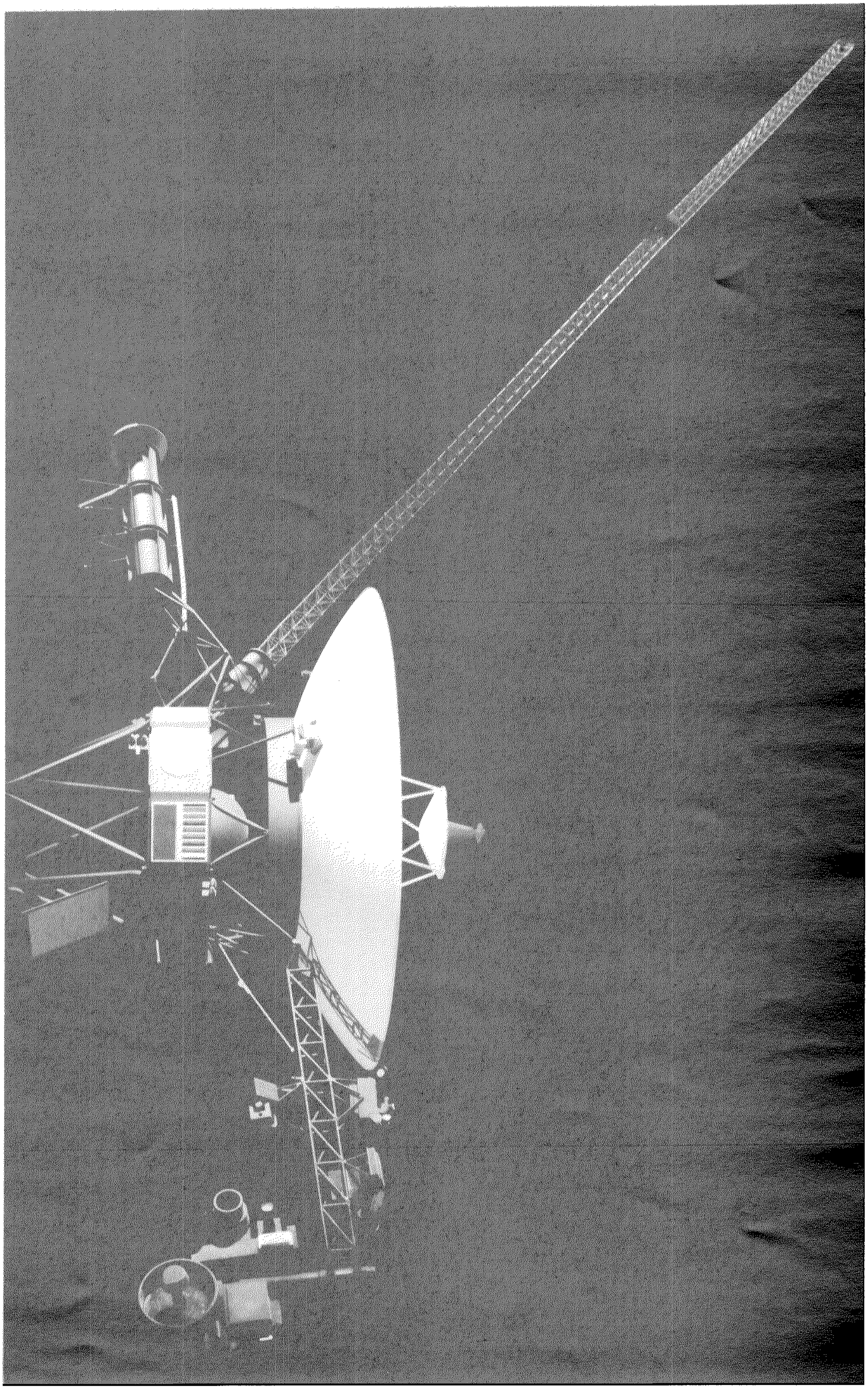


Voyager and the Grandest Tour Ever: Catching the Wave of the Century

by Bruce Murray

The Voyager spacecraft, the most productive robot explorer ever built, is now approaching Neptune, its final encounter in a spectacular tour of the solar system. But it had to survive political and technical frustrations before even getting off the ground a dozen years ago.

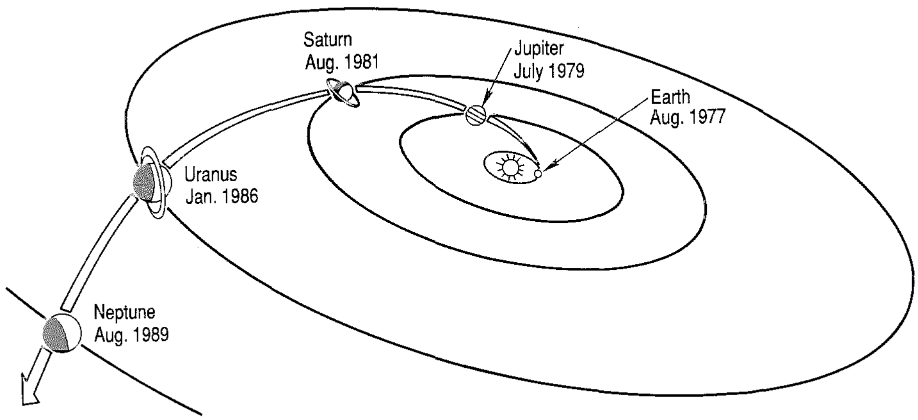
This chapter is excerpted from Journey into Space: The First Three Decades of Space Exploration *by Bruce Murray, published in July 1989. (Copyright © 1989 Bruce C. Murray) It's reprinted here with permission of the publisher, W. W. Norton & Company, Inc. Murray, a member of the Caltech faculty since 1960 and currently professor of planetary science, was director of the Jet Propulsion Laboratory from 1976 to 1982, a tenure that included the Viking landings on Mars and the Voyager encounters with Jupiter and Saturn.*

Imagine "Star Trek." An alien starship exploring our portion of the Milky Way trains high-powered sensors on a still-distant star of no apparent distinction. As the starship moves nearer, four cold, uninhabited planets come into view, orbiting majestically about the ball of burning hydrogen we call the sun. A few hours later (the starship is moving at nearly the speed of light), four rocky spheres are sighted orbiting much nearer the star than the four big planets. One of those is our home, the water-covered ball where we live, dream, and die. The starship aliens (or, more likely, their robotic surrogates) might soon streak on in search of a more interesting stellar environment, rather than expend fuel and time in a close-up inspection of insignificant rocky debris, orbiting a rather average star.

Those four conspicuous planets—Jupiter, Saturn, Uranus, and Neptune—are very large indeed. They constitute 99.8 percent of the aggregate planetary mass orbiting the sun. Viewed from interstellar space, these gas giants *are* the planetary system. Earth, however, is luckier. Tucked into a narrow zone of optimal solar warming, it has a moist surface, and because of that moisture life has evolved on it.

In ancient and medieval times it was fashionable to speak of the harmony of the spheres. The users of that phrase could not know how true that was. Jupiter, Saturn, Uranus, and Neptune *are* harmonious. Every century and three-quarters a magical alignment occurs among them. During this short-lived alignment a properly designed spacecraft launched to Jupiter from Earth can, with the right choice of close trajectory at Jupiter, break the sun's gravitational pull and fly on to Saturn, Uranus, and Neptune—the Grand Tour—and then, past Neptune, disappear forever into interstellar space. When that once-in-this-century opportunity occurred, in 1977, the United States was ready to ride that cosmic "wave" and make stunning discoveries about our giant planetary cousins.

James Van Allen, of the University of Iowa, was one of the world's first space scientists. In 1958 he discovered invisible, globe-girdling belts of lethal charged particles, belts that now bear his name. In the spring of 1970 he sat at the head of our conference table, chairing a scientific group brought together by NASA to explore the scientific opportunities offered by the Grand Tour trajectory discovered in the early 1960s. Of the 15 specialists meeting that day at JPL, I was the lone geologist, and the only member of the team especially interested in rocky worlds. My role rapidly became clear—to evangelize not just for good imaging but also for serious and



The alignments and motions of Earth and the outer planets very rarely coincide such that a spacecraft can be launched from Earth to Jupiter, be perturbed by Jupiter's gravity to move on to Saturn, and so forth all the way to Neptune. The last time the planets were aligned similarly for this trajectory, Thomas Jefferson was president of the United States.

On opposite page: Bruce Murray holds a model of Voyager. (Photo by Eric Myer)

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close observation of the many satellites, the moons of these gas giants.

From Earth the moons of Jupiter and Saturn *look* insignificant, being no more than smudges on the photographic plates. Jupiter and Saturn dominate the telescopic views, physically and intellectually, presenting enormous challenges to the practitioners of physics. Jupiter's magnetic field challenges even the sun's. Intense radiation trapped within huge belts by that field generates the solar system's strongest radio signals. Jupiter's Great Red Spot, a giant vortex visible even from Earth, has persisted mysteriously over three centuries. Larger than Earth, that oval eye rules a colorful kaleidoscope of atmospheric swirls and bands, begging for theoretical interpretation. To be able to fathom the rings of Saturn would alone have justified the voyage. We were only a little wiser about those rings than Galileo was when he first described them.

In 1970, as we met at JPL, the first spaceships intended to scout Jupiter were already under construction only forty miles away at TRW. Called Pioneers 10 and 11, they were launched in 1972 and 1973, respectively, to sample Jupiter's environment—its electrical currents, magnetism, and energetic particles. Completely controlled by ground commands, the Pioneers spun passively in space like giant tops. These two spinning spacecraft were sturdily built to scout the gateway to the outer planets. They were mechanically and electrically simple and therefore relatively inexpensive. However, as every amateur photographer knows, imaging (and other remote sensing) is best carried out from a rock-steady and carefully pointed platform. Pioneers 10 and 11 did pack a small light-scanning sensor, from which a few images of Jupiter and Saturn were built up line by line by the spacecraft's spinning motion during the flyby. But no useful photography of Jupiter's or Saturn's moons was possible with such rudimentary equipment.

Pioneer 10 blazed a historic trail through the unknown hazards of the asteroid belt and extended humankind's reach to Jupiter on December 3, 1973, encountering far more damaging radiation than had been expected. Pioneer 11 reached Jupiter a year later, then blazed the trail past Saturn. In September 1979 it certified the safety of the narrow zone adjacent to Saturn's rings that leads on to Uranus and Neptune (just as Mariner/Venus/Mercury had found the tiny target adjacent to Venus that led on to Mercury). The success of Pioneer 11 silenced fears that unseen ring particles lurking there would pepper the unwary robotic explorer like a natural antisatellite weapon.

In 1970 those accomplishments of Pioneers 10 and 11 were still years away. Intense planning was taking place for the Grand Tour, for visiting all four giant planets in one flight. The Pioneer flights were overtures to the big show. For that next, giant step, new plutonium cells would be used to power the most intelligent robot ever conceived. A breakthrough in artificial intelligence (as it is now called) was essential for sophisticated exploration light hours from Earth. The state-of-the-art brain used on the Grand Tour would have to be as robust as the

control mechanism of a nuclear weapon in order to survive Jupiter's murderous radiation. That was the biggest problem, the hidden surcharge for the free ride to Saturn and on to Uranus and to Neptune.

As the months of 1970 passed, meetings proliferated. By October the small, dreary JPL conference room, crammed with engineering diagrams and plans, had become all too familiar. I was running one of Van Allen's subcommittees—the Data Handling Subcommittee for the Grand Tour Mission Definition Phase. Jupiter is half a billion miles away. Radioing back thousands of pictures and other data to Earth would challenge every link in the communications chain—the spacecraft, the Deep Space net, and the ground computers. But it could be done. The Grand Tour was no economy-class mission like the flights to Venus and Mercury. Expensive new technology was to be its hallmark. I experienced déjà vu, recalling nearly a decade of previous meetings for Mars and Mercury missions at which we had labored over the same technical issues.

Suddenly, a revelation hit me. Three successive missions to Mars, plus the upcoming flyby of Venus and Mercury, were enough for me. Other people could convert the promise of the Grand Tour into reality. After MVM, I would not return again to the "trenches" but would move on to something new.

Meanwhile, the Grand Tour seemed to have a sound basis for governmental approval, for it offered the following:

- Great scientific promise for countless physicists, astronomers, meteorologists, and geologists (although official scientific support still reflected a concern that the Grand Tour might suck up a disproportionate share of space resources).
- The cutting edge of space technology, to challenge JPL once again.
- The prospect of historic American achievement, clearly beyond Soviet capability, certain to elicit worldwide acclaim.
- A billion-dollar, high-profile program for NASA, well suited to pick up the budget slack after Viking.

NASA promoted the Grand Tour concept strongly. In April 1971 it charged nearly a hundred diverse scientists to put scientific flesh on the concept Van Allen's group had laid out.

Over the next seven months two optimal trajectories were identified. The first involved a blast-off in August 1977 toward Jupiter, where the spacecraft was to catch the free trip to Saturn, Uranus, and Neptune. A few weeks later, the second spacecraft would be launched, also to Jupiter and Saturn. But the Grand Tour gateway to Uranus and Neptune would already have closed. Tiny Pluto would therefore become Number 2's final destination. Fifty-four separate scientific objectives for the Grand Tour were spelled out, but only eight even mentioned the satellites, and only two did so uniquely. For most of the scientists involved, those dozens of little worlds orbiting the gas giants remained insignificant smudges on photographic plates. Geographical discovery—the progenitor of so much natural science on Earth—was not fashionable with the laboratory physicists, chemists, and biologists who dominated American (and Soviet) science.

But Bud Schurmeier, JPL's new project manager, understood the importance of photographic exploration. Schurmeier had put JPL and America into the lunar race in 1964 when his Ranger lunar-impact probes radioed back the first close-up pictures of the moon. This was a crucial preparatory step for Apollo. In 1969 he led the work on Mariners 6 and 7 that achieved a hundredfold gain over tiny Mariner 4 in the return of pictures from Mars. With Schurmeier, JPL was clearly giving the Grand Tour its best effort. The exploration of even those unknown moons would now receive a sympathetic hearing.

Events moved rapidly in late 1971 and early 1972.

- On August 3, 1971, Dave Scott, the test pilot Chuck Yeager's protégé, and his Apollo 15 crew took viewers all over the world on a roving television ride across the rocky and forbidding lunar landscape.

The Apollo momentum that had powered a generation of virtuoso American planetary first looks was fast dissipating. The Grand Tour simply reached the starting gate too late for a new planetary endeavor of such cost.

- On November 12, 1971, Mariner 9 (launched in March of that year) eased into Mars orbit to wait out the dust storm before astounding us with images of mountains, canyons, and valleys larger than any on Earth.
- On January 5, 1972, President Nixon announced the beginning of a new era in space with the development of the Space Shuttle.
- On January 11, 1972, NASA notified JPL that the Grand Tour project had been killed for budgetary reasons.

The Apollo momentum that had powered a generation of virtuoso American planetary first looks was fast dissipating. The Grand Tour simply reached the starting gate too late for a new planetary endeavor of such cost.

JPL responded to this situation by formulating a cheaper, less ambitious alternative. Within days Bud Schurmeier and his engineering team transfused a decade of hard-won experience in space exploration into an attractive new engineering concept for a rich comparative examination of Jupiter and Saturn and of their moons. It was modestly termed Mariner/Jupiter/Saturn. MJS matched the most promising scientific objectives at Jupiter and Saturn with capabilities already largely proven by previous Mariners, by Pioneers 10 and 11, and by JPL's large new Viking orbiter development then under way.

A greatly enhanced electronic brain, however, remained to be developed because MJS needed an exceptionally good memory and great intelligence. But Schurmeier and his project were more than five years away from launch, almost twice as long a lead time as earlier Mariner and Pioneer developments had enjoyed.

An immediate challenge loomed. MJS would have to be sold to the Nixon administration practically overnight. Just how fast, I learned in February 1972, in a telephone call from the Old Executive Office Building, adjacent to the White House.

"There are questions around here about Mariner/Jupiter/Saturn, Bruce. Any comments?" was the cryptic opening from an old friend, Russell Drew.

He was alerting me from within Nixon's secretive staff deliberations that MJS needed more justification in Washington. Drew, a naval aviator with a PhD in electrical engineering, and an active-duty captain in the Navy, had joined the science adviser's staff in 1966, swelling the civilian-garbed brigade of military officers that inconspicuously strengthens the White House's staff.

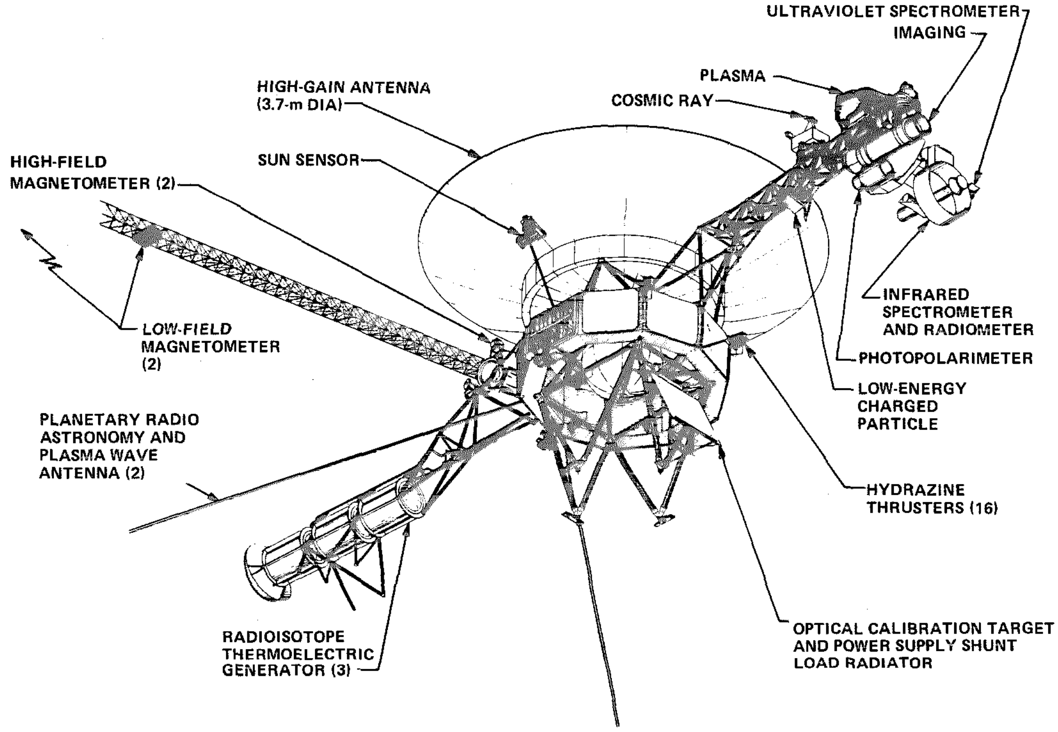
By February 1972 and our off-the-record phone conversation, the President's Science Advisory Council (PSAC), which Russ had ably served, had been reined in. (It would be eliminated altogether in January 1973.) But Drew still cultivated his old PSAC network, quietly funneling outside expert opinion into the budgetary deliberations of the executive branch. Trying to neutralize the damaging scientific opposition that had helped kill the Grand Tour, I told him that the Mariner-class investigation of Jupiter and Saturn was more promising scientifically than any new mission I could think of. The Space Science Board (SSB) of the National Academy of Sciences had sensed another expensive Viking-scale mission that would threaten other space science projects.

"It could be incredibly visual and popular," I said. "And once the Uranus, Neptune, and Pluto requirements are dropped, the mission is more within reach technically, and much cheaper." Then I pointed Russ toward what I hoped was still a key factor at the Nixon White House, despite the national ebbing of interest following the first Apollo landings: "It's certainly the most cost-effective space competition with the Soviets imaginable."

He knew from the secret PSAC briefings, as I did, that, despite the massive Mars and Venus efforts of the Soviets, Jupiter—let alone Saturn—was way beyond their reach. "Very interesting," chuckled the always cheerful Drew as the telephone clicked off.

Broad support for MJS coalesced rapidly. On February 22, 1972, the Space Science Board endorsed MJS as first-rate science (and much more affordable than the Grand Tour). NASA, Congress, and the Office of Management and Budget (OMB) waived their usual procedures in order to consider MJS right in the middle of the annual budget cycle. NASA approved JPL's MJS proposal officially on May 18, just a month before brief press reports mentioned that five men had been arrested for breaking into Democratic National Headquarters in the Watergate Office Building.

In fact, congressional and OMB support for MJS was so strong that an additional $7 million was added to the MJS appropriation for scientific and technological enhancements. The new autonomous electronic brain would now be made reprogrammable to an unprecedented degree. Moreover, some flashy new computer tricks would be built into the spacecraft to assure deep-space communications even under drastic conditions. A new, more efficient computer-driven attitude-control system could also be counted on. No one imagined then that these extra "mental" capacities, intended to assure



Voyagers 1 and 2 had identical structure and instrumentation.

that MJS got safely to Jupiter and Saturn, would first almost disable the spacecraft at launch and subsequently enable it to explore Uranus and Neptune.

At that time neither Uranus nor Neptune figured seriously in MJS's plans. Far from the sun, Uranus receives only 1/400 as much sunlight as Earth. It is *really* cold and dark on Uranus. Few of the remote-sensing instruments designed for Voyager, as MJS was called after 1975, were expected to yield much at Uranus, let alone at Neptune, a billion miles farther yet. In addition, more immediate problems were showing up in tests of that brilliant, autonomous electronic brain. JPL was learning the hard way that it is easier to build complex computer programs and systems than to test them adequately for the unforgiving space environment. But technical challenges are the stuff good engineers thrive on. Most important, MJS had gotten started and was on the way to becoming the most productive robot explorer ever built.

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Things were going less well for JPL as an institution, however.

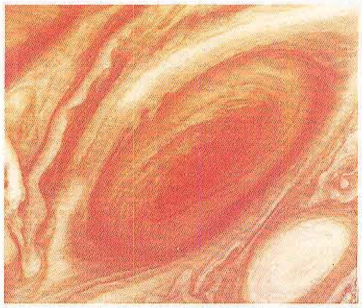
NASA, JPL's sole sponsor, lacked the presidential political support that it had enjoyed before the Apollo moon landings. Since then the agency had steadily declined in national clout and technical capacity. The challenging and uplifting Apollo project had become a glorious, almost mythic, memory for NASA, rather than a gateway to the future. JPL was NASA's only center not staffed by government employees. That made it a natural target for elimination in tough times, a circumstance that added to the "creative tension" inherent in the three-sided relationship between NASA, JPL, and Caltech. Furthermore, JPL had no important role in the post-Apollo focus on the Shuttle and on related uses of astronauts in low-Earth orbit. In fact, JPL seemed to be on everybody's rumored "hit list," awaiting the next big NASA cut. Russ Drew sometimes dropped alarming hints to me of draconian measures under discussion at OMB that would have eliminated JPL.

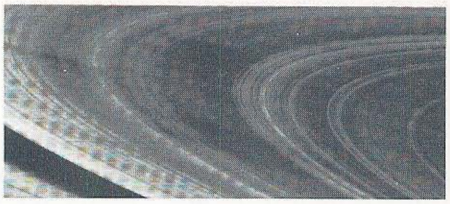
Nevertheless, such alarmism had seemed to me unwarranted in June of 1975, when I flew to Washington for my first official visit with NASA Administrator James Fletcher. Harold Brown, Caltech's president (and soon to be Jimmy Carter's secretary of defense), was waiting for Fletcher's approval before he would announce publicly that I was to succeed William Pickering as director of JPL.

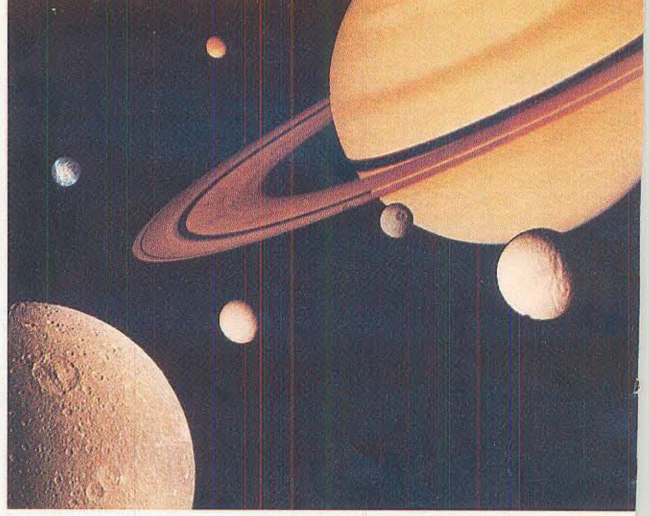
Affable as always, Fletcher had only one substantive question for me. "Bruce," he said, "How do you feel about JPL working for the Defense Department?"

JPL had done no significant military work since 1958, when it became a charter member of the NASA-led civilian space program. I had no personal problem with future JPL defense work, but what a strange question for the head of the American civilian space program to raise! And Fletcher had nothing at all to say to me about planetary exploration, even though he kept prophesying publicly that the 1980s would be "a golden age of planetary exploration."

The message was clear: NASA, a declining institution, felt it could not support JPL as it







What Voyager saw—from left: geyser plume on Io, one of Jupiter's moons (1979); Jupiter's Great Red Spot (1979); the rotating spokes on Saturn's B-ring (1980); a montage of Voyager 1 images of Saturn and its moons (1980); the rings of Uranus (1986); and Ariel, a Uranian moon (1986). Also on this page: Voyager scientists receive the first polarimeter data on Saturn's rings; and on the opposite page, project scientist Ed Stone talks to the media.

had during the halcyon days of the building of America's first satellite, first moon probes, and first planetary explorers.

Unlike my predecessor Pickering, I would thus have a twofold task as director of JPL—to push U.S. planetary exploration to the hilt and, at the same time, to develop a second governmental role for JPL that would be independent of NASA. In 1976, following the oil-price shocks of 1973, government-supported energy research and development was the best (really the *only*) practical alternative for a high-tech, nonprofit, civilian-oriented place like JPL.

So, on April 1, 1976, my first day as director of JPL, I promoted Bud Schurmeier with great fanfare and with instructions to carve out a meaningful role for JPL in energy R & D. Neither Bud nor I, as it turned out, would find deep satisfaction in these new strategic responsibilities. The ebbing of the old Apollo spirit was merging with a broader retreat of American self-expectations in the face of failures in Vietnam and at home. America would not blaze new paths in either alternative energy or planetary exploration. But in 1976 we had to try to create the kind of future that JPL, and America, deserved.

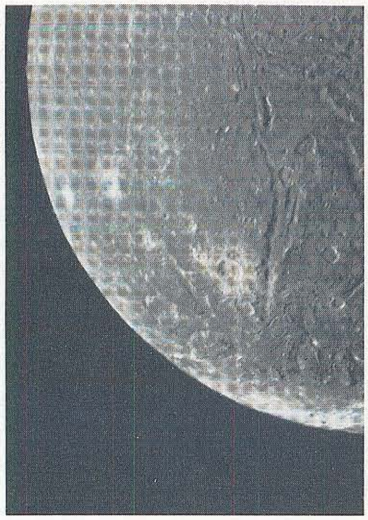
Schurmeier's replacement to head Voyager was John Casani, who at last had his own project. He loved every minute of it—at least until August 20, 1977, the date of the first Voyager launch at Cape Canaveral.

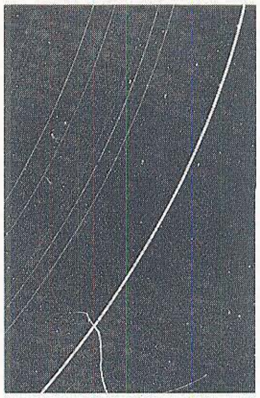
The day before that launch Suzanne and I stood on top of Pad 41 at Cape Canaveral, 160 feet up. The great red gantry tower clutched Titan/Centaur Number 5. Flickers of Florida lightning punctuated the sun-and-rain-washed panorama. The lightning was still far away, but if those scattered thunderstorms came within a mile and a half of us, we and everyone else would have to get out of there fast. We were standing on nearly 700 tons of high explosives.

Beneath us, twin 250-ton, solid-fuel boosters stood ready to power the Titan/Centaur, the largest existing U.S. launch vehicle, off the pad the next morning. The boosters supported a 70-foot-long, two-stage Titan rocket originally designed to fling a city-destroying nuclear bomb. Tomorrow's purpose was sublime in contrast. Two liquid propellants tanked separately within the Titan would mix precisely in a delicately sustained spontaneous explosion lasting six and a half minutes. These rocket firings of the Titan would thrust the graceful Centaur stage and its heavy Voyager cargo through Earth's atmosphere and part way into Earth-circling orbit. Then the intelligent Centaur stage would take charge.

As we gingerly descended the winding stairway of the gantry tower on that glorious Florida afternoon, a quick glimpse of a busy engineer working *inside* the Centaur surprised me. It was a reminder that unmanned rockets do indeed fly by the skill and dedication of humans—on the ground. The engineer was checking this giant's intricate computer brain.

At launch, delicate instruments at the very tip of the Centaur stage would sense precisely the rumbling flight motion produced by the noisy solids and the storable-liquid Titan rocket. As soon as the second Titan stage burned out and





fell away, Centaur's electronic brain would ignite the liquid hydrogen–liquid oxygen mixture of the Centaur high-performance engine.

Then would come the brilliant part. The Centaur's electronic brain would automatically compensate for any shortfall in the propulsion of the earlier stage. It would "fly" the Centaur and its payload precisely into a predetermined low-Earth orbit. The Centaur brain would then shut down the engine temporarily while the rocket, with its remaining fuel and the attached planetary spacecraft, would coast along in that orbit for the tens of minutes required to reach a precise location for that day's planetary departure. At that point, out over the Atlantic, liquid hydrogen–liquid oxygen would be reignited by the brain in the cold silence of space to enable the craft to break free of Earth's gravity and to build up most of the final velocity that would propel it to another planet. Then the final burst of velocity to reach Jupiter would be supplied by yet another rocket stage, fastened directly to the Voyager spacecraft.

Throughout these eventful minutes, Centaur's brain would measure thrust and calculate flight path. At the exact second when the correct velocity was reached, the brain would shut off the Centaur rocket engine forever. Explosives would then separate the precious spacecraft from the now useless Centaur.

This is what is meant by a smart machine. Inside it, working intently, was the even smarter engineer who understood it all.

We continued down the gradually widening gantry tower in the yellowing afternoon, past dormant liquid and solid explosives ready to send Voyager 2 into history the next morning. The lightning drifted harmlessly seaward into a darkening sky.

Why launch Voyager 2 before Voyager 1? The decision had to do with keeping open the possibility of carrying out part of the old Grand Tour dream. Voyager 2, if boosted by the maximum performance from the Titan/Centaur, could just barely catch the old Grand Tour trajectory. In that way the "Uranus option" from Grand Tour days could be maintained. Two weeks later Voyager 1 would leave on an easier and much faster trajectory, to visit Jupiter and Saturn only. Voyager 1 would make up time and reach Jupiter four months ahead of Voyager 2 and then go on to arrive at Saturn nine months earlier. (That's why it was called Voyager 1.) The nine-month separation between the arrivals at Saturn ensured that if Voyager 1 failed in its Saturn objectives, Voyager 2 could still be retargeted to achieve them—but at the expense of any subsequent Uranus or Neptune encounter.

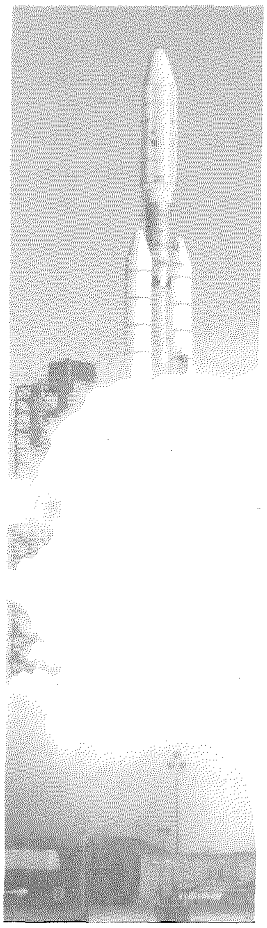
At 10:29 a.m., August 20, 1977, the blast from the twin solids and the Titan core shattered the clear blue Florida morning. Exactly as planned, the Titan/Centaur powered Voyager 2 into Earth orbit, and thence on a path toward the outer planets.

Voyager 2's gyroscopes and electronic brain were alive during the Titan/Centaur launch, monitoring the sequence of events in order to take control upon separation. But here the unexpected happened: Voyager 2's brain experienced robotic "vertigo." In its confusion, it helplessly switched to backup sensors, presuming its "senses" to be defective. Still no relief from its disorientation. Mercifully, the panicky robot brain remained disconnected from Voyager's powerful thrusters, so it did not cause damage to the launch. The Centaur attitude-control system—under its normally behaving brain—stayed in charge, suffering no "vertigo" and, as planned, electronically correcting the disequilibrium of Voyager's brain just before separation.

From the control center John Casani and his tense engineers helplessly watched (though mostly they listened, because there were not enough monitors available to us in Florida) the antics of Voyager 2's disoriented brain. One hour and 11 minutes after lift-off, Voyager 2 fired for 45 seconds its own special solid rocket to provide the final push it needed to get to Jupiter.

One and a half minutes after Voyager's key rocket burn ended, a ten-foot arm holding the

If the two Titan/Centaur rockets for Voyager had been fired in reverse order . . . Voyager 2 would not have received enough velocity to catch the Grand Tour trajectory.



A Titan/Centaur rocket launches Voyager 2 on August 20, 1977. Shortly after launch Voyager's electronic brain became disoriented, and the spacecraft almost didn't even begin its historic journey.

television camera and other remote-sensing instruments was unlatched and deployed as planned. Then, more trouble. Voyager's anxious brain once again sensed an emergency. This time it switched thrusters and actuated valves to control the tiny bursts of gas used to stabilize its orientation. Voyager's robotic "alter ego" (its executive program) then challenged portions of its own brain in a frantic attempt to correct the orientation failure it sensed. Next, Voyager followed the procedures JPL engineers had installed to cope with the most dreaded emergency for a robot in deep space—spacecraft attitude disorientation. (In August 1988 the Phobos 1 spacecraft of the Soviet Union succumbed to such an emergency after receiving an erroneous ground command, and in March 1989 Phobos 2 evidently met a similar fate.) Voyager shut down most communications with Earth in order to begin its reorientation.

Seventy-nine minutes passed while Voyager 2 struggled alone and unaided to find the sun and establish a known orientation. Finally, it radioed confirming data. For the moment, Voyager 2 was stable.

It was all work and no celebration that afternoon in the dimly lit High Bay Conference Room, where, just days earlier, a seemingly healthy Voyager 2 had checked out perfectly. Were the redundant sensors malfunctioning? Was the state-of-the-art brain defective?

The technical discussion in the room was poorly illuminated too. All the new, super-sophisticated fault protection in Voyager's electronic brain operated on the now-painful presumption that it would be triggered *only* by a hardware failure billions of miles from Earth. In that event Voyager would be unable to establish even emergency communications with its human handlers, who could not help it much at that distance in any case. As a consequence Voyager had been programmed virtually to shut off communications with Earth during such emergencies and to fix itself. But, somehow, these deep-space procedures had been triggered right after the launch.

Now, because of those disrupted communications, we were not receiving the useful flow of engineering-status measurements. We simply lacked enough information to figure out the causes of Voyager's mysterious behavior, even though the spacecraft was so close to Earth that communications normally would have been feasible under any emergency.

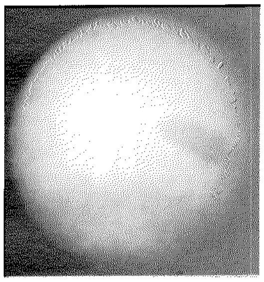
Voyager was proving to be far more autonomous than anyone had foreseen or wished.

Casani's frustrated specialists substituted coffee for sleep in that dark and dreary High Bay area. They crowded around the solitary speaker phone while reviewing the skimpy facts with their equally puzzled colleagues back at JPL. Even as they spoke, Voyager experienced yet another spasm of thruster firing, accompanied by frenzied switching of its redundant brain components. What was going on out there? Had Voyager's massive propulsion module, so gently jettisoned after launch, continued as a ghostly companion on Voyager's trajectory? Was it actually bumping into Voyager from time to time?

Ted Kopf, an attitude-control specialist at JPL, had designed some of that intricate computer logic now running rampant on Voyager 2. He had come to the Florida launch on his own hook for pleasure, not work. But that was before the emergency. I listened now as Kopf and a brilliant JPL systems engineer, Chris Jones, served up precise clues afforded by Voyager 2's scattered radio transmissions. So detailed were their mental images of that complex Voyager brain that they could reconstruct each stage of its successive anxiety attacks since the launch. There had been no hardware problems in the brain—just a slight but serious missetting of computer parameters.

Subsequent detective work shed light on the computer problems first encountered after rocket separation. These were complicated by unexpectedly large vibrations from the unlatching of the instrument boom. There had been no "bumps in the night" from a ghostly companion. Those spacecraft disturbances were simply a complex and overly sensitive reaction by the autonomous Voyager to a familiar space-engineering problem. Small dust particles released by the vibrations from rocket propulsion sometimes drift near a spacecraft. Being close, and being lit by the sun, they are much brighter than the star images that the spacecraft's optical detector normally tracks. In trying to follow the dust particles, the tracker reorients the spacecraft.

A lot of robotic technology and human expertise had accumulated over the years, ensuring that situations like this would be recognized and compensated for. But this new, superautonomous robot did not have that repertoire of human judgment and experience built into it. So it mistrusted itself but was finally righted by its own logic.



Coming soon: Neptune, August 25, 1989.

This could not be allowed to happen again. Desperately, corrections were patched onto the computer programs in Voyager 1, now waiting to be entombed for launch, even as the analysis of Voyager 2 stumbled along. A new mechanism to reduce the excessive vibrations from the instrument boom was designed, tested, and installed. Time was running out.

Sixteen days after Voyager 2's heart-stopping launch, on September 5, 1977, Voyager 1 flew. The last Titan/Centaur in the world shook the ground for miles around Pad 41. NASA had phased out America's most powerful rocket long before a replacement capability, the Shuttle, would be ready. (Indeed, not until the early 1990s will comparable rocket capability be available for American space endeavors, civilian or military—a gap of nearly 15 years.)

Our attention in the control room was riveted on the continued radio updating describing the execution of key rocket sequences. "Solid booster burnout and separation," a voice over the control room intercom said. "Titan core ignition . . . Titan burnout and separation."

But wasn't that sooner than shown on the projection? Yes, there definitely had been an anomaly. In fact, a slight error in the mixture ratio of the two liquid fuels in the Titan had left 1,200 pounds unburned. This was serious. Titan had underperformed, not propelling Centaur and Voyager fast enough. "Centaur ignition," came the words from the public address system. The Centaur's brain, recognizing the Titan performance deficiency, smoothly extended its burn just enough to compensate. After coasting, and then restarting, the Centaur put Voyager and its propulsion module precisely on course—with only a squeaky 3.4 seconds of propulsion left.

"Wow, that was pretty close," I thought at the time. It was only later, over a beer in Cocoa Beach, that I realized that if the two Titan/Centaur rockets for Voyager had been fired in reverse order, if the underperforming one had been used for the more demanding trajectory, Voyager 2 would not have received enough velocity to catch the Grand Tour trajectory. It would have reached only Jupiter and Saturn. The opportunity of the century would have passed us by (even though the rich Jupiter/Saturn comparison would still have taken place). Pure chance had assigned the unexpectedly low-performing Titan to Voyager 1 rather than to the more demanding launch of Voyager 2.

But in September of 1977 it was hard to take seriously any hypothetical extension to Uranus, 2 billion miles from Earth. We were not even off to a good start toward Jupiter, a mere 500 million miles and 18 months away. □