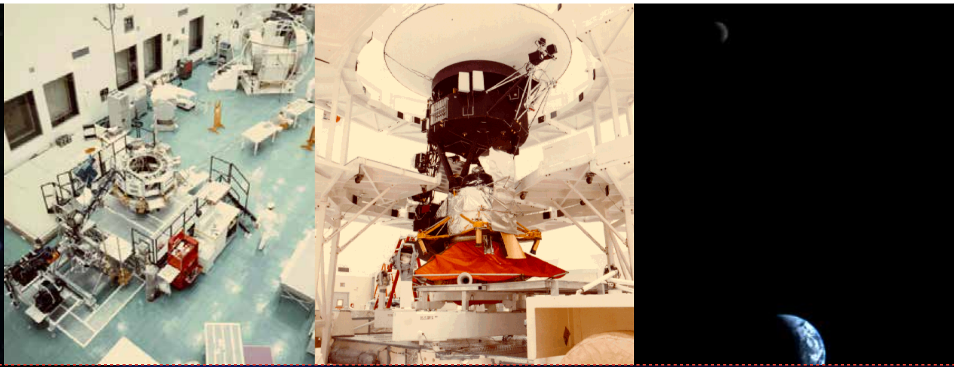


THE OTHER SIDE

by Douglas Smith

In a press conference on September 12, NASA announced that Voyager 1 is now officially cruising among the stars. This resilient robot, built by NASA's Jet Propulsion Laboratory (JPL), had burst through the sun's magnetic "bubble" and crossed into interstellar space on August 25, 2012—almost 35 years to the day after its launch on September 5, 1977. It's now more than 11 billion miles from home and still going strong.

"We got there!" exulted Ed Stone, the Voyager mission's project scientist, principal investigator for the Voyager Cosmic Ray Experiment, and Caltech's David Morrisroe Professor of Physics. "We all hoped, when we started on this 40 years ago, that this would happen. But none of us knew how big this bubble was, and none of us knew any spacecraft could last as long. . . . Setting sail on the cosmic seas between the stars, Voyager has joined other historic journeys of exploration such as the first circumnavigation of the earth, and the first footprint on the moon."

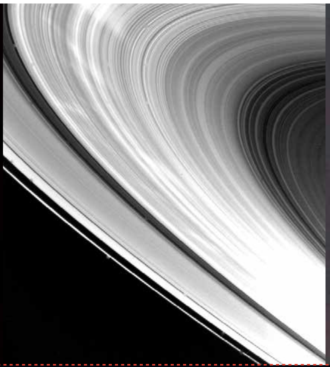
Just how *did* we get there?

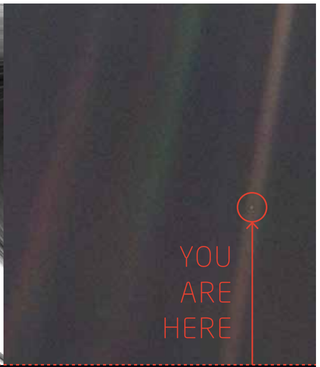
As the outer planets plod through the frozen void, once every 175 years they line up in such a way that Jupiter's gravity can be used to fling a properly aimed spacecraft on toward Saturn, and thence to Uranus and Neptune. In the spring of 1965, Caltech aeronautics grad student Gary Flandro (MS '60, PhD '67) was working part-time up at JPL analyzing so-called gravity-assist trajectories when he realized that such a four-for-one alignment would occur between 1976 and 1979; intrigued by the possibilities, he set about matching possible paths of departure from one planet to lines of approach to the next one. All the path segments had to align perfectly in time and space; like Tarzan swinging from vine to vine through the jungle, missing a transition by even the smallest of margins would spell disaster. A few months and several reams of graph paper later, Flandro had worked out hundreds of itineraries—some reaching all the way to then-planet Pluto—for the upcoming launch window. His boss, Elliott "Joe" Cutting, booked him a meeting with the chief of JPL's advanced technical studies office, aeronautics professor Homer Stewart (PhD '40). Stewart embraced the idea, christening it the Grand Tour.

But despite Stewart's passionate promotion and some glossy publications, the Grand Tour failed to get off the ground. In 1965, simply hitting the broad side of the moon was hard enough, and getting Mariner 4 close enough to Mars to take a handful of decent pictures had pushed JPL to the limit. Still, the notion lingered out on the fringes—much like Uranus and Neptune themselves—waiting for time, technology, and human expertise to catch up.

JPL formally proposed the Grand Tour in 1970, with Harris M. "Bud" Schurmeier (BS '45, MS '48, ENG '49) as the project manager. This was an A-team effort: Schurmeier had just presided over the Mariner 6 and 7 flybys of Mars, and his collaborators included JPL's planetary program director, Robert Parks (BS '44), and its spacecraft systems manager, Raymond Heacock (BS '52, MS '53). It was also a gold-plated Cadillac of a mission—a flotilla of four mother ships carrying probes on parachutes to be dropped off at the various planets en route. The billion-dollar price tag (much of it for technology development) proved too much, and the Tour was axed in December 1971; the following month President Nixon signed a NASA budget authorizing $5.5 billion to be spent developing a space shuttle instead.

But all was not lost. "They told us, 'If you guys can come up with something less grandiose, we'll consider it,'" Schurmeier recalls. "So we went home and quickly put together what we called Mariner Jupiter Saturn [MJS] '77." Saturn was a mere three-year journey instead of 10; instead of four spacecraft, only two would be built, largely





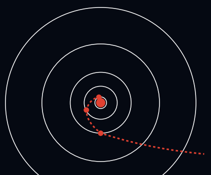
with existing technology; and the probes were deep-sixed. The scaled-back proposal was worked up within weeks, and MJS was officially approved in May 1972 by NASA administrator James Fletcher (PhD '48).

JPL had promised Saturn, but still intended to deliver the full Tour. "One of the Grand Tour's key objectives had been to measure cosmic rays that were unmodified by the sun," Schurmeier says. "Of course, the scientists then didn't really think the heliopause was so far away. So we thought, OK, if we can make it to Saturn, maybe we can last long enough to get out there." The heliopause is the theoretical boundary where the sun's outward flow of charged particles meets a counterflow from the Great Beyond—the unmodified cosmic rays that Voyager 1 is now sampling. "The Cosmic Ray Experiment was proposed by [Caltech physics professor Rochus] 'Robbie' Vogt," says Stone, who inherited the instrument when Vogt became provost in 1984. "He pushed hard for it, and succeeded in making the hunt for interstellar cosmic rays a goal of a *planetary* mission. We thought maybe we'd only have to go twice as far out as Saturn, but it turned out to be twelve times farther away than Saturn."

But first, MJS had to make it to Saturn itself.

Caltech had organized JPL to develop rockets for the Army, and the Lab had maintained its engineering-based approach when it became part of NASA in 1958—if something doesn't work, tweak it and try again. JPL's first steps into space had had a 50 percent success rate, perfectly reasonable for the times. But after going one-for-eight in the early 1960s, director William Pickering (BS '32, MS '33, PhD '36) had assigned Schurmeier and Jack James, who had overseen the Lab's only recent success—Mariner 2's 1962 flyby of Venus—to write an operations manual that might have been subtitled *How to Build a Spacecraft Without Embarrassing Yourself*. Says Schurmeier, "In the early days, people would say, 'Oh, gee—I had a glitch, but it's gone now, so forget it.' We said, 'Any glitch—any time the electronics don't do what they're supposed to—we find the reason and fix it. And if we can't find it, we've got to create work-arounds for all of the possible failures that could have caused it.' And that had to be done before launch."

Schurmeier practiced what he preached. "On Voyager, we were very meticulous about looking at the individual electronic components," he says. "They had to be thoroughly tested before they could be used. Even before you started to build the electronics, the parts had already cost us a bundle. But we knew their pedigrees, how they'd been manufactured, what kind of failures they'd had. It was a big, big effort, but I think it was key to the lifetime we've had."



Of course, components that work flawlessly on the ground can still get fried in deep space, so each Voyager carries A and B copies of every critical system. "For the Grand Tour, we'd designed a triply-redundant computer that would control everything," Schurmeier says. "With Voyager, we couldn't afford to do that, but we did make dual radios, dual computers, and a lot of other dual equipment." The Voyagers' computers were designed to be reprogrammable to an unprecedented degree—and over unprecedented distances. Space is a harsh mistress, and despite rigorous quality assurance, scan platforms sometimes stick, radios die, power converters short out . . . and JPL engineers need to uplink new software that works around the damage.

Detailed design work had begun in earnest in October 1972, and the entire project almost went out the window a little more than a year later, when Pioneer 10 took humankind's first close-up look at Jupiter in December 1973 and encountered intense radiation. Although the Grand Tour proposal had called for "hardened" spacecraft to be built with armored shielding around delicate instruments and military-grade electronics designed to withstand nuclear war, this fiendishly expensive option had been discarded in favor of simply keeping a safe distance. After all, no one had known how strong Jupiter's radiation belts actually were. Now they did. "If we flew far enough away to need no radiation-hardened parts, we wouldn't have a mission," Schurmeier says. "That forced a very large change very late in the process, but we got enough hardening so we could fly close enough for a decent mission."

Mariner Jupiter Saturn was officially renamed Voyager in March 1977; Voyager 1 was launched that September and flew by Jupiter in 1979. In November 1980, it dove around and behind Saturn's Mercury-sized moon, Titan, in order to study its atmosphere before skimming past Saturn's rings on a track across the planet's southern hemisphere that would fling the spacecraft up and out of the plane of the solar system.

On Valentine's Day, 1990, Voyager 1 took one last look over its shoulder, snapping a family portrait of the solar system from about 32 degrees above—and 4 billion miles away from—it. The cameras were then turned off for good.

The ship is now flying blind, but it's not deaf. On August 25, 2012, the cosmic-ray data changed dramatically and Voyager's magnetic-field readings jumped by 60 percent—both signs that the spacecraft *might* have reached the heliopause. However, the key data—the plasma measurements proving that Voyager had left the hot, diffuse "solar wind" behind and entered the cold, dense interstellar medium—was unobtainable because Voyager's plasma science experiment had died just after the Saturn encounter 20 years earlier. Fortunately, on April 9, 2013, Voyager's plasma-wave antennas began picking up oscillations of the plasma that had a steadily increasing pitch. "These oscillations were triggered by a solar eruption that traveled outward through the solar wind like a tsunami crosses the ocean," says Stone. "Although the solar wind ions don't travel out to Voyager, the wave energy does, and our antennas pick up the plasma oscillations caused by the arriving wave. The frequency of the oscillation tells us the density of the plasma Voyager is traveling through."

The plasma team members at the University of Iowa realized that they were hearing the reverberations of the cold, dense interstellar medium from within. They went back through their data, and found a fainter signal with the same rising pitch that had been recorded from October 23 through November 27, 2012. The pitches fell on a line pointing straight back to August 25 as the date of entry to be stamped on Voyager's interstellar passport. "Voyager is now on a 10-year journey through the space between the stars," says Stone. "We should have enough power to keep all of the instruments running for another six years, and we'll turn the last one off in about 2025. Who knows what we'll find before then?" e&s

SNAPSHOTS OF A VOYAGE *On page 11, from left to right: Voyager gets its initial system test at Cape Canaveral Air Force Station prior to launch in 1977; the robot spacecraft at the Kennedy Space Center, where it was assembled and encapsulated; Voyager's first attempt at photography, showing a crescent-shaped Earth and moon, taken on September 18, 1977, 13 days after liftoff. On page 12, from left to right, images taken by Voyager: a dramatic view of Jupiter's Great Red Spot taken in February 1979; Ganymede, a satellite of Jupiter and the largest moon in the solar system; and Saturn, taken from a distance of 11 million miles in October 1980. The graphic on page 12 shows an illustration of Voyager's path through the solar system. On page 13, Voyager captured, from left to right: a montage of images of Saturn and a few of the planet's 60 moons, taken in November 1980; a close-up of Saturn's ring system; and part of the first ever "portrait" of the solar system taken by Voyager, with Earth showing up as a pale blue dot.*