-science program from space-based astronomy [the Hubble Space Telescope had, by the early 1970s, reached the formal design stage] and earth sciences [the first Landsat launch occurred in 1972]; and allocation of priorities within the planetary program, which at times would array parts of JPL against each other.

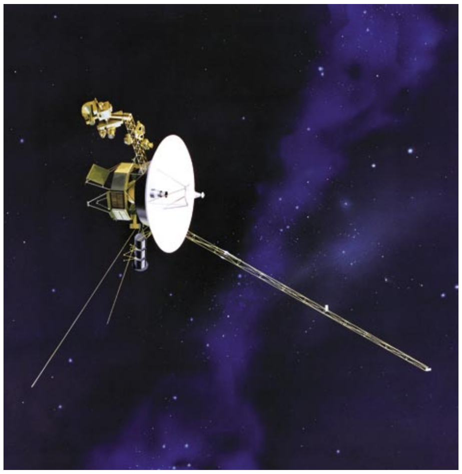
In 1976, NASA commissioned a study of public interest. The study concluded, "The picture of NASA that is in focus is Big Budget, Big Spectaculars and, bottom line, a hundred pounds of moon rocks." NASA was not doing much to dispel the big-budget image. In 1972 President Nixon had approved the space shuttle program. To win approval, NASA had cut its cost estimates to $5 billion and inflated the projected number of launches to sixty per year. Both proved unrealistic. By the time the first shuttle flew in 1982, four years after the expected initial launch date, the program had doubled in cost and could deliver only about six flights in its first two years of operation. In the meantime, to ensure customers for the shuttle NASA had stopped buying expendible rockets, leaving planetary missions with no ride into space.

http://www.jpl.nasa.gov

Bruce C. Murray, professor of planetary science and geology, emeritus, was director of the Jet Propulsion Lab from 1976 to 1982, succeeding William Pickering, who had served since 1954.

Purple Pigeons and Gray Mice: Or, How to Fill a Bathtub

The decline of the planetary program manifested itself at JPL first in the projected rampdown from Viking and Voyager. The Viking workforce dropped off sharply from more than 400 staff in 1975 to almost zero by 1977; Voyager would undergo a similar decline starting in 1977. The lab expected to ramp back up for the Jupiter orbiter-probe and a possible lunar orbiter starting in 1978, but that left a deep two-year dip in the graph of



Right: Voyagers 1 and 2 were launched in 1977. Far right: The boulder-strewn vastness of Mars's Utopia Planitia reaches to the horizon nearly two miles from Viking 2, which, with its twin Viking 1, made the first successful landings on the red planet in 1976 after three unsuccessful Soviet attempts.

http://photojournal.jpl.nasa.gov

staff levels. Even if the Jupiter or moon missions were approved for 1978, the lab would have to lay off staff; if neither project were approved that year, perhaps 500 JPL employees and a similar number of contractor staff at JPL would lose their jobs.

The lack of new missions for 1977 and 1978 became known as the "bathtub," after the U-shaped bend in the workforce charts. The staffing shortfall had long-term implications. Experienced engineers were not easily replaced; despite the documentation of systems engineering, lab staff viewed their expertise as a form of tacit knowledge. Murray wrote to NASA's space science manager that "no amount of documentation or procedural manuals can enable

Murray dubbed the collective of missions the "purple pigeons." The name addressed perceptions of a lack of pizzazz at NASA, with the colorful pigeons replacing the "gray mice" generated by the current planning process.

inexperienced engineers to by-pass entirely the many subtle opportunities for potentially serious, even catastrophic mistakes. The knowledge and understanding now embodied in our staff was painfully acquired in the l960s and has been maintained by the subsequent continuity of project activities." The argument that JPL's expertise was a national resource meriting upkeep by the federal government would become a recurring theme.

JPL managers would seek to fill the bathtub in part with non-NASA work, especially in energy and then defense, but they also sought to keep planetary missions flowing. One of Murray's first acts as director in April 1976 was to assemble a team to come up with imaginative new missions. The group spent three months brainstorming and arrived at a list of seven candidates: Mars rovers; a Venus radar orbiter; a tour of Jupiter's inner moons with a landing on Ganymede; an orbiter to Saturn with a lander on Titan; a flyby of several asteroids; an unmanned station on the moon's south pole; and development of a "solar sail," which would use solar radiation pressure to propel a mission to Halley's comet.

Murray dubbed the collective of missions the "purple pigeons." The name addressed perceptions of a lack of pizzazz at NASA, with the colorful pigeons replacing the "gray mice" generated by the current planning process. Murray intended the pigeons to combine "first-rate science . . . with broad popular appeal"; the popular aspect, he noted, was required to generate and sustain political support for the several years from project approval to launch. The purple pigeons coincided with the Viking encounter and aimed to capitalize on the media presence; when journalists asked what was next for the planetary program, Murray and the JPL public affairs people pushed the pigeons. The colorful pigeons caught the media's eye, and NASA soon approved supplemental funds for the solar sail and Mars missions and added other pigeons to its long-range plans. By the end of 1976 Murray concluded that "the outlook is more encouraging now than for some time."

The lab meanwhile was awaiting formal approval of the Jupiter Orbiter-Probe (JOP) as a 1978 new start. With support from scientists, NASA, and OMB, approval seemed likely. But on 4 May 1977, the House appropriations subcommittee responsible for NASA's budget deleted all funds for the project. The chair of the committee, Rep. Edward Boland, had consistently pressed NASA to prioritize, and he now correctly judged the space telescope a higher priority for NASA and the Space Science Board. After the Senate appropriations subcommittee approved the Jupiter mission, and a House-Senate conference committee failed to resolve the impasse, the matter returned to the House for a special vote.

In the week before the vote, Murray mobilized the lab to defeat Boland. The campaign recruited the California congressional delegation, the House and Senate science committees, planetary scientists, sympathetic media outlets, and the sci-fi community, including thousands of *Star Trek* fans convening for their annual convention. On July 19 the House engaged in a dramatic floor debate over the Jupiter proposal. Boland and members of his committee stressed that they did not oppose NASA's mission or even the value of this specific project, bur rather felt compelled to impose some discipline on NASA and space scientists. A succession of congressmen rose to defend the project and the overall deep-space program. Aside from scattered references to technological spin-offs and international prestige and cooperation, their justifications appealed mainly to the goal of space exploration, the importance of the science results and their relevance to terrestrial climate research, and the need to sustain the expertise at JPL. The time allotted for debate expired, and Boland called for a quorum. The final tally produced a sweeping victory for JPL: 280 supporting the Jupiter Orbiter-Probe to 131 opposed, with 22 abstentions.

The possible loss of JPL's next major flight project was "a rude awakening" to lab staff. The planetary program did appear to settle down after the flurry of activity to save the Jupiter mission, which was soon renamed Galileo. But while Galileo sparked the recovery, its early development foreshadowed future trials. With no expendible rockets in NASA's inventory, Galileo was at the mercy of the shuttle schedule. JPL wanted to launch in January 1982 to take advantage of a gravity-assist trajectory past Mars to Jupiter. By 1979, however, it was apparent that the available shuttle at that time would be overweight and underpowered, and hence unable to lift the 30-ton Galileo spacecraft (a 2.5-ton spacecraft plus booster and support equipment). To meet the launch date, NASA asked JPL to split the spacecraft in two and launch the orbiter and probe separately. But that plan required the purchase of an additional transfer stage at \$100 million, almost one-fourth the total project cost at that point. More important, a split launch required two shuttles—and NASA would not have two by 1982. So Galileo was postponed until 1984, when a second shuttle would be available, with the delay inflating the cost increase to \$225 million. The saga of Galileo would not end there.


http://grin.hq.nasa.gov

The first Space Shuttle mission, STS-1, was launched on April 12, 1981. *Columbia*, piloted by Robert Crippen and commanded by John Young, spent 54 hours in orbit and traveled more than a million miles before the test flight ended at Edwards Air Force Base in California.

The delays and overruns in the shuttle program heralded an impending crisis. As the new decade dawned, *Science* magazine was reporting that planetary science was "on the brink again." The newfound pessimism stemmed from a lack of new starts. Lab managers had planned for a lunar orbiter, Venus radar orbiter, Halley's comet rendezvous, and Mars sample return, but none of these won approval through 1981. In 1978 NASA and JPL did win approval for the International Solar Polar Mission (ISPM), which would send two spacecraft, one American and one European, over opposite poles of the sun to map solar radiation out of the ecliptic plane for the first time. But the ISPM spacecraft would be built by industrial contractors and would thus engage only a few dozen staff at JPL, and in 1980 it had its budget halved, forcing a two-year delay in the launch.

Some of the crisis was self-inflicted. JPL mission planners presented congressional critics with fat targets, evident especially in Mars mission planning. Viking had revealed a Martian environment chemically hostile to life, suggesting that any life on Mars would have to be concentrated in remote oases or buried underground; hence scientists sought either rovers or penetrators. JPL quickly drew up plans in early 1977 for two missions to Mars in the 1980s, an orbiter/rover to launch in 1984, and a sample return to launch in 1988. The first soon evolved into a proposal for a 400-kilogram rover capable of ranging 100 kilometers; the cost reached \$1.4 billion—and NASA cost reviewers thought JPL had low-balled the figures to win approval.

Even after the threat to Galileo in 1977, Mars planners had continued to disdain a lower-cost polar orbiter, on the theory that several smaller projects would be harder to sell than one big one. Although a few planetary scientists argued for an incrementalist approach, the majority soon abandoned plans for the billion-dollar rover in favor of a sample return that would cost twice as much; by contrast, the Jupiter proposal targeted by Boland was for $410 million. The rallying cry of "sample return or nothing," although based on a political calculation, again suggests a lack of political acumen among JPL managers and planetary scientists, who failed to recognize the prevailing political winds and instead indulged what one NASA manager called "delusions of grandeur."

A tendency toward cost growth of JPL projects did not encourage political support. Galileo quickly ran into cost overruns, which also afflicted the Venus Orbital Imaging Radar (VOIR). Initial studies of a Venus radar orbiter began at JPL in 1971 and received a boost from the purple pigeons. By 1979 the lab had developed a formal proposal for VOIR, to launch in 1984. Its main instrument was a synthetic aperture radar, to penetrate the clouds of Venus and compare its hothouse environment to the frigid desert of Mars and Earth's more hospitable climate. NASA managers, however, expressed concern "about the high cost of this mission"—$400 million—and asked JPL to find ways to reduce it. By 1981 cost estimates had far surpassed the levels that had alarmed NASA and now approached $700 million.

http://nssdc.gsfc.nasa.gov

The Magellan spacecraft—seen here as it was released from the space shuttle *Atlantis*'s payload bay in 1989—was a downscaled version of VOIR.

The persistent effort to win a mission to Halley's comet would become the most visible victim of the planetary decline.

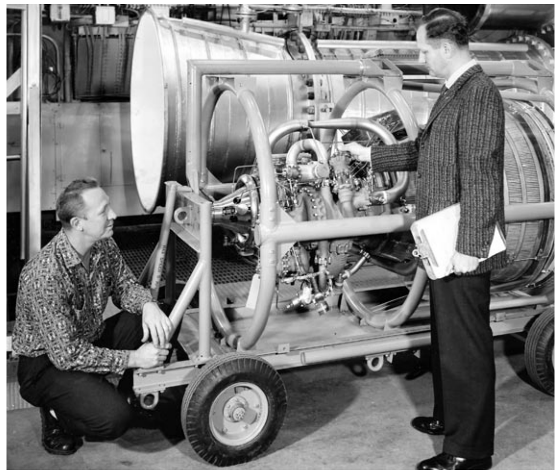
VOIR also encountered competition from other JPL proposals. Although NASA's "roles and missions" review had removed Ames and Langley from the planetary program, that just displaced competition to within JPL, where champions of particular projects squared off. VOIR planners in particular jockeyed against a Halley mission. Halley's orbital period of 76 years was due to return the comet to the inner solar system in the mid-1980s, and JPL in the mid-1970s began planning to take advantage of this once-in-a-lifetime chance. Halley met Murray's mandate that missions combine popular and scientific interest: its periodic and very visible appearance had attracted public attention throughout recorded history; and in the early 1970s space scientists had identified comets as a prime desideratum for inspection because they could provide clues to the initial constitution of the solar system. Halley's retrograde and highly eccentric orbit and high velocity, however, put it out of reach of conventional chemical propulsion. NASA and JPL managers then shot down a purple pigeon, the proposal to fly a solar sail to Halley, and an alternative proposal using solar-electric propulsion, also known as ion drive, saw its cost estimates balloon to $200 to $300 million. By 1979 JPL still had no Halley mission.

The persistent effort to win a mission to Halley's comet would become the most visible victim of the planetary decline. Murray meanwhile tried to regenerate the excitement of the purple pigeons, by convening another study group in 1979 to study "far-out" ideas for deep-space missions twenty to forty years in the future. Replicating the purple pigeons might have seemed a dubious exercise in retrospect: four years after the pigeons first flew, none of them had come to roost in approved flight projects. Beset by annual battles to save existing missions, NASA managers had little inclination to ponder the possibilities for forty years in the future. Any interest they might have had was definitely dispelled by a redoubled assault on the deep-space program.

Black September

The crisis in planetary exploration came to a head in 1981. If Murray spoke of low morale and soul-searching at JPL in October 1980, the effects of the presidential election the next month would not help. Ronald Reagan had campaigned on a platform of fiscal austerity, except for national

The Centaur upper-stage rocket was developed in the 1960s at the Propulsion Systems Laboratory at Lewis Research Center, now John H. Glenn Research Center. An ambitious design using liquid oxygen and liquid hydrogen—the first to use hydrogen as a fuel—it underwent a difficult development period before becoming a workhorse that launched hundreds of NASA, commercial, and military payloads.



http://grin.hq.nasa.gov

security, and upon inauguration he immediately set about implementing it. In February 1981 Reagan's OMB not only cancelled VOIR, but it also required NASA to cancel either the space telescope, Galileo, or the solar-polar mission, even though each was years into development. NASA elected to kill the solar-polar mission, an unprecedented cancellation of a well-established project that also involved international cooperation.

The budget actions led Murray to paint a bleak picture to Congress: "Frankly, . . . the U.S. deep space program is in deep jeopardy and even may face extinction." Although spared the budget ax, Galileo now faced additional delays, again owing to the launch vehicle. The problem now concerned the so-called Inertial Upper Stage (IUS), a new solid-fuel rocket that would boost the spacecraft from the shuttle's orbit. In 1979, even as NASA decided on the split-launch configuration, problems with IUS performance required JPL to design new gravity-assist trajectories to reach Jupiter, and also spurred Representative Boland to press NASA to use the well-tested, liquid-fuel Centaur instead of the problematic IUS. The more-powerful Centaur allowed a return to the original single-launch configuration of the Galileo orbiter and probe together, at the cost of a one-year delay in the launch, to 1985. JPL thus embraced the plan, and NASA committed to the Centaur in January 1981. The decision, however, made Galileo dependent on a redesign of the Centaur, with its own technical and political hurdles; and the additional delay—eventually to 1986—would have important consequences. And Galileo engineers returned yet again to the drawing board to reintegrate the spacecraft and plot a new trajectory.

The Halley mission meanwhile was undergoing its own parallel odyssey. After the demise of the Halley plans of 1979, JPL the next year proposed a low-cost Halley Intercept Mission (HIM), with "low cost" soon defined as about $300 million. But comet scientists had earlier stated their distaste for a simple flyby, and NASA noted as well that the European Giotto mission to Halley would accomplish many of the same objectives. Like the Grand Tour in 1971, the Halley intercept suffered from a lack of advocacy within NASA, the agency that is supposed to back space projects, despite indications of support from OMB, usually the enforcer of austerity. A Halley mission became Murray's personal hobbyhorse, and he made a determined push to procure it. Why did he perceive a Halley mission as so crucial? Since the 1960s JPL was accustomed to having two major flight projects in development, with one expanding while the predecessor ramped down. But after Viking and Voyager the lab had only one team, Galileo, at full strength. VOIR could provide only a partial stopgap, since it would be built by industrial contractors; a Halley spacecraft promised to employ perhaps three times as many staff as VOIR. Along with institutional considerations, Murray personally viewed Halley as a unique chance to combine bold exploration with solid science and to make the first visit to an object of historical fascination. But Murray's fixation with Halley would have its costs, both within JPL and without.

Halley's comet as shot from Easter Island on March 8, 1986, by W. Liller for the International Halley Watch Large-Scale Phenomena Network.

http://nssdc.gsfc.nasa.gov

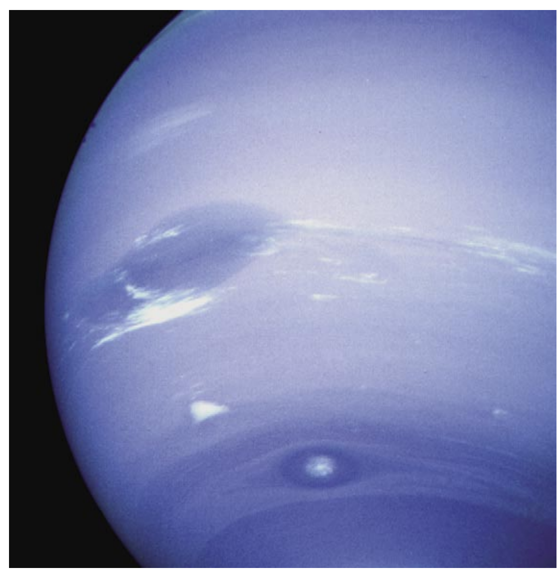
To replace HIM, JPL naturally suggested HER: Halley Earth Return, which would fly by Halley, unroll a long thin plastic tube "like a Chinese New Year party whistle" to sweep up cometary particles, then reel the tube back in and swing the spacecraft back toward Earth to return the sample. The plan quickly earned approval from the Space Science Board, and it offered a different approach than the European or Soviet Halley missions. But after a month of negotiations between NASA and the White House, on 30 September 1981 NASA directed Murray to stop all work on Halley missions.

The official end of JPL's hopes for Halley came as a jolt to Murray, who spoke bitterly of "Black September." That was not all. First, budget cuts on the Centaur project again put Galileo at risk, until JPL designers came up with yet another gravity-assist trajectory to get to Jupiter on the IUS booster. Then NASA floated a proposal to shut off the Voyager spacecraft, saving $222 million by foregoing the Uranus and Neptune encounters. It finally became clear that not just single projects but the entire deep-space program was at stake. In summer 1981 the OMB cut $1.1 billion from NASA's budget request. The new NASA administrator, James Beggs, insisted that such a shortfall would require dropping one of NASA's major programs, such as the shuttle, earth applications, or planetary exploration, and requested higher-level policy approval. But he did offer a suggestion. At his confirmation hearings in June, Beggs had called planetary exploration "a hallmark of the agency. It would be a disaster if we gave it up." He now pushed the planetary program on the table as a high-stakes wager in the budgetary standoff, naming it as the first item NASA would be willing to cut. He again cited the program's value, but he ranked it below astronomy in immediate potential: "the most important missions" in deep space had already been done, and the next phase of landers and sample returns could await the shuttle. He added, "Of course, elimination of the planetary exploration program will make the Jet Propulsion Laboratory in California surplus to our needs."

The budget standoff continued through the fall, as dire rumors swirled concerning JPL's possible demise. The lab got little support from Reagan's science advisor, George Keyworth. In an interview published 2 December, a week before the final budget review, Keyworth "recommended halting all new planetary space missions for at least the next decade," in favor of astronomy and shuttle-borne experiments. He soon backtracked, stating that he did not propose ending missions altogether, just doing them more cheaply. Despite the public statements, Keyworth's testimony to the budget review board supported the decision to cancel Galileo and VOIR; "the cut in planetary exploration represents an example of good management."

JPL likewise lacked support from key elements of NASA. In particular, Hans Mark, deputy to Beggs, proved an unreliable ally. Mark had long viewed the space shuttle as the focus of the space program, a necessary step toward the longer goal of a space station, and also held an ambivalent view of planetary exploration. In 1975 he had noted the substantial investment in the program, from which he believed "no *fundamental* or *unexpected* discovery" had emerged. And the program itself, he observed two years later, was running out of steam: "we have reached a point in the planetary exploration where, for the missions planned between now and the early 1980's, we will have done just about everything we can given our current technology. In other words, we soon will have 'saturated' our capabilities."

Mark brought these views with him to NASA. In August 1981 Mark and his aide Milton Silveira circulated a long-range plan for NASA. The document noted the space agency's role in scientific exploration, but it urged a focus on shuttle-borne experiments, especially for astronomy or cosmology, and a hiatus in planetary exploration until the construction of a space station as a base for spacecraft launch and sample return. As for what to do with JPL, Mark had long-held opinions on that too, which reinforced his views on the expendability of planetary exploration; JPL would have to seek other sponsors, which to Mark meant the military. He was thus pursuing, in parallel, a campaign to enlist JPL's skills for the Department of Defense.



http://photojournal.jpl.nasa.gov

Had NASA been forced to turn off the Voyagers in 1981, our best view of Neptune would remain a fuzzy point of light in a telescope. This photo combines two images taken by Voyager 2's narrow-angle camera, and includes the Great Dark Spot (middle), a bright feature below it nicknamed "Scooter," and the bright-cored "Dark Spot 2" further below.

Planetary Society cofounders Bruce Murray (seated, at left), Cornell astronomy professor and science popularizer Carl Sagan (seated, at right), and Louis Friedman (standing behind them), when the organization was incorporated in 1979. Behind Sagan is Harry Ashmore, a Pulitzer Prize–winning journalist and leader in the Civil Rights movement, who served as an invaluable advisor.

http://www2.jpl.nasa.gov

Into the Political Arena

Mark's statements on the planetary program undermined NASA's defense of JPL. Beggs did not help with his negotiating ploy of August, which backfired in December when the OMB cited his assignment of a lower priority to the deep-space program in its arguments before the budget review board. With a lack of advocacy at key levels, JPL undertook its own political campaign, one that would bring lobbying for programmatic goals to a new level of coordination and organization. But Murray first had to overcome an initial aversion to political activism, instilled not so much by principle as by practical considerations of JPL's relations with NASA. In 1976, for example, several JPL staff proposed Project Columbus, a long-term planetary program of one launch per year through 1992; the planners, however, bypassed NASA and took the proposal straight to OMB and Congress. Murray quickly reined them in and considered firing their leader, Lou Friedman, for insubordination.

A few years later Murray would institutionalize political freelancing far beyond that undertaken by Friedman, as Murray himself would admit. The congressional struggle over the cancellation of the Jupiter mission in summer 1977 provided the first test for Murray's misgivings. There remained perceptions of limits. NASA, at least, thought the lab had crossed a line. A legal affairs manager chastised Murray in May about direct contacts between JPL and Congress and reminded him that NASA policy required all congressional contacts with NASA personnel to go through his office. The lab's lawyers, however, pointed out that JPL was *not* a NASA field center; JPL staff were Caltech employees and as such were not bound by NASA's policy. JPL's distinctive, dual status as a Caltech-run lab under NASA thus gave Murray and his managers leeway for lobbying. They also took refuge in semantics. What, exactly, constituted lobbying? The lab's NASA liaison was careful to refer instead to the "education" of Congress.

Murray and his staff also attended to the sources and justifications for political support. JPL had started as an army lab, which gave it a strong political advocate, but its new mission in planetary spacecraft made its main political constituency the community of planetary scientists—a narrow group with little political clout, as interest groups go. In the late 1970s *Science* magazine estimated that the community numbered about "600 or so" scientists in the United States. And it was competing with a formidable array of other interests, within NASA and without, for a share of the federal budget. Since JPL did most of its work in-house, the lab's projects elicited little political support from industry. To broaden the constituency, Murray and his friend Carl Sagan in late 1979 created the Planetary Society, together with Friedman. The society quickly built up a membership of 70,000 in its first year, a substantial base of enthusiasts to enlist in support of JPL's political initiatives.

Why *should* the public get excited about very expensive missions that return data on distant planets to a small group of planetary scientists? Murray appealed to the ideal of exploration: "More than just science is involved, and it should be—for what

"Bruce, you have a good fight and an important one, and it's time to use these big guns." — Mary Scranton

Caltech Trustee Mary Scranton

it has cost. If there isn't a justification beyond what you might call narrow scientific objectives, then planetary is far overpriced in terms of what it has cost to accomplish. The reason it has been justified and continues to be is because it has broad cultural and social significance beyond the changing of the perceptions of individual scientists." Similar attitudes permeated NASA. Program manager Dan Herman observed that "above a certain dollar level, science-for-science sake is not a salable commodity in the planetary program area"; missions had to include exploration.

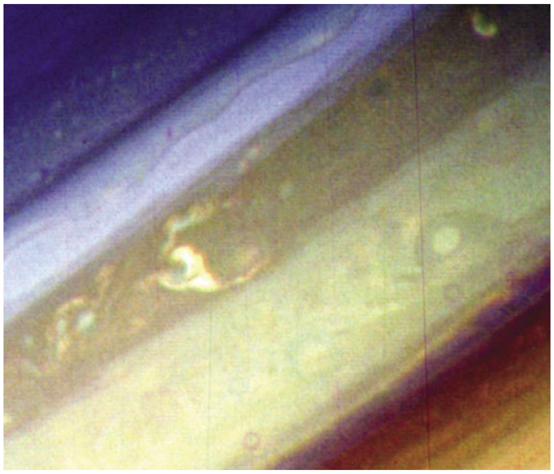
The decline of planetary prospects in 1980 quickened political activity at the lab, inspired by the rescue of Galileo in 1977. In its political campaign to defend the deep-space program, JPL had an important ally in the Caltech board of trustees. As part of Caltech, an elite institution with friends in high places, Murray and the lab sought to capitalize on connections to the inner circles of government. In 1976 Murray had created an advisory council for JPL, consisting of Caltech faculty, trustees, and eminent public citizens, to provide a source of high-level advice but also advocacy. An especially dedicated partisan was trustee Mary Scranton, wife of William Scranton, a one-time Republican candidate for president and then governor of Pennsylvania. Mary Scranton had extensive connections in Washington and she exercised them assiduously on behalf of JPL, advising Murray on congressional sentiment and urging him in October 1980 to find a back-door approach to the White House, perhaps with the aid of other trustees: "Bruce, you have a good fight and an important one, and it's time to use these big guns."

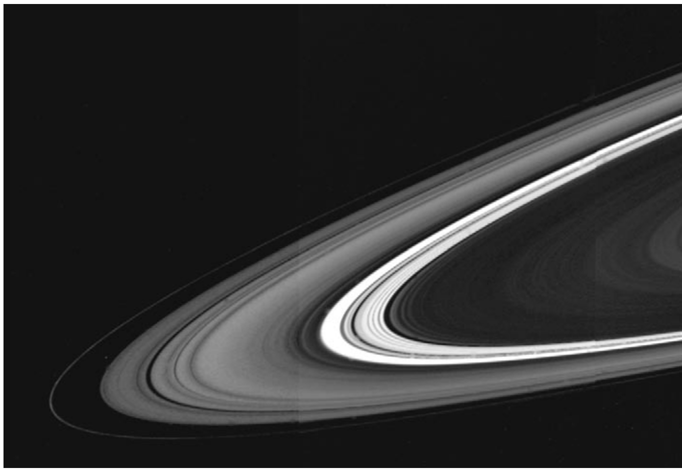
With Reagan's election that November, Murray brought in the artillery. At Reagan's private victory party on election night, Caltech trustee Earle Jorgensen delivered a JPL position paper on the Halley mission to Reagan aide Michael Deaver. A week later trustee Stanley Rawn, Jr., sent the same Halley plea to Vice-President-elect George Bush in a "Dear George" letter, followed by a letter in February 1981 to Chief of Staff James Baker III ("Jimmy," to Rawn). On the day of inauguration, 20 January 1981, Murray sent a letter to Edwin Meese III pleading for the Halley mission and the future of space exploration in general.

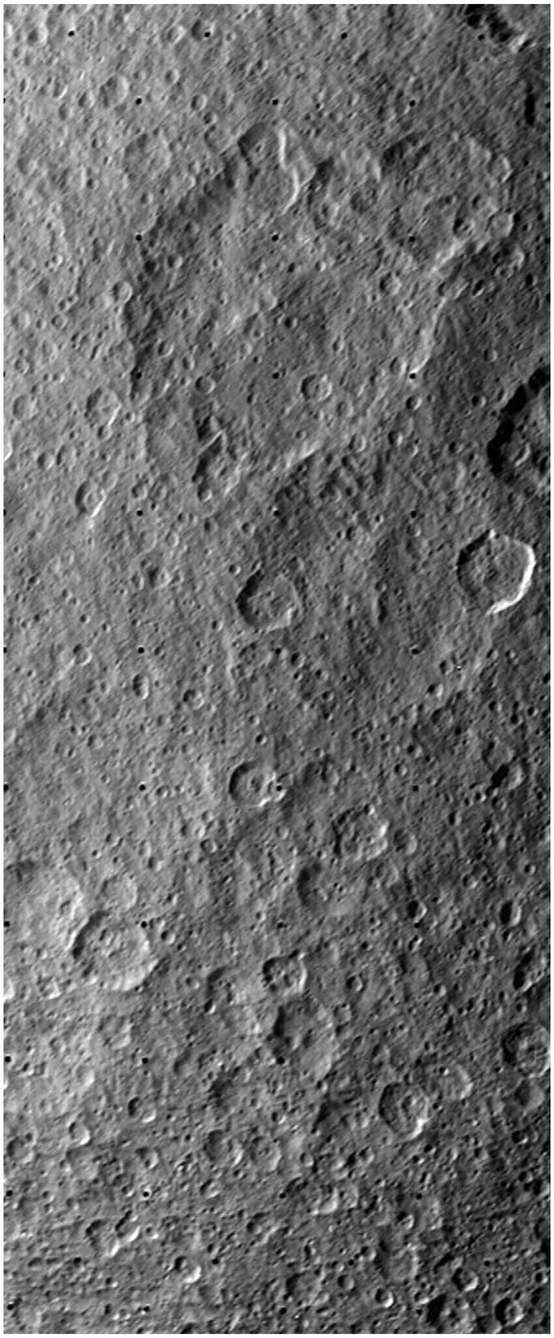
The responses to these missives were noncommittal. As the Reagan administration settled in and the OMB budget targets began circulating in early 1981, Murray became a whirlwind, making several East Coast trips for meetings with dozens of congressional representatives and staffers, NASA and OMB officials, science writers and editorial boards, and key aerospace executives. He also created an institutional framework within JPL for the campaign. In January 1981 he set up the Director's Interface Group (DIG) to devise "marketing strategies," produce campaign literature, and cultivate contacts in Washington, industry, and the media. Murray also apparently hired a prominent local Republican, Robert Finch, who had access to the Reagan administration. Although Finch was not a professional lobbyist, his hiring tested and perhaps exceeded the limits imposed by the lab's relation with NASA.

JPL's campaign found endorsements from across the political spectrum. In November 1980 Senators Strom Thurmond and Alan Cranston—a Deep South Republican and a left-coast Demo-

Right: This image of Saturn's northern hemisphere, taken by Voyager 1 on November 5, 1980, at a range of 9 million kilometers, shows a variety of features on a planet that, unlike Jupiter, appears very bland from Earth. Far right: When seen from behind, Saturn's rings look very different—the bright, reflective rings we see, which are made of larger particles, turn black; other areas filled with smaller particles that diffuse sunlight shine brightly. Opposite page: Saturn poses for Voyager 1 with two of its moons, Tethys (the upper) and Dione. Bottom: Voyager 1 also got the first high-resolution views of Saturn's moons, including this shot of the north polar region of Rhea. These images and those from Voyager 2 revealed an amazing diversity among these hitherto unexplored bodies.







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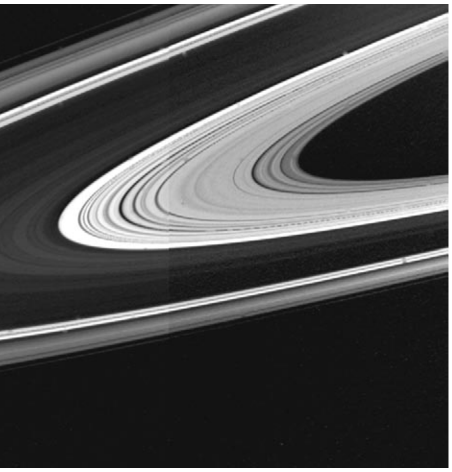
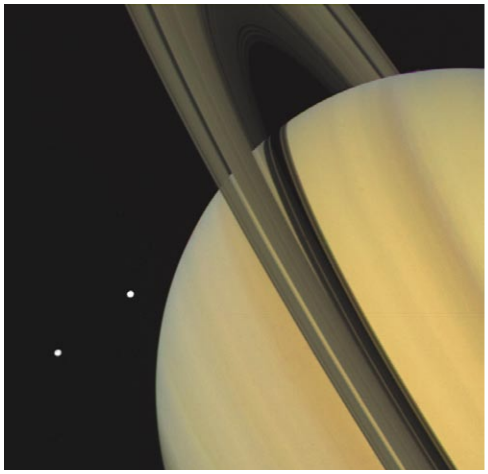
crat—used the occasion of the Voyager encounter with Saturn to laud the deep-space program. The budget cuts of Spring 1981 raised editorial objections from both Edmund (Pat) Brown and George Will, and from the *New York Times* as well as the *Wall Street Journal*. Perhaps the strangest bedfellows were California Governor Jerry Brown and Representative Newt Gingrich. As the highest expression of socially directed technical innovation, the early space program had received its main support from politicians on the left, especially for the ideal of exploration against a more limited focus on science. But in the late 1960s political liberals sought to direct federal spending toward social problems instead of technoscientific extravaganzas that seemed to benefit only a few scientists and aerospace corporations. Like others on the left, Brown had come to oppose large, centralized technologies as symptomatic of the ills of modern society, but inspired in part by his attendance at the Viking encounter, Brown embraced space with a typically visionary approach. He no doubt recognized a political constituency, at JPL and in the California aerospace industry, but he also acquired a keen personal interest. The *Los Angeles Times* commented on the conversion of "our new, spaced-out governor": "Gov. Brown is blasting into space. But to achieve lift-off he has had to jettison much of his old rhetorical baggage. He no longer speaks of an 'era of limits.' His new high is the 'era of possibilities.' Nor is small always beautiful. 'In space,' he exults, 'big is better.'"

For his part, Gingrich, the young Republican firebrand from Georgia, proved an equally ardent space buff, founding the Congressional Space Caucus and suggesting $9 billion instead of $6.6 billion as an appropriate budget for NASA in 1983. The support from Gingrich, Thurmond, Senator Barry Goldwater, and other conservatives stemmed from an ideological sea change concerning the space program. As political liberals drifted





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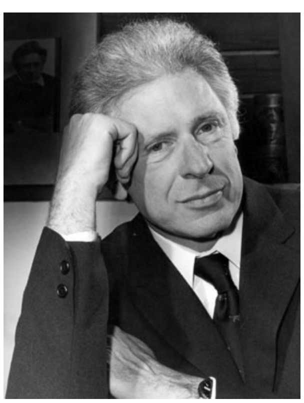
down to earth, conservatives were abandoning fiscal austerity and embracing the vision of space as new frontier first advanced by Kennedy; the space program could rekindle the old pioneer spirit, inspiring noble achievements and opening up a new realm for commerce. Liberal commentators for their part came to view the frontier myth as an emblem of imperial conquest, environmental damage, selective government subsidies, and corporate profiteering. Hence public opinion polls in the early 1980s showed that conservatives were more likely than liberals to see space spending as inadequate.

The support from political conservatives and liberal iconoclasts failed to stem the tide. Although the Reagan administration would come to extol the frontier image of space, its initial priority remained fiscal conservatism. In July 1981 Caltech president Marvin "Murph" Goldberger, prodded by Murray, created a new trustees subcommittee on JPL, chaired by Scranton, to mobilize more fully the potent influence of the trustees. The initial membership packed considerable political punch and included, among others, former Secretary of Defense Robert McNamara; Shirley Hufstedler, education secretary under Carter; Simon Ramo, a founder of the aerospace firm TRW and a longtime adviser to presidents; and Hollywood mogul and political insider Lew Wasserman.



Marvin Goldberger

As the budget crisis deepened in fall 1981 Caltech and its trustees again waded into the fray on behalf of JPL. Their preferred approach remained the back door of the White House. At the suggestion of Arnold Beckman, a longtime trustee, Goldberger in October sent a letter to Reagan via Attorney General William French Smith. Goldberger defended the deep-space program on three main grounds: intellectual curiosity, international prestige, and technological spin-offs for industry and especially defense; two of the three justifications thus derived from the cold war. Beckman followed with a letter of his own to Meese, with a more practical political justification: the cuts threatened "rapid disintegration of a 5,000-person, $400 million Southern California enterprise. . . . There are obvious implications to the support of the President and to his Party should the Administration permit such a catastrophe to take place." In addition to Scranton's persistent activity, and further interventions with Vice President Bush by Finch and Rawn, Goldberger made his own trip to Capitol Hill, where he pressed his case in particular with Senate Majority Leader Howard Baker. Baker wrote Reagan and followed up with repeated phone calls, stressing that he had no "parochial Tennessee interest" but rather a strong personal concern in the issue.

Dénouement

The combination of Beckman's pressure on Meese and Goldberger's buttonholing of Baker proved decisive. The White House budget review committee met on 15 December 1981 to resolve the fate of the planetary program. Keyworth suggested a compromise: preserving Galileo, and hence JPL, at a cost in fiscal 1983 of $90 million. The budget would include neither VOIR, effectively killing it, nor the Centaur upper stage, forcing yet another Galileo redesign, but the lab was safe for the immediate future.

The crisis scarred JPL, however, both externally and internally. Murray approached the political

The Space Shuttle *Atlantis*—at long last carrying the Galileo spacecraft—soars above Florida on Oct. 18, 1989. The scene was recorded with a 70mm camera by astronaut Daniel Brandenstein.

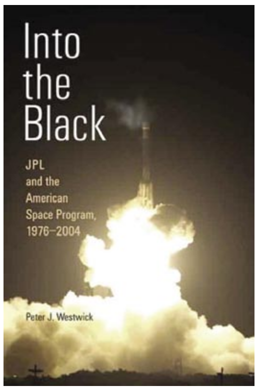
http://solarsystem.nasa.gov

http://solarsystem.nasa.gov

An artist's impression of Galileo's probe descending into Jupiter's atmosphere on December 7, 1995. The probe measured temperature, pressure, chemical composition, cloud characteristics, sunlight, and lightning bolts during its 58-minute, 200-kilometer plunge into Jupiter's depths before being crushed, melted, and/or vaporized by the heat and pressure—the first direct analysis of a gas giant's atmosphere.

battles with the enthusiasm of the true believer: "we must be zealots." Indeed, although he decried the need to play the political game, Murray seemed to relish the strategems and the chance to roll up his sleeves for a good fight. But Murray proved perhaps too zealous. His end-runs to Congress and the White House exasperated NASA. He also moved away from his pragmatic, incrementalist approach toward a harder political line. In October 1980 he chastised comet scientists for insisting on a rendezvous instead of a flyby: "The coalition got itself into the position of saying 'All or Nothing,' and it got nothing." But a few months later, as his worst fears materialized in early 1981, Murray rejected compromise, for instance, the possibility of sacrificing one mission to save another—say, forsaking Halley to preserve Galileo. "We must not permit the staff in OMB or Congress to trap us or other advocates in a no-win situation. There is no way to win by giving up one thing to get another, even if that were possible, which it normally is not. The only way to win is to protect Galileo, to get a successful reconsideration of some kind of U.S. Solar Polar mission in 1986, and to get the Halley in as an option. Anything else will mean losing. That is JPL's position." In short, Murray proclaimed to lab staff, "In the deep space area we do not bargain. . . . We have to go for the whole enchilada."

Murray's tactics exposed Galileo and roused resentment at NASA and within JPL. In October 1980 Murray had warned planetary scientists to provide balanced advocacy: "We have to avoid overselling of a particular mission." Some NASA managers now viewed him as doing just that on behalf of Halley and noted that "the actions taken by JPL management to 'sell' the Halley mission created, at times, the general impression that NASA and/or JPL were willing to forego the development of the Centaur and/or delay the Galileo project in the interest of committing to a Halley Intercept Mission." They added that a



Into the Black: JPL and the American Space Program, 1976–2004
By Peter J. Westwick
Yale University Press
2006
408 pages
$40.00 hardcover

byproduct was morale problems on Galileo; John Casani, Galileo project manager, and others on Galileo questioned Murray's high-stakes wager with their work. Murray, for his part, viewed the Halley mission as the linchpin, "the key link in the trestle across the gorge," and he could not understand why his staff did not share his assessment. At a retreat held by the lab's executive council of senior managers, Murray asked how many thought cancellation of Halley and Venus missions would be a really serious problem. Only one person besides Murray thought it serious while fourteen others thought it not so bad.

Murray was not the only planetary scientist to mobilize politically, but his especial activism stemmed from the failure of other lobbying efforts. In fall 1981 David Morrison, chair of the Division of Planetary Sciences of the American Astronomical Society, sent a circular letter to his colleagues: "The time has come to politicize the planetary science community." But resistance to such appeals persisted among scientists, and both the division and the Space Science Board sought to preserve their objectivity by staying out of the political arena. The Planetary Society also proved an ineffectual means of influence. A society campaign organized in August 1981 to support the Halley mission generated 10,000 letters to the White House, which simply routed them all to NASA unopened.

Why did the apparent public interest in space fail to translate into political support? The planetary program had attracted unprecedented interest from the Voyager encounters and Carl Sagan's "Cosmos" and received endorsements from a range of public and political commentators. But the general American public, the ultimate underwriters of the endeavor, did not share the commitment. NBC News polls in 1980 and 1981 found that most people still thought the United States was spending too much or just enough on the space program; only one-fifth thought support was inadequate. A clear majority also thought the space program should emphasize defense over science, a view that cut across political and demographic categories. JPL itself was already starting to reflect such an orientation. □

Peter J. Westwick, a visiting researcher in the Department of History at UC Santa Barbara, was previously an Olin Fellow in International Security Studies at Yale. His first book, The National Labs: Science in an American System, 1947–1974*, won the Book Prize of the Forum for History of Science in America in 2004.*

This book is the second volume of JPL history, picking up where Clayton Kopp's JPL and the American Space Program *(Yale University Press, 1982) left off. A political and institutional history rather than a scientific one,* Into the Black *examines the relationship between the civil and military space programs and between manned and unmanned space programs, and the role of government as a sponsor of research for national security, international prestige, and economic competitiveness.*

Westwick was given a faculty appointment at Caltech while writing the book, which was supported by grants from Ed Stone and Charles Elachi out of the JPL Director's Discretionary Fund, and had unfettered access to campus and lab archives and staff; neither institution, however, exerted any editorial control over the result.

The book's title, says Westwick, riffs on lyrics by Neil Young: "Out of the blue and into the black. . . . And once you're gone, you can't come back," referring not only to a spacecraft's departure from our blue skies to the black of space, but the fact that, once launched, these highly sophisticated robots are on their own—AAA doesn't offer roadside assistance on Mars. The title also reflects the "black" of the classified military space program—JPL had largely shed its army origins by the early 1970s, only to be called into service again in the depths of the Cold War '80s. And finally, it refers to the "black" of balance sheets, in this case for a national repository of intellectual capital.

Honors and Awards

Felix Boehm, Valentine Professor of Physics, Emeritus, and **Robert Christy**, Institute Professor of Theoretical Physics, Emeritus, have been elected fellows of the American Association for the Advancement of Science in the Section on Physics.

The **Caltech astronomical observatories**, and the scientists, researchers, and students associated with them, have been selected by the Space Foundation to be the group recipient of the John L. "Jack" Swigert, Jr., Award for Space Exploration. Named after the late Apollo 13 astronaut, who died of bone cancer in 1982 shortly after being elected to Congress by Colorado's newly created Sixth District, the award recognizes "the trailblazing body of astronomy research and discoveries made by the Caltech astronomy community, and the successful management of one of the world's most impressive portfolios of observatories," which includes the Palomar Observatory, the W. M. Keck Observatory, and the Owens Valley Radio Observatory, among others. JPL received the award last year.

Ron Drever, professor of physics, emeritus, has been chosen a recipient of the American Physical Society's 2007 Einstein Prize, which is supported by the Topical Group on Gravitation. Drever and his corecipient, Rainer Weiss of MIT, are being recognized "for fundamental contributions to the development of gravitational wave detectors based on optical interferometry, leading to the successful operation of the Laser Interferometer Gravitational Wave Observatory"; they will share a $10,000 prize.

James Eisenstein, Roshek Professor of Physics and Applied Physics, has been named a corecipient of the American Physical Society's 2007 Oliver E. Buckley Prize in Condensed Matter Physics "for fundamental experimental and theoretical research on correlated many-electron states in low dimensional systems." He will share the $10,000 prize with Steven Girvin of Yale and Allan MacDonald of the University of Texas, Austin.

Richard Ellis, Steele Family Professor of Astronomy, has been named the inaugural John Bahcall Distinguished Professor at the Space Telescope Science Institute in Baltimore, and will give the Bahcall Lecture at the Space Telescope Science Institute and a public lecture at the Goddard Space Flight Center in early December. Ellis was selected on the basis of his research accomplishments and his "activities and vision in building for the future," as well as his "ability to communicate both the substance and the excitement of frontier astrophysics."

Michael Elowitz, assistant professor of biology and applied physics and Bren Scholar, has been awarded a Packard Fellowship for Science and Engineering, whose intent "is to provide support for unusually creative researchers early in their careers." Elowitz will receive $625,000, payable over five consecutive years.

Marc Kamionkowski has been named the Robinson Professor of Theoretical Physics and Astrophysics. His research interests include how the large-scale distribution of mass in the universe originated, galaxy formation, the formation of the first stars, and the problems of dark matter and dark energy.

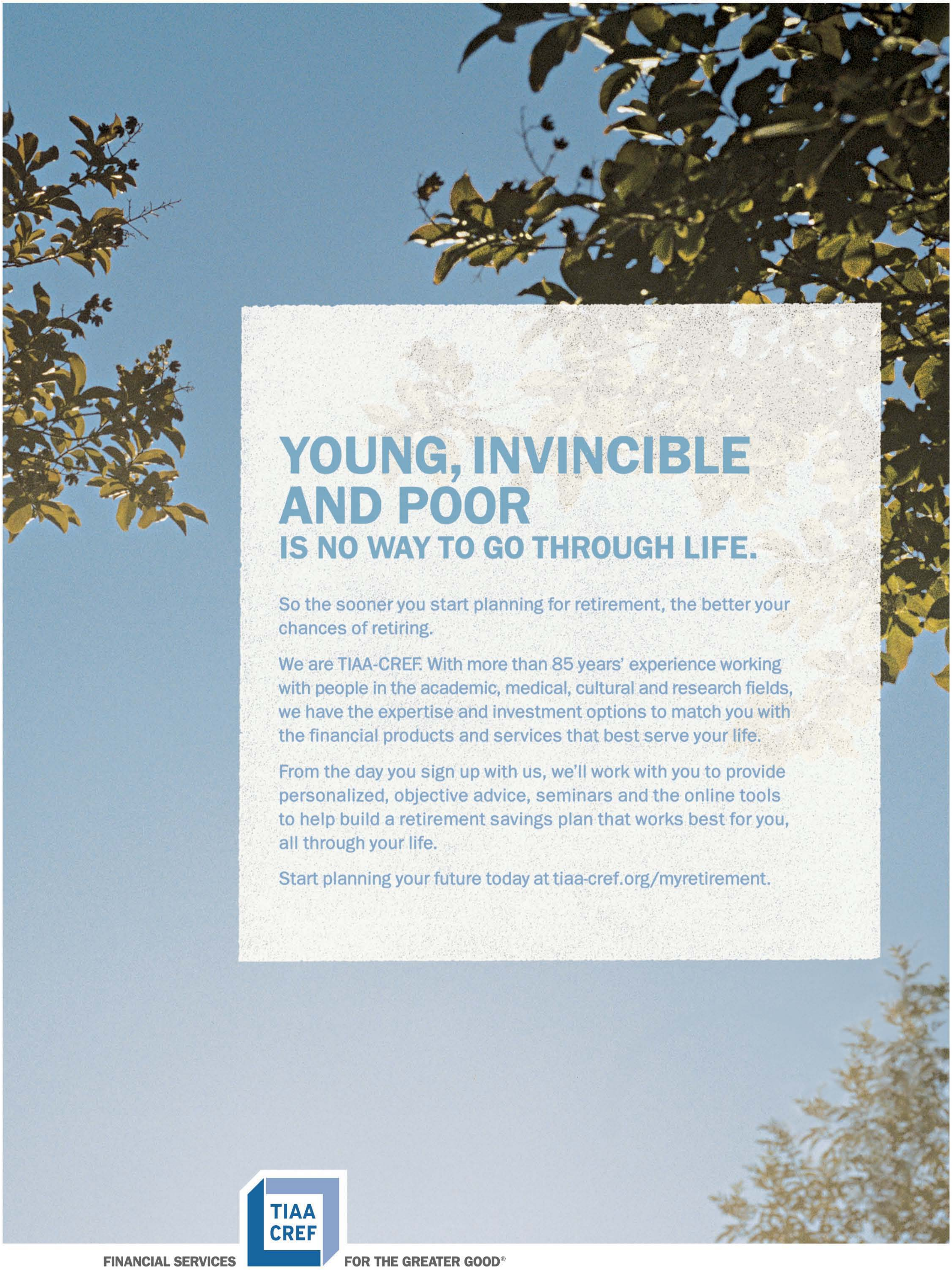
Frederick Raab, a member of the professional staff in the Laser Interferometer Gravitational-Wave Observatory (LIGO) Laboratory, has been elected a fellow of the American Physical Society on the recommendation of the Topical Group on Gravitation.

Guruswami Ravichandran, Goode Professor of Aeronautics and Mechanical Engineering, has been awarded the honorary degree docteur honoris causa by Paul Verlaine University, Metz, France, "in recognition of his pioneering contributions to the mechanical behavior of materials under extreme conditions and for promoting international collaboration with researchers" at that university.

Barry Simon, IBM Professor of Mathematics and Theoretical Physics, has been chosen to be the 2007 Wolfgang Wasow Memorial Lecturer at the University of Wisconsin–Madison; the lecture will be given next fall. □

Hall Acting V.P. for Student Affairs

John Hall, professor of civil engineering and dean of students, is wearing yet another hat as acting vice president for student affairs. In the memo announcing his appointment, President Jean-Lou Chameau said, "As acting vice president, John will initiate discussions with students, faculty, and staff to gain insight into our students' experience at Caltech (academic and nonacademic), the selection and recruitment of students, and the overall function of the Student Affairs organization. John will be working closely with [Provost Paul] Jennings and myself as this process moves forward. In the coming weeks, we will also appoint ad hoc working groups to examine key issues in detail. The information gathered through the work of these committees and the broader campus discussions will bring the best of Caltech forward and serve as an effective guide to the selection of the new leader for our student-related activities." □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