OUTWARD BOUND

Ed Stone has spent 36 years guiding the twin Voyager spacecraft through the Solar System. Next stop, interstellar space.

BY ALEXANDRA WITZE

The 44 notebooks lined up neatly in Ed Stone's office span just half a metre of shelf space. But inside these journals, in meticulous black printing, Stone has chronicled the longest journey that humans have ever launched.

Since they left Earth in 1977, the twin Voyager spacecraft have conducted pioneering explorations of Jupiter, Saturn, Uranus and Neptune, revealing these gas giants and their moons to be far more active than scientists had expected. Now the two probes are cruising towards the edge of the Solar System — a boundary that has yet to be crossed by any emissary from Earth.

Stone has chaperoned the Voyagers from their conception. He is the mission's first and so far only project scientist, tasked with juggling the competing needs of the scientists who use the Voyagers' instruments against those of the engineers that fly the craft. By all accounts, he has succeeded. "Somehow he got that discordant orchestra to play together," says Andrew Ingersoll, a planetary scientist at the California Institute of Technology (Caltech) in Pasadena who was on the team as the spacecraft flew past Jupiter and Saturn.

To many, the Voyagers are synonymous with the unflappable Stone. The man and the mission are bound together, even as the probes enter yet another phase in their storied lifetime. Almost 19 billion kilometres from Earth, Voyager 1 is flirting with the edge of interstellar space, the medium between the stars. Last July, it saw the flood of charged particles from the Sun subside to a mere trickle — a sign that the spacecraft may soon break out of the Solar System.

Stone, who is now 77, plans to be around when it happens. He is not about to dial back his legendary work habits — not as Voyager nears such a historic milestone, with its promise of provocative science. Sitting in his Caltech office, with the Voyager logs behind him, the trim, elfin physicist looks mildly astonished at any suggestion of retirement.

Talking about his spacecraft, Stone could just as easily be describing his own drive. "What keeps Voyager still alive," he says, "is that it's still discovering."

ATOMIC AMBITIONS

Stone grew up in Burlington, Iowa, a town on the Mississippi River where his father worked in construction and was always tinkering with machines. Young Edward devoured copies of *Popular Science* magazine and *The Book of Knowledge*, and taught himself to build radio receivers.

The atomic age was well under way as Stone finished high school, and a teacher at his junior college told him about the world-renowned physics programme at the University of Chicago, Illinois, home to nuclear pioneer Enrico Fermi. Off Stone went, planning to study nuclear physics. But in October 1957, the launch of Sputnik inspired him to switch to space physics. For his graduate work, he helped to develop balloon- and satellite-borne detectors to track fast particles and cosmic rays streaming into Earth's atmosphere from space. In 1964, that led to a research position — and then a faculty job — at Caltech, which was starting a

space-physics group.

His successful work on cosmic-ray detectors caught the eye of engineers at the Jet Propulsion Laboratory (JPL) in Pasadena, who were developing a mission initially called Mariner Jupiter–Saturn '77. They recruited Stone in 1972 to serve as project scientist — the person who oversees a spacecraft's scientific goals.

The mission grew into the most ambitious planetary exploration ever. Its two probes would each survey the outer Solar System with 10 instruments and a radio-science experiment — a set of investigations more sophisticated than those carried out by the Pioneer 10 and 11 craft that had reached Jupiter and Saturn before them.

The two spacecraft launched from Cape Canaveral, Florida, in August and September 1977, carrying golden records engraved with messages and recordings from Earth. Before the launch, they were renamed Voyager 1 and Voyager 2.

It was not all smooth sailing. The boom carrying the scientific instruments for Voyager 2 could not deploy fully after launch. And the main radio receiver on the same probe failed completely in the spring of 1978, forcing engineers to turn to a back-up system.

Those and other glitches put added pressure on Stone, who had to coordinate between the principal investigators in charge of the instruments and the mission engineers who were troubleshooting the issues. He was the one who had to work out what science was achievable, given the constraints of the craft.

The results started to pour in during 1979, when first Voyager 1, then Voyager 2, flew past Jupiter. They spotted sulphur volcanoes belching from Jupiter's moon Io, as it was flexed by the giant planet's powerful gravity. Passing by the moon Europa, the probes photographed long, dirty-looking fractures in its icy surface, a possible clue to a subsurface ocean that could harbour extraterrestrial life. And they discovered a plasma, with temperatures of hundreds of millions of degrees Celsius, enshrouding Jupiter's magnetosphere. These and dozens of other finds now fill planetary-science textbooks.

When the probes arrived at Saturn in 1980–81, they uncovered 'shepherd' moons that herd the ice and dust in Saturn's outermost ring, which turned out to have a strange kinked appearance. The Voyagers also studied gigantic aurorae that swallowed much of the planet's northern and southern poles.

Next, mission controllers sent Voyager 1 on a trajectory out of the plane of the planets and towards the boundary with interstellar space. Voyager 2 sailed on to Uranus in 1986, where it found two new rings, ten new moons and an odd magnetic field oriented far away from the planet's rotation axis. Images taken of Miranda, the smallest and innermost of Uranus's major moons, showed a strikingly complex face with a deep, chevron-shaped groove that hints at a bizarre geological past.

When Voyager 2 reached the seemingly placid

NATURE.COM

For a slideshow of Voyager history, visit:

go.nature.com/cqffep

GOING, GOING...

Launched in 1977, the twin Voyager spacecraft have toured the outer planets (centre) and are now hurtling towards interstellar space (bottom). At nearly 19 billion kilometres from the Sun, Voyager 1 is in the process of leaving the heliosphere, the region protected by the Sun's magnetic field (left).

blue disk of Neptune in 1989, it discovered winds blowing at 2,100 kilometres per hour, the fastest in the Solar System, which fuelled storms such as an Earth-sized Great Dark Spot. Scientists had not expected such violent atmospheric activity on a planet that receives just 0.1% of the solar energy that bathes Earth and drives its weather patterns.

Stone is fond of saying that the Voyagers have returned 200% of the science he had expected: “We learned so much more than we possibly could have imagined.”

TEAM PLAYERS

Voyager alumni say that Stone deserves a major share of the credit for that achievement. As project scientist, he has from the beginning chaired the science-steering group, which is composed mainly of the 11 principal investigators. When the group could not agree on which observations to prioritize, Stone stepped in and made that decision — essentially choosing who would get to make discoveries.

Hence his shelf of notebooks. By carefully recording everyone's input, Stone says, he let everyone know that he considered all perspectives. "We always knew he was fair," says Ellis Miner of the JPL, who was assistant project scientist for the Saturn, Uranus and Neptune encounters.

In a shift from usual practice at the time, Stone forced Voyager

scientists to work across the clique-like teams that had sprung up around each of the 11 investigations. Before the Jupiter fly-by, he created overarching working groups around four key themes: moons, rings, atmosphere and magnetosphere. Each group was tasked with focusing on the scientific questions that could be answered by all of Voyager's instruments. This forced members of the instrument teams to talk across boundaries, Stone says, so that "I didn't have to be a referee all the time".

Tension still cropped up. Stamatis Krimigis, the principal investigator for the instrument that measures low-energy charged particles, remembers one particular stand-off with the plasma-instrument group. Krimigis's particle detector worked by rotating sensors to scan different parts of the sky, which shook the nearby plasma instrument and irritated the scientists in charge of it. Stone negotiated a compromise schedule: sometimes the particle instrument rotated quickly, sometimes it rotated slowly to reduce the vibrations, and at other times it remained still. "We were all in the end equally unhappy," says Krimigis, of the Johns Hopkins University Applied Physics Laboratory in Laurel, Maryland, and the Academy of Athens. "That's the sign of a good negotiator."

After Voyager 2 left Neptune in 1989, the two craft earned a new name to reflect their next assignment: the Voyager Interstellar Mission (see 'Going, going...'). The title carried a fair dose of hope, given that no one

knew how long it would take to coast to the edge of the Solar System. In the intervening years, however, Stone had plenty to keep him busy. From 1991 to 2001 he served as director of the JPL, overseeing mission successes such as the 1997 Pathfinder landing on Mars as well as spectacular failures such as the loss of both a Mars orbiter and a Mars lander that followed Pathfinder. It was the era of NASA's 'faster, better, cheaper' approach to spacecraft, and Stone admits that the missions failed because the JPL pushed that ethos too far.

After retiring from that hectic post, Stone returned to teach and do research at Caltech. Today, he rarely travels up the 210 freeway to Voyager mission control at the JPL. There is little need, because engineers carry out the daily tasks necessary to keep the probes healthy and in touch. Their job gets tougher every day: Voyager 2 is 15.2 billion kilometres from the Sun and Voyager 1 has reached 18.6 billion kilometres — more than three times the distance between the Sun and Pluto.

One early morning in April, the team engages in an agonizingly slow conversation with Voyager 1. Engineer Roger Ludwig is testing a new command sequence that would allow Voyager to delay some tasks to better cope with the limits on Earth-bound communications. It took more than 17 hours for the commands to travel at light speed to the spacecraft, and a similar span for the response to return. Now, in the predawn hours, Ludwig is eager for the answer.

A slow stream of numbers pops up on a pair of computer monitors, and Ludwig checks to see whether the sequence has worked. The results look promising, but the Voyager team will test the code several more times before making any changes. This long into the mission, engineers don't want to make any silly mistakes. "We all feel like we're flying a national treasure," says Ludwig.

That includes Stone, who has stuck with Voyager because he is eager for more discoveries. It has been a long wait since Neptune. The team has talked so many times about the impending departure into interstellar space that office doors around mission control are decorated with a photo of a forlorn-looking Voyager with the quote: "Whenever people stop paying attention to me, I pretend to leave the Solar System."

THE FINAL FRONTIER

The exit has turned out to be more complicated than scientists had anticipated. Voyager 1 is somewhere near the edge of the heliosphere, the giant cocoon of charged particles from the Sun that surrounds the Solar System and protects the planets from the high-energy particles that streak through interstellar space (see *Nature* 489, 20–21; 2012).

In December 2004, the low-energy-particles instrument on Voyager 1 indicated that the solar wind had slowed abruptly, a sign that the craft had entered a turbulent boundary region surrounding the heliosphere.

Then, in July and August 2012, the speed of the solar wind dropped to essentially zero even as Voyager began recording higher-energy particles. Krimigis calls those changes "totally and completely unanticipated". By themselves, they might suggest that Voyager 1 had crossed from the boundary region into interstellar space.

But the science team has remained cautious because another expected signal has not yet appeared. When Voyager 1 enters interstellar space for real, Stone and others expect the orientation of the magnetic field to change from predominantly east–west (as driven by the Sun) to randomly changing directions. So far, data from Voyager 1's magnetometer show essentially no change in the direction of the magnetic field.

The team has struggled to make sense of these signals. One day in April, Stone wrinkles his forehead while looking over some plots of particle data. "We're now seeing what's outside, even though we're not outside," he says. "The magnetic field says we haven't gone out yet." He and other mission scientists think that Voyager 1 is on some kind of 'magnetic highway' that connects the Sun's magnetic field lines to those of interstellar space, allowing charged particles to enter the border zone. The team described the latest results in December at the American Geophysical Union (AGU) meeting in San Francisco, California, and will report details in an upcoming suite of papers in *Science*.

Stone works to keep tight control over the Voyager message. In March,

for example, he moved quickly to counter a press release from the AGU announcing that Voyager 1 had left the Solar System. It will leave when he says it does.

At that point, the spacecraft will enter a realm completely new to science. The particle detector will measure galactic cosmic rays that are too weak to penetrate the heliosphere and enter the Solar System. Voyager's magnetometer will gauge the strength of the magnetic field between nearby stars for the first time. Scientists will finally get a glimpse of what truly deep space is like.

The information coming back from Voyager 1 as it leaves the heliosphere "is the only data we'll ever get from this region, and it's incredible," says Merav Opher, an astrophysicist at Boston University in Massachusetts, who is not part of the Voyager team.

With the key transition so close, Stone is getting nervous. To make sure that scientists catch the change when it happens, he made a strong pitch for more coverage by the worldwide system of giant antennas known as the Deep Space Network. The mission is now getting as many as ten precious hours of antenna time daily.

ENERGY CRISIS

But Stone and his team know that they have limited time. Voyager 1 is 124 times as far from the Sun as the Earth–Sun distance, and gaining 3.6 of these astronomical units every year. Signals are steadily fading. Both spacecraft are powered by about 315 watts from the radioactive decay of on-board plutonium-based generators, but that power drops by about 4 watts every year. Of the 10 original instruments, five are still working on Voyager 2 and four on Voyager 1.

**"WHENEVER PEOPLE STOP
PAYING ATTENTION TO
ME, I PRETEND TO LEAVE
THE SOLAR SYSTEM."**

By 2020, the power will have ebbed to the point that mission managers will have to start switching off more scientific instruments, one by one. The job of choosing which goes first will fall to the project scientist.

Stone says that he has not yet thought about which instruments to let die, should he be around to decide.

By 2025, all the plutonium power will be gone, and the Voyagers will become lifeless hulks. They will probably never come as close to another star as they have been to the Sun, and their famous golden records will drift mutely through space.

Yet Stone has no time to get nostalgic; there is more discovering to be done. Among other jobs, he serves as vice-chairman for the board of the Thirty Meter Telescope, which will be the world's largest optical telescope when it is completed in the early 2020s on Mauna Kea, Hawaii. One day, its giant mirrors will gaze past the Voyagers towards distant star systems.

Stone is also helping to develop Solar Probe Plus, a mission designed to go closer to the Sun than any other spacecraft. It will follow an elaborate looping path that will take it past Venus seven times and then into a series of close solar encounters, swooping within 10 solar radii of the Sun's surface again and again. The probe's heat shield will protect it from temperatures of 2,000 °C, and its instruments will collect information about how and where the solar wind is born.

Standing outside his office, Stone gazes at a bulletin board covered with printouts of the Sun's activity over the past few solar cycles. "I've never been frustrated with exploration," he says. "I've been lucky to have the right thing to do, to be on projects that have been successful."

Solar Probe Plus is planned for a 2018 launch, which would put its first close encounter with the Sun in December 2024. By then Stone will be pushing 89. But even so, he would like to be around when the science starts streaming in — about the same time that the Voyagers will be fading beyond communication into the cold cosmos. ■

Alexandra Witze reports for *Nature* from Boulder, Colorado.