TERMINATION SHOCK

Last Days of a Lonely Interstellar Spacecraft

By Oliver Roeder
Photography by Ryan Young

The Voyager spacecraft are the frontier scouts of our species and, given their head start, they may be for ever. One day in the distant future, when the Sun expands and engulfs the Earth, they may be the only evidence that we ever existed. But last November, Voyager 1, the most distant human-made object from our planet, stopped speaking to us.

Voyager 2 launched first, in the summer of 1977, atop a Titan-Centaur rocket from Cape Canaveral, Florida. Voyager 1 followed a couple weeks later. It was the faster craft, and quickly overtook its sibling. The spacecraft is now 15.2 billion miles away from Earth and adding to that distance at more than 10 miles per second. So fast you wouldn't see it if it flew overhead.

The Voyager twins were embarking on a grand tour of the giant outer planets, Jupiter, Saturn, Uranus and Neptune, photographing them and collecting scientific data. In 1977, those planets were aligned as they are only every 176 years, allowing the two spacecraft to slingshot among them, using "gravity assists" to steal a bit of the planets' momentum and accelerate through the solar system. The solar system being a large place, the tour spanned the 1980s.

As the spacecraft approached a planet, eager Voyager scientists would bring sleeping bags to the office or nap in their cars. Our knowledge of these heavenly bodies hadn't yet extended much beyond Galileo Galilei. Data on magnetic fields and chemical composition flowed back from the twin spacecraft, as did haunting images, a meagre 800 pixels on a side, crawling on to screens and turning mythology into reality. At Massachusetts Institute of Technology, an undergraduate hacked into Nasa's image feed, and professors raced to his dorm room to take a look. "Well, that's just not possible," said one, glimpsing the strange beauty of Saturn's rings.

When the Voyager twins were finished with the planets and their moons, they just kept flying. Given the laws of physics, what choice did they have? They now speed through the cold dark of interstellar space, beyond the influence of our Sun.

Mounted on each spacecraft is an aluminium phonograph record, plated with gold. This is just in case they are ever scooped up by aliens and contains images of our DNA, ourselves, our creations and our world. It holds greetings in 55 languages, and the sounds of animals and machines. It also plays music, including Beethoven, Mozart, Louis Armstrong, Blind Willie Johnson and a choir of Georgian folk singers. As a result, the Voyager mission is wildly popular in the country of Georgia.

On Valentine's Day, 1990, Voyager 1 turned its camera homewards, four billion miles away, and took a photograph now known as "Pale Blue Dot". The Earth is microscopic, a tenth of a pixel, a pinprick lost in inky dark and shafts of light. "On it everyone you love, everyone you know, everyone you ever heard of, every human being who ever was, lived out their lives," wrote Carl Sagan, who chaired the committee that developed the golden record.

Then Voyager 1 shut off its camera and flew away. Powered by small balls of plutonium-238, it's been flying away ever since. And then it broke. In recent months, engineers have been digging through archives, trying to remember how the spacecraft works and how to talk to it again.

IN MAY, I TRAVELLED TO VOYAGER'S BIRTHPLACE and headquarters, Nasa's Jet Propulsion Laboratory (JPL), near Pasadena, California. Dozens of buildings are layered into foothills of the San Gabriel Mountains. The lab is larger than Disneyland, festooned with intricate piping and towering scaffolding, and protected by armed guards. Its facilities are named things like the Celestarium and the Mars Yard, and it has its own fire station. The campus is peppered with yellow warning signs: "Flight Hardware – Safeguard It". Even waste bins here caution that their contents are "government property".

The space scientists and engineers in California refer to Voyager 1's problem as "the anomaly". A skeleton team of about a dozen people work on the Voyager project now, many of them part time, down from hundreds at the time of the planetary encounters. They are housed in a corner of one floor in Building 264. Their offices have the same dun carpets, taupe filing cabinets and particleboard shelves as local insurance adjusters. The mission costs only about $7mn a year, around 0.03 per cent of Nasa's budget.

Their labour is marshalled by aerospace engineer Suzanne Dodd, Voyager's project manager. Voyager was Dodd's first job out of college in 1984, working on the Uranus encounter. She was a "sequencer", relaying instructions to the spacecraft in its arcane language. She stayed on through Neptune, three years later, then left for other jobs in the space business. When JPL approached her about returning to run the show, in 2010, she thought, Voyager is still going? It was and she accepted. "People resonate both with the discoveries of Voyager and with this idea that we're sending a piece of ourselves out into interstellar space for some being to find in the future," Dodd told me.

Linda Spilker, a physicist and the mission's project scientist, joined Voyager in 1977, also right out of college, just before launch. She'd been staring at planets since she was a child. "I used to look at Jupiter and Saturn and see some of the moons as pinpoints of light," she told me. "So I said, 'Sign me up for Voyager. I want to see these worlds that I've seen through my tiny telescope.'"

Dodd and Spilker's longevity is typical of Voyager, but rare elsewhere. "People don't spend their whole careers on one spacecraft because the spacecraft don't last," Dodd said. But Voyager did last, as did its staff, many of whom devoted decades and entire careers. One estimate pegs the total work hours put into Voyager on the same magnitude as the Great Pyramid of Giza. That poses challenges when staffers retire or die. A great accretion of human knowledge erodes. Ed Stone, the spacecraft's great eminence who died on June 9 at age 88, was Voyager's project scientist for 50 years. "No matter how hard you try to write things down on paper, you can't capture everything that you've learnt," Dodd said. "And sometimes those things become important later on, when we have an anomaly."

When Voyager broke, the team couldn't fix it. They did not, for example, have any flight-software engineers. No one remembered the intricacies of its arcane source code. They could not decipher its whimpering messages. They didn't know how to build a pyramid any more. They needed craftspeople and they needed archives.

They call them the tiger team – an elite squadron of experts in software, systems, telecoms and other assorted wizardry plucked from every corner of the Jet Propulsion Laboratory, charged with diagnosing and fixing the anomaly. It was led by Jeff Mellstrom, chief engineer of JPL's astronomy and physics directorate. He'd also worked at JPL for decades and his own retirement was just a few months away. "I was anxious," he told me. "I made commitments to people I love." Along with Dodd, they began recruiting. One by one, the wizards' phones rang. "You're not going to believe this, but would you like to work on Voyager?"

The lab became a Level 1 trauma ward for a geriatric spacecraft, staffed, in many cases, by greybeards. At least a couple of wizards were lured out of retirement, one of whom first started working on the project before it launched. They were the "freakin' geniuses" of the lab, as Kareem Badaruddin, the acting Voyager mission manager, told me. JPL was getting the band back together.

That both Voyagers have survived and functioned for 47 years is a miracle. Their data is stored on eight-track cassette tapes. Their external wiring is wrapped in aluminium foil bought

at a local grocery store. Their computers are ten million times slower than a modern laptop. The power of their signals when they reach Earth are microscopic zillionths of a watt. Essentially, the tiger team would have to reverse-engineer and rescue a spacecraft that was 50 years old and 15.2 billion miles away.

"It was an archaeological dig," Dodd said. "You're going through old, yellowed schematics and lots and lots of memos."

Across the hall from Spilker's office is a vault-like archive, heavy with grey cabinets and shelves. On a table near the entrance, a pair of thick orange binders, dated 1977, are titled "Spacecraft Functional Requirements Book". Blue binders are filled with lithographs of the outer planets and snapshots of Sagan. Black binders hold graphics on atmospheres and magnetic fields. In a cubicle there are cupboards of film canisters, floppy disks, VHS tapes, CDs, DVDs and paper bags stuffed with God-knows-what. And there are thousands of bound pages of handwritten notes, and notes on those notes – they reveal calculations, insights and intra-office disputes. On a wall nearby they'd hung an original schematic of the spacecraft.

After word of the anomaly spread, Spilker got emails from the spacecraft's extended family, eager to help. *My dad worked on Voyager, and there are all these boxes in our garage. Do you want me to mail them to you?*

VOYAGER 1 SUFFERS MANY AILMENTS OF AGE. It has arthritis. During its planetary encounters, the team excitedly swung the camera and other instruments this way and that; this squeezed the lubricant out of the bearings of its articulated platform. Only painstakingly slow movements could loosen its joints.

It also has heart disease, as Todd Barber, its propulsion engineer, explained. The arteries that deliver its propellant, which keeps it perfectly pointed at Earth, are partially clogged. Barber calls himself a space plumber and wore a shirt with flying saucers on it as we spoke in the Voyager office. He had considered all the usual cardiological remedies. Diet: unfortunately, Voyager eats only the propellant hydrazine, total junk food. Exercise: they haven't thought of a way to fire the thrusters to clear the blockage. Medication: so they've relaxed its alignment a bit and fire its thrusters less often; in other words, Voyager is on beta blockers.

Most pressingly, Voyager 1 has severe memory loss.

It stopped speaking clearly on November 14. All they received at JPL was a carrier signal. This was described to me in many ways: flatlining, an interstellar dial tone, useless ones and zeros, gibberish, no data. Imagine your friend is on a long journey and sends you a detailed letter every day, then, one day, empty envelopes start arriving. What happened to your friend? How do you help?

By December, the tiger team began examining the post. At least they were receiving something. They knew, therefore, that the spacecraft had power, and that it was pointed at Earth. It had to be a computer problem. There are three computers aboard Voyager: the attitude and articulation command subsystem, the computer command subsystem and the flight data subsystem (FDS). They do more or less what they say on the tin. And because it is meant to collect and bundle information, and ship it to Earth, the tiger team quickly suspected the FDS.

They started with a few safe and easy tricks, hoping for a magic fix. Switching between certain

FROM LEFT: SUZANNE DODD; JET PROPULSION LABORATORY'S MISSION CONTROL CENTRE; DOCUMENTS ARCHIVE
PREVIOUS: SCALE MODEL OF VOYAGER I AT NASA'S JET PROPULSION LAB

ONE ESTIMATE PEGS THE TOTAL WORK HOURS PUT INTO VOYAGER ON THE SAME MAGNITUDE AS THE GREAT PYRAMID OF GIZA

TODD BARBER WITH LUCKY PEANUTS

primary and back-up hardware was one. When nothing worked, they began to suspect the FDS's memory, and that posed a problem. Normally they could load a fix on to the back-up memory and then swap that with the prime memory. But Voyager 1's back-up memory was abandoned in 1981. One bit in each of its words is stuck. The last pattern the engineers wrote to it was "3333" in every location. Because of the broken bits, every word reads "333B" and always will.

The FDS computer runs 10 different programs, called telemetry modes, which alter the messages sent back to Earth. For example, EL-40 sends simple engineering data about the spacecraft, while CR-5T sends back richer science data about outer space. Perhaps one of these programs had an error in the memory. By February, the tiger team decided to ask Voyager 1 to cycle through them one by one. A similar tactic had fixed Voyager 2 in 2010. But it wasn't as easy as typing in a command.

Voyager's mode depends on two variables in its memory, both of which the code was too broken to access. To access and change them would require a now-infamous "hardware poke", bypassing the software and going straight to the memory. It was a manoeuvre that the Voyager team had studiously avoided, at all costs, since launch. The tiger team knew from the archival memos that "they were really afraid of it, but we had no choice", Dave Cummings, a tiger-team software engineer, told me.

On a Friday, they poked across the solar system, the world's most-distant software update. They gave each mode a few minutes to percolate before switching over to the next one. And then they waited. "It's like doctors with an EKG," Badaruddin said. "We were looking for the signal."

VOYAGER'S CHASSIS IS A DECAGONAL aluminium "bus", about six feet wide and a foot tall, each side packed with electronics. A high-gain antenna sits on top like a sombrero, and seven arms called "booms" poke out like whiskers. It's ungainly, but perfectly suitable for doing 38,000mph in outer space. Including all the appendages, it's about the size of a truck. The golden record is bolted to the side like a number plate.

But Voyager would be just a distant metal sculpture without Nasa's Deep Space Network, a trio of parabolic-antenna sites in California, Spain and Australia. Built into bowl-like, semi-mountainous terrain, they uplink to and downlink from our machines in deep space, typically defined as anything beyond the moon. JPL calls it "the largest and most sensitive scientific telecommunications system in the world". Voyager and the Deep Space Network have grown up together.

The Goldstone site in California sits on a treeless military base in the Mojave Desert, 100 miles north-east of the lab. Its antennas are set miles apart, in a landscape of sagebrush and wild burros. The largest of these, 70 metres in diameter, is roughly the same size as Centre Court at Wimbledon. As I write, it is receiving something from Voyager 1 at a rate of 160 bits per second. Voyager communicates with radio waves, which travel at the speed of light. The round trip to Voyager 1 at that speed is 45 hours.

From these global antennas, the data flow into JPL mission control in California, a place known as the dark room, or "the center of the universe" as a sign on its wall reads. It is via this room that we gather much of our knowledge about outer space. On a recent weekday afternoon, it was staffed by a small crew who drank Mountain Dew and stared at complicated and colourful charts on large monitors, co-ordinating antennas and spacecraft, like galactic air-traffic controllers.

The Sunday after their initial poke, the tiger team got an email from an engineer monitoring the inflow: "At this time, no joy." No observable change in the ground data system, no heartbeat detected. As the software wouldn't respond, the team considered going directly at its hardware again – reloading the whole works just as they'd done on the ground the first time they ever started the computer. Voyager was originally run on an operating system of punch cards. This approach, a sort of brain transplant, also scared everyone. "We'd have to just go in blind, with a tremendous amount of faith, and assume that everything's going to work," Mellstrom said.

Meanwhile, they began preparing a piece of code, so small you could memorise it, called min cmrot, short for "minimum command routine". All it does is acknowledge its own existence, an interstellar "Hello, world" program. The instructions for writing it were discovered in some handwritten notes. The team gained confidence when they also discovered a typewritten version. Again office memos warn their readers never to touch this program, and no one had in more than 30 years. When they were satisfied they'd got it right, they modified it to min mro – "minimum memory readout". The galactic geriatricians desperately needed to hear more from Voyager about its symptoms.

OVER THE COURSE OF A MONTH, OTHER TIGER-team members were dissecting carrier signals and subcarrier signals, raw radio data. They'd been recording Voyager's "gibberish" and were listening to it with special tools. In data from one of the 10 programs, these wave wizards, including Andrew O'Dea and Daniel Kahan, found a faint blip. That single blip held a cascade of clues: the processor was working, some memory was working and their poking hadn't killed the spacecraft. And the envelope might have something in it after all. Upon further examination, one of them noticed, "You know, there's a whole bunch of 333Bs in here."

Voyager was dumping its memory back to Earth, though without the usual digital markers that make it easy to identify. On the ground, they reconstructed the message piece by piece and compared the dump to a "golden copy" saved before the anomaly. Within another couple of weeks, a tiger-team hardware maven discovered that 256 words of memory, one chip's worth, had been corrupted. Whatever caused the problem, "it clobbered that particular part, clobbered some critical subroutines", Mellstrom said. The chip was deemed a total loss. The processor couldn't work through such a large mess, and so the code that was there would have to be rewritten and relocated.

That daunting task was given to two intergenerational flight-software engineers: Cummings, 70, and Armen Arslanian, 28. Cummings was plucked off the devilishly complex Mars sample-return mission, and Arslanian was seconded from Psyche, a hypermodern spacecraft bound for a metallic asteroid. "Sure, why not? It's a historic mission," Arslanian said when he got the call. He'd got his start writing code for small satellites in college. The three of us spoke at JPL near a life-size model of the spacecraft that they helped rescue.

The memory on the FDS is equivalent to 16 kilobytes, much smaller than the plain text of this article, and it was already densely packed. The lost code wouldn't fit anywhere wholesale, nor would its component parts, so it had to be finely diced, gently massaged and carefully replaced. Cummings and Arslanian relied on hand-drawn circuit diagrams, unearthed in the archive, which they posted on a wall and annotated with sticky notes. And, terrified of a botched surgery, they relied on pages and pages of an ever-growing checklist.

"We agonised over each command, because anytime you send a command to the spacecraft, you're potentially changing something up there. And the spacecraft is so old and so compromised in certain ways that it's…" Cummings trailed off.

"Delicate," Arslanian said. "Delicate."

JIM BELL WAS AN "INEXPERIENCED PUNK UNDER-grad" when he took a job working nights for a lead engineer on Voyager's camera team. He was invited

FROM LEFT: PHOTOGRAPHS OF THE VOYAGER TEAM, INCLUDING CARL SAGAN, FROM THE TIME OF THE LAUNCH; SCALE MODEL OF THE GOLDEN RECORD ON VOYAGER I

'WE'D HAVE TO JUST GO IN BLIND, WITH A TREMENDOUS AMOUNT OF FAITH, AND ASSUME THAT EVERYTHING IS GOING TO WORK'

JEFF MELLSTROM, CHIEF ENGINEER

inside JPL for the Uranus encounter, in 1986, making coffee and photocopies and picking up pizzas at the front gate. The job was his "gateway drug into robotic space exploration". He is now a planetary scientist at Arizona State University and author of *The Interstellar Age*, a book about the mission.

Bell recalled glimpsing distant planets in an era before the internet, "the thrill of seeing this place get bigger in the windshield and then flying past it", he told me. In particular, he marvels at the "national parks" of the solar system, discovered by Voyager. There is a sheer cliff on Miranda, a Uranian moon, 12 miles high. You could jump off it and fall at comfortable speed for an hour. On Titan, orbiting Saturn, you could stand in a waterfall made out of methane and, with a good running start, you could fly. On Io, you could marvel at the most active volcanoes we know of, powered by the tidal force of Jupiter's gravity.

Voyager itself has spacecraft children: Cassini returned to Saturn, Galileo to Jupiter. And now it has a grandchild. Europa Clipper, built in and recently shipped out from the colossal JPL clean room, will head to the Galilean moon of Europa later this year. With vast water oceans beneath an icy crust, Europa is thought to be a candidate for extraterrestrial life. Bell describes this clean room as the modern inner sanctum of a Gothic cathedral, where illuminati wear ritualistic garb to ensure purity, crafting holy relics to commune with the heavens. When I toured it, a group of Georgian tourists shuffled through.

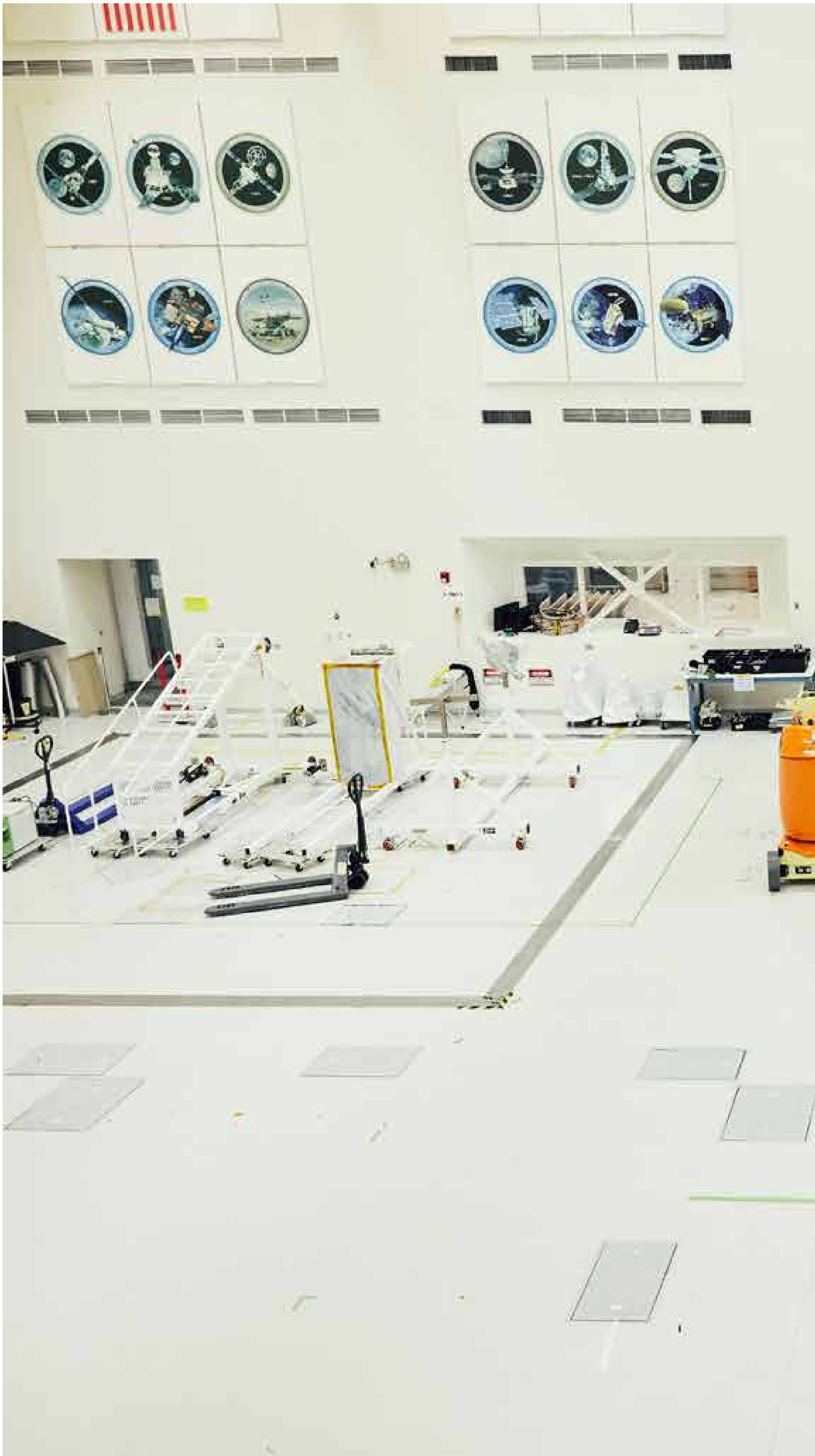
"Five hundred years from now, what are they going to remember about our time?" Bell said. "It's not going to be Madonna or Stormy Daniels or OJ. It's going to be, 'Oh, that's when they first set out off their planet. That's when they figured out the neighbourhood.'"

In recent years, by luck of longevity, Voyager has evolved from a planetary mission to a solar mission. Over the decades, most of its instruments have been turned off to save energy, including its camera. There is nothing left to see. Even the heaters have been turned off, and the spacecraft's four alive instruments (the cosmic-ray subsystem, low-energy charged particles experiment, magnetometer and plasma wave subsystem) operate at about minus 80C. These remaining instruments are concerned not with beautiful marbles but with what Bell calls "squiggly-line science", the invisible exotics of outer space.

Every star, including our Sun, generates a bubble around itself, inflated by the plasma of solar wind. This bubble, called the heliosphere, protects us from harsh galactic radiation. Imagine running your taps into the empty sink basin. The crashing water (plasma) will generate a tight oval of fast-moving liquid (the heliosphere), holding back the slower incoming water outside (harsh galactic radiation). The turbulent border where they meet is called the termination shock.

Voyager 1 crossed the shock in 2004, and Voyager 2 in 2007. They are the only machines gathering in situ data outside our bubble. Until this phase of the mission, no one knew how big our bubble was, and we still don't know exactly what shape it is.

Merav Opher directs the Shield (Solar wind with Hydrogen Ion charge Exchange and Large-scale Dynamics) project at Boston University, a centre devoted to studying our protective bubble. The group is attempting to build a digital twin of the heliosphere using Voyager data, recreating what



THE CLEAN ROOM WHERE VOYAGER AND MANY OTHER MACHINES WERE BUILT


EUROPA
CLIPPER

Opher calls our "habitable astral sphere". "It's an ancient team, it's the pioneers of space physics," she said of Voyager. "But you need to pass a baton."

But when the plutonium runs out, or the computer breaks for good, or the thrusters jam tight, or the signal dims irretrievably, the knowledge of the ancients will stop flowing. "It is something that has kept me awake at night," Opher said. "It's an existential feeling. What's going to happen?" For Opher, one thing that's going to happen is the introduction of a young, diverse new generation to heliophysics, using data from a geriatric spacecraft.

As she walked me through some fresh analyses of interstellar data, Opher recalled the routines of her orthodox religious upbringing. "We would read the Bible six, seven, eight times," she said. "I always thought, 'Oh my God, this is so boring.' But every time we read, we got a new meaning. I feel with Voyager it is the same."

CUMMINGS AND ARSLANIAN WROTE CODE IN an archaic assembly language with no name, for an ancient custom-built computer with no equal. They had no test bed, no simulator, no debugger. Everything had to be checked "by inspection", or just by looking at it over and over again. Documentation of the code was hard to come by, though the team had found a low-quality scan of a hard copy of the source code, printed "sometime in the distant past". The letter B could easily be mistaken for an 8, for example. And they were working awfully close to the metal.

"In modern times, you use high-level languages. You write your 'if-else' loops and all that stuff," Arslanian said. "But we don't have that. We're actually changing the ones and zeros."

They'd managed to filch enough memory for their patch, from a largely unused program, and they'd looked at it over and over again. But writing in this ancient tongue was fraught.

"Are we just missing something?" Cummings would wonder. "Because this is almost 50 years old, and from whatever documents we have, we're getting any information that we can, but are we missing something in the larger picture?"

"We were never 100 per cent," Arslanian said. "We couldn't be."

On April 18 they beamed up their code. Early on the morning of April 20, the Voyager lifers and the tiger-team craftspeople sat in a small conference room, its walls adorned with decades of plaques and commendations, and passed around a jar of lucky peanuts, a hallowed JPL tradition. They hadn't heard their spacecraft's voice clearly in more than five months. They stared at laptops, one of which was projected on to a large screen. Arslanian turned to a nervous Cummings.

"It is what it is," Arslanian said. "Whatever happened, happened 22 and a half hours ago."

"Ah, youth," Cummings said, and laughed.

In the silent conference room, numbers finally populated the screen. Someone broke the silence: "It's in sync!" Voyager 1 was speaking again, sending back legible reports of its health, and it was healthy. For Mellstrom, the tiger-team leader, it was not a moment too soon. After 35 years at JPL, he retired as planned on May 2. He spoke to me from a lakehouse in the woods of Wisconsin, with his family.

THE CURRENT THINKING AS TO THE CAUSE OF the anomaly was that either the spacecraft was struck by a cosmic ray, a particle moving at nearly the speed of light, or it is very old and it broke. Either way, it survived. In workplace genealogy, "This spacecraft was designed by our great-great-

FROM LEFT: DAVE CUMMINGS; HANDWRITTEN NOTES; ARMEN ARSLANIAN; SLIDE FROM THE ARCHIVE
FAR RIGHT: LINDA SPILKE

IN WORKPLACE GENEALOGY, SAID TIGER-TEAM LEADER BADARUDDIN, 'THIS SPACECRAFT WAS DESIGNED BY OUR GREAT-GREAT-GRANDPARENTS. THEY PUT A LOT OF LOVE INTO IT'

grandparents," said Badaruddin, the new tiger-team leader. "They put a lot of love into this spacecraft."

Using the same techniques, the tiger team has also begun to restore not only engineering data but some science data. While I was at JPL, they fixed two of the four remaining science instruments.

One yet-unfixed instrument, the cosmic-ray subsystem, represents the life's work of astrophysicist Alan Cummings. He is an 80-year-old Texan with a white moustache curled to geometric precision. (He is no relation to Dave the software engineer.) His office at Caltech is decorated with armadillos and cramped with file cabinets and tall shelves packed with a rainbow of binders filled with Voyager materials. In a drawer is the technical "bible" of his cosmic-ray detectors. He'd been following the anomaly closely, he told me, and contributed to the cause. "I sent them some documentation."

Cummings's career began flying enormous balloons to the top of the atmosphere to track particles. One of these got loose over Canada, traversed the planet one and a half times over and crash landed in the Soviet Union. A minor diplomatic incident ensued, involving a disappeared postdoc, he said, the net result of which was his abandoning balloons and moving on to spacecraft. He joined Voyager years before launch, before it even had its name. Ever since, he's been pursuing the holy grails of cosmic-ray physics. "The backbone of the whole thing has been the Voyager mission," he said.

From a shopping bag, Cummings pulled out a pair of particle detectors whose exact twins are flying through interstellar space. When installing them, he became the last person to ever touch the Voyager spacecraft. "It's going to circle around the centre of the Milky Way for ever," he said. "I don't expect it to hit anything."

According to one academic study, it'll be about 20,000 years before Voyager pokes through the Oort cloud, a shell of ice and comets surrounding the solar system, and 30,000 years before it comes anywhere near another star. It'll be about 500 million years before it completes a lap around the galaxy. The golden record is given good odds to survive at least 5 billion years, interstellar dust posing the biggest risk. Modelling gets more difficult after that, as our Milky Way is set to collide with the Andromeda galaxy.

Cummings and I got to talking about his broken stove and my broken dishwasher and how they just don't make machines like they used to. We decided it was time to say goodbye. That same day, instructions were being sent through the Deep Space Network to try to fix his beloved instrument. Whatever the result, Cummings had etched his initials into the metal of the machine decades ago. "I feel a little immortal," he said.

IN THE YEARS TO COME, JPL WILL PROVIDE hospice care for the twin spacecraft. For one thing, the plutonium that fuels Voyager, set in canisters along an arm a safe distance from the electronics, is finite. Eventually that power will run out and Voyager will go silent. "It'll be like a death in the family," Dodd said.

"It's carrying a sense of hope and optimism for what we can be and what we can do," Spilker said. "I see Voyager as a source of pride, that we've managed as a species to send something out to the stars."

Will we ever go back?

One proposed spacecraft, called the Interstellar Probe, is under consideration in a National Academies' decadal survey. A 500-page document lays out its planned "epic 50-plus-year journey". It could travel twice as fast as Voyager and much further. "We're on the brink of discovering something much bigger than ourselves," Pontus Brandt, its project scientist, told me. "The solar system and the heliosphere have evolved together. They're one intrinsic system that we need to look at to understand not only life but how the solar system formed. It's mouthwatering physics that's going on."

JPL is suspicious of hero stories. My interview transcripts contain the word "team" hundreds of times. "If you could build a spacecraft in your garage, most of us would be at home building a spacecraft in our garage," said Badaruddin. "But it takes these resources."

And heroes can serve in unlikely roles. In 1997, the American Institute of Aeronautics and Astronautics published an oral history called *Voyager Tales*. Alongside senior astrophysicists and JPL luminaries, the book includes an interview with a woman named Anita Sohus, Voyager's "doc rep" in the early days, the designated editor for all of the mission's paper: plans, procedures, policies, requirements, specifications, user's manuals.

Sohus recounts a story about a rocket that was destroyed because of a single misplaced minus sign. Haunted by this, she recalls seeing new staff clean house, throwing out or shipping away files. "I would always cringe and try to stop that when I saw it happening," she said. "All of the formal documentation is available; it's just a matter of ploughing through it... Without that body of 'corporate knowledge', a lot would have been lost." Look no further than interstellar space for an argument for library funding.

The Voyager brass is preparing for a termination shock of its own and predicts a wave of human retirements when the robots die. Dodd plans to continue working until the 50th anniversary of the launches in 2027. The current belief is that at least one of the spacecraft should hold out until then. She will throw "the biggest possible party". There will be champagne, peanuts and, she hopes, Georgian folk singers. FT

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