BBC Sky at Night MAGAZINE

DISCOVER SPACE

THE STORY OF VOYAGER

THE GRAND TOUR TO INTERSTELLAR SPACE

EXCLUSIVE

IN-DEPTH INTERVIEWS WITH VOYAGER SCIENTISTS

PLUS, NASA TELLS US HOW THE VOYAGERS CONTINUE TO SHAPE TODAY'S MISSIONS

MARVELS AND MYSTERIES: THE VOYAGERS' GREATEST DISCOVERIES REVEALED

OUR FARTHEST ENVOY: WHAT VOYAGER 1 IS TELLING US ABOUT INTERSTELLAR SPACE

MESSAGES FOR ET: HOW THE GOLDEN RECORD COULD HELP ALIENS FIND EARTH

CELESTRON®

TECHNOLOGICALLYSUPERIOR

THE ALL NEW CGX-L

GERMAN EQUATORIAL MOUNT

Celestron's newly designed CGX-L Computerised Equatorial mount and tripod is the latest addition to the fully computerised equatorial mount series. Capable of carrying Celestron's largest optical tubes with ease, CGX-L is designed for backyard observatories and remote imagers looking for exceptional load capacity to weight ratio, compact design, and innovative features that fully support large telescopes, imaging kits, and the latest in wireless tech accessories.

- Extra large 75lb capacity
- Larger 144 mm diameter worm wheels
- Longer 270 mm dovetail saddle to support larger optical tubes
- Remote operation friendly features
- Internal cable management
- Mechanical and ergonomic improvements throughout
- Sturdier, easier to use, and easier to transport.

**COMPACT.
ERGONOMIC.
INNOVATIVE.**

Control software in conjunction with PlaneWave INSTRUMENTS

"If you're looking for a portable heavy duty mount... the CGX-L is a worthy contender"

Astronomy Now, June 17 issue

Additional Ports

Longer Dovetail Saddle

Smoother Belt Drive System

Compact Designed Tripod

ALSO AVAILABLE THE ORIGINAL CGX

- Large 55lb capacity
- All-new design. Sturdier and more rigid with quicker dampening time
- Improved motors and drive systems.

BBC Sky at Night Magazine ★★★★★ REVIEWED IN Issue 141 February 2017

WARRANTY 2 YEAR

StarSense™ TECHNOLOGY COMPATIBLE

WiFi COMPATIBLE

WELCOME

"BETWEEN THEM THE VOYAGERS VISITED FOUR PLANETS AND 48 MOONS, 23 OF WHICH WE HAD NO IDEA EXISTED"

The twin Voyager spacecraft have been speeding through the cosmos for two-thirds of the entire Space Age. Dreamt up in those heady, halcyon years that preceded the Apollo 11 landing as a 'Grand Tour' of the outer planets, and finally launched in 1977, they went on to redefine our understanding of the Solar System.

The past 40 years have been revelatory. Between them the Voyagers visited four planets and 48 moons, 23 of which we had no idea existed. They saw new rings, volcanoes, geysers and even aurorae. Now Voyager 1 is pushing the very limit of exploration, as it ventures beyond the solar bubble our star forces out around it and into the unknown of interstellar space. It's an astounding legacy for a pair of probes that each have around 240,000 times less computing power than an average smartphone and an eight-track tape for a brain.

The story of Voyager is one of the most complex there is – so as well as giving you the rundown of their myriad discoveries, we asked the people involved in the mission to relive it in their own words. They include Carolyn Porco, who spotted the still-unexplained spokes in the rings of Saturn and helped organise the Solar System's 'family portrait'; Suzanne Dodd, mastermind of the ongoing interstellar mission; and Ed Stone, Voyager's project scientist since 1972 – before the spacecraft were even called 'Voyager'. But what of the future? NASA director of planetary science James Green reveals how the Voyagers continue to shape modern space exploration.

It's a majestic tale that's echoed through the years and is expected to continue for a decade more. Won't you join us for the ride?

Kev

Kev Lochun, Editor

EDITORIAL
Editor Kev Lochun
Managing Editor Chris Bramley
Art Editor Steve Marsh
Production Editor Rob Banino

CONTRIBUTORS
Ben Evans, Mark Garlick, James Green, Elizabeth Pearson, Ben Skuse, Paul Sutherland, Iain Todd

THANKS TO
Bonnie Buratti, Suzanne Dodd, Linda Morabito, Carolyn Porco, Ed Stone

CIRCULATION / ADVERTISING
Head of Circulation Rob Brock
Advertising Managers
Neil Lloyd (0117 300 8276)
Tony Robinson (0117 314 8811)

PRODUCTION
Production Director Sarah Powell
Production Coordinator Derrick Andrews
Reprographics Tony Hunt and Chris Sutch

PUBLISHING
Publisher Jemima Dixon
Managing Director Andy Marshall
CEO Tom Bureau

BBC WORLDWIDE
President of UK and ANZ Marcus Arthur
Director of Consumer Products and Publishing Andrew Moultrie
Director of Editorial Governance Nicholas Brett
Publishing Director, UK Publishing Chris Kerwin
Publisher Magazines and NPD Mandy Thwaites
UK Publishing Coordinator Eva Abramik
(uk.publishing@bbc.com)

www.bbcworldwide.com/uk--anz/ukpublishing.aspx

IMMEDIATE MEDIA Co

Like what you've read?
Email us at: contactus@skyatnightmagazine.com

COVER IMAGE: MARK GARLICK · FURNISHED WITH PHOTOGRAPHIC ELEMENTS © NASA/JPL-CALTECH/PROCESSING BY STEVE MARSH, THIS PAGE: NASA/JPL-CALTECH

Contents

MARK GARLICK

US artist Ken Hodges created paintings of many NASA missions; here's his imagining of Voyager 1's encounter with Jupiter in 1979

PHASE I
GRAND IDEAS

Before Voyager, our knowledge of the outer giants was patchy. Jupiter had only been visited twice by human probes, Saturn only once, and Uranus and Neptune not at all. Then in 1965, JPL intern Gary Flandro noticed something extraordinary: in the late 1970s, all four outer planets would be ranged on the same side of the Solar System, offering the tantalising prospect of one spacecraft completing a 'Grand Tour' of them all. Translating this idea into the eventual Voyager spacecraft was not easy. Their development was plagued by tightening budgets and technical concerns; and, when the probes finally launched in August and September 1977, they were only officially bound for Jupiter and Saturn. That the Voyagers were built with an extended mission to the outer giants in mind is testament to the optimism that steeped the mission as a whole.

GRANGER HISTORICAL PICTURE ARCHIVE/ALAMY STOCK PHOTO

Galileo first demonstrated his telescope design in 1609. His observations revealed Jupiter's moons in 1610

The pre-Voyager years

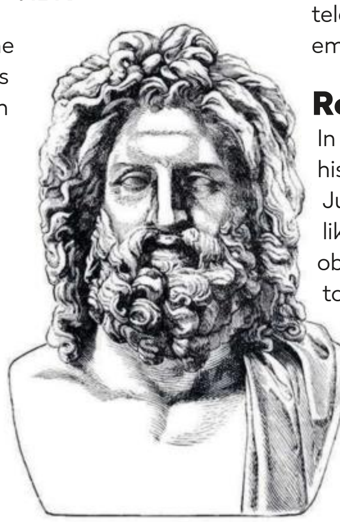
Long before scientists sat down to discuss Voyager's grand adventure across the Solar System, people were looking up and wondering about the planets the twin spacecraft would one day visit

Words: Ben Evans

JULY 2011 MARKED Neptune's first full orbit of the Sun since its discovery 165 years earlier – the completion of a journey it had traced out millions of times before whilst we on Earth were none the wiser.

It seems strange now to think that, only 230 years prior, both Neptune and Uranus were unknown to us and that the Solar System 'ended' with Jupiter and Saturn. Even after the existence of Neptune was confirmed by observation in 1846, our ideas about these four outer worlds were far removed from what we know today. They were little more than points of light in the night sky.

Known to astronomers and astrologers since antiquity, it's fitting that Jupiter – one of the brightest objects in the sky – was named after the Romans' most important god. Saturn's slow movement across the heavens, on the other hand, was associated with Jupiter's father, the god known for being the 'Bringer of Old Age'. Unknown to the early stargazers was the fact that these planets lay hundreds of millions of kilometres away, so they could scarcely have imagined the worlds would be far larger than our own. Only with the invention of the telescope did the distant planets emerge from the gloom.



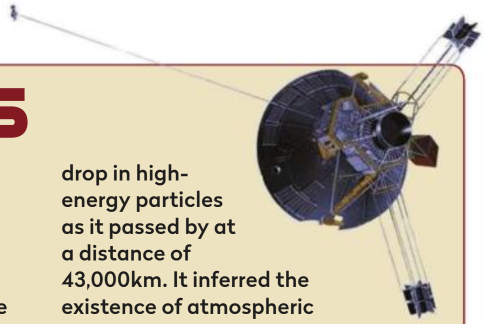
◁ Jupiter, the Solar System's largest planet, takes its name from the king of the gods in the Roman pantheon

Revelations

In 1610, Galileo Galilei focused his handcrafted telescope on Jupiter and spotted four star-like objects nearby. Subsequent observations revealed them to be natural satellites – the earliest-known after our ▷

SCIENCE HISTORY IMAGES/ALAMY STOCK PHOTO, ISTOCK, NASA X 8

THE PLUCKY PIONEERS



In December 1973, three and a half centuries after Galileo peered at Jupiter, Pioneer 10 became the first man-made machine to visit the planet. During its passage, the probe suffered circuit failures, triggered false commands and absorbed 1,000 times the human-lethal dose of high-energy radiation. Yet against all the odds, Pioneer 10 survived.

It passed 130,000km over Jupiter's magnetic equator, revealing an electron flux 10,000 times stronger than Earth's. It showed the vast magnetic field was inverted, compared to Earth, and its 500 images revealed bright features on Europa and Ganymede. Radio occultations verified the extent and density of Io's ionosphere, confirming a doughnut-shaped plasma torus and a complex magnetic relationship with Jupiter. Close-range views of atmospheric features, including the Great Red Spot, were returned, as well as the first vertical temperature profiles of the planet's outer gaseous envelope.

After Pioneer 10 came Pioneer 11. In December 1974, this second probe raised suspicions that Jupiter was a ringed world when it measured a brief drop in high-energy particles as it passed by at a distance of 43,000km. It inferred the existence of atmospheric aurorae, photographed the northern polar regions – revealing cloud tops substantially lower than at the equator – and confirmed Callisto to be 1.5 times more massive than Earth's Moon.

Like Pioneer 10, Pioneer 11's visit to Jupiter had its fair share of drama. As the probe prepared to make its closest pass, a strike by operators of a diesel generator threatened to shut down the Australian tracking station to which much of Pioneer 11's data would be sent. The station remained open, however, and the probe's tour of the giant planet ended successfully before it headed on to Saturn. In September 1979, it swept 20,000km past the ringed world, imaging (and almost hitting) the tiny moon Epimetheus. Passing 'beneath' the ring plane, Pioneer 11 discovered the thin F ring and revealed that Titan was too cold to support life.

△ Pioneer 11 pictured the Cassini Division between Saturn's A and B rings

△ Jupiter's gas bands were seen in unprecedented detail by Pioneer 11

△ Pioneer 10 also took shots of Ganymede, Jupiter's largest moon

△ Jupiter's Great Red Spot and the shadow Io as seen by Pioneer 10

△ Pioneer 10 caught sunrise on Jupiter as it approached and passed the planet

△ Saturn's largest moon, Titan, appeared as Pioneer 11 approached the planet

△ After passing by Saturn, Pioneer 11 came within 360,000km of Titan own Moon – and they were eventually christened Callisto, Europa, Ganymede and Io.

That same year Galileo saw two mysterious 'ears' on Saturn. He didn't realise it, but he was witnessing its majestic rings as they moved from partly open to edge-on and he expressed astonishment when they briefly vanished. Alluding to mythology, he lightheartedly mused that Saturn really had swallowed his children. Describing the sight as "so surprising, so unlooked-for and so novel", Galileo wondered if he was seeing a triple planet.

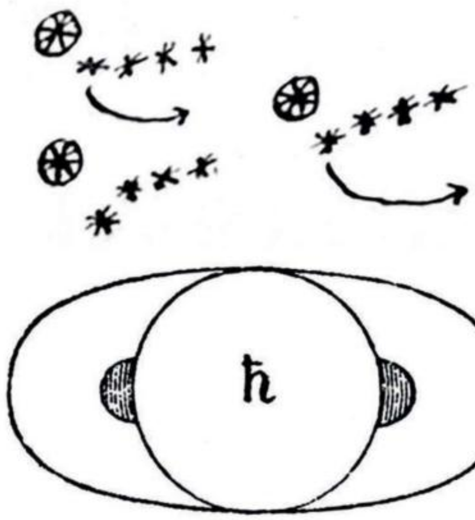
Not until 1655 did Christiaan Huygens correctly infer that Saturn was encircled by a thin ring and it was 1675 before Giovanni Cassini identified an eponymous 'gap' between the A and B rings.

The nature of the rings was harder to pin down. Many assumed they were solid, although in 1660 the French writer Jean Chapelain argued that they might be made up of numerous tiny objects. But the notion of 'solid' rings endured and was endorsed by Pierre Laplace, a French scholar, and the German-born astronomer and composer William Herschel, until the discovery of the gauzy C ring cast doubt on their solidity. It was the Scottish scientist James Clerk Maxwell who predicted "an indefinite number of unconnected particles" before America's James Keeler showed that the sunlight they reflected was Doppler-shifted, meaning that the particles forming the rings occupied discrete orbits.

Inside the four giants

Understanding the outer planets' interiors began by examining the bands of cloud that move across Jupiter's face, an approach that revealed parts of its atmosphere rotate at different speeds. Cassini noticed that the planet seemed flattened, or oblate, at the poles – a characteristic shared by all four giants – and this enabled early calculations of Jupiter's rotation rate.

Jupiter's low density hinted at a composition predominantly made up of hydrogen that radiates twice as much heat as it receives from incident sunlight. This led English astronomer Richard Proctor to argue that the planet's interior was a boiling fluid, raising early notions of Jupiter being a 'failed star'. Spectroscopy later

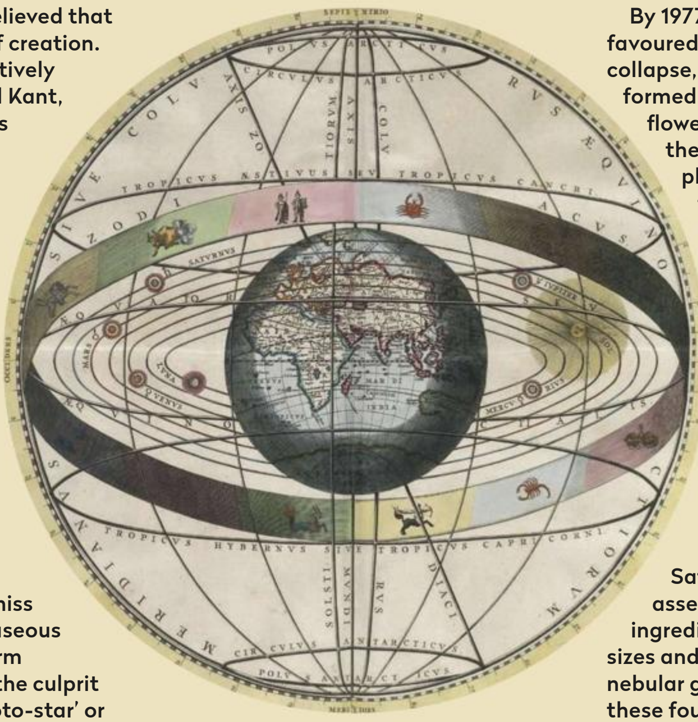


△ **Galileo observed Saturn as having 'ears' (above), and the movements of Jupiter's four largest moons, represented, as asterisks (top)**

THE ORIGINS OF THE OUTER PLANETS

For millennia, humans believed that Earth lay at the centre of creation. That belief changed relatively recently, when Immanuel Kant, Pierre Laplace and others argued that the Sun and its retinue emerged from a gaseous 'nebula' that collapsed, drawing in surrounding dust and gas to form a super-dense, super-heated core. But the question of how our parent star gained its energy remained unanswered, until Hans Bethe realised in 1938 that the Sun was powered by the fusion of hydrogen and helium.

Several astronomers postulated that a near-miss with another star tore gaseous strips from the Sun to form planetary cores. Maybe the culprit was a smaller, cooler 'proto-star' or perhaps a binary companion that exploded, leaving a fertile breeding ground for planets in its wake.



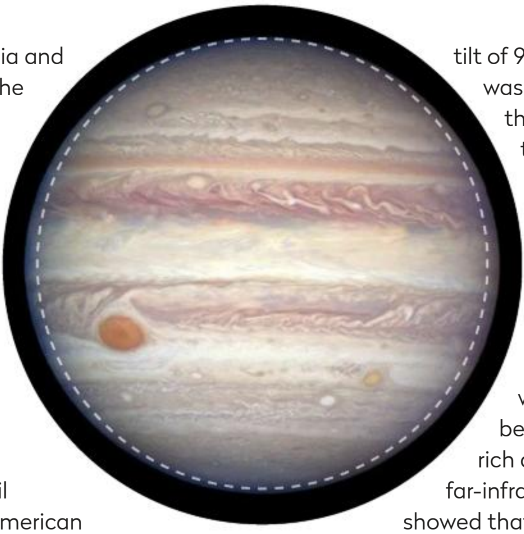
△ **The geocentric model, with Earth at the centre of the Universe, held sway for centuries**

By 1977, scientific consensus favoured the idea that the nebula's collapse, 4.5 billion years ago, formed a protostar, around which flowed a disc of gas. Gradually, the disc cooled and formed planetary cores that gorged themselves on surrounding material. Nebular densities at various distances from the centre led to the differing chemical compositions of the planets: heavier elements condensed inward and lighter volatiles migrated further out. The result was two planetary classes: rocky and gaseous.

The cores of Jupiter, Saturn, Uranus and Neptune assembled their chemical ingredients and grew to sufficient sizes and masses to hold more nebular gas. It was the secrets of these four outer worlds, many times more massive than Earth, that the Voyager probes sought to unlock in the summer of 1977.

SCIENCE HISTORY IMAGES/ALAMY STOCK PHOTO, NASA/ESA/AND A. SIMON (GSFC), NASA/JPL/SWRI, HORST ZIEGLER/CCDGUIDE.COM revealed ammonia and methane, while the work of Harold Jeffreys, Rupert Wildt and others led to theories of a rocky core, an icy mantle and a deep gaseous atmosphere.

A magnetic field remained hypothetical until 1955, when the American astronomers Bernard Burke and Kenneth Franklin serendipitously discovered radio bursts at 22.2 MHz, matching Jupiter's 10-hour rotation rate. This allowed the field's existence to be inferred for the first time. All four giants have magnetic fields, but Jupiter's is by far the strongest and the only one that can be measured in the radio range. Efforts to observe emissions from Saturn were inconclusive until 1974, when bursts at 1 MHz were recorded.



△ A perfect circle projected over this Hubble shot of Jupiter reveals the giant planet's oblateness, a trait spotted by Giovanni Cassini

Extending our reach

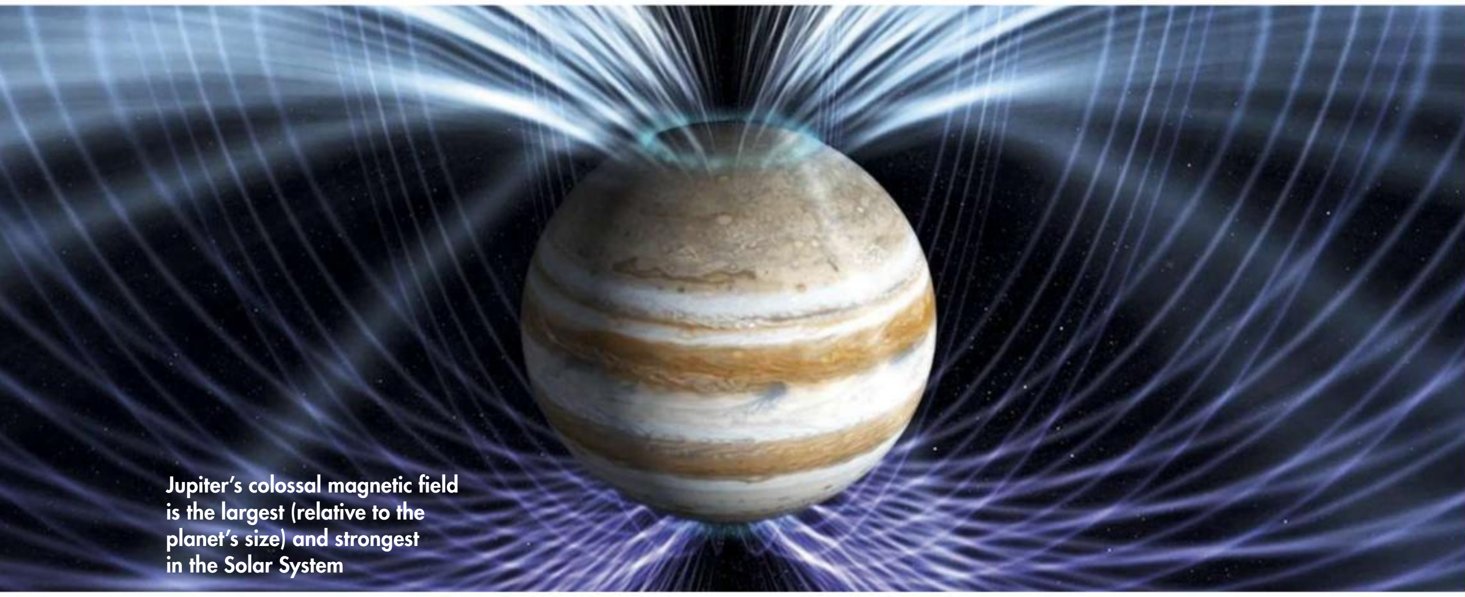
If our knowledge of Jupiter and Saturn was sketchy, the two outermost giants were a virtual blank before the Voyager probes. Uranus, discovered telescopically by William Herschel in 1781 – but seen and mistaken for a star, many times before that – exhibits a peculiar rotational tilt of 98°, while Neptune was found in 1846, through a stranger-than-fiction mix of inexplicable orbital mechanics, clever mathematics and direct observation.

Uranus's plain aquamarine façade was interpreted as being a methane-rich atmosphere, and far-infrared spectroscopy showed that it radiated as much heat as it received from the Sun. In 1977, during a stellar occultation, five narrow rings were detected by astronomers aboard the Kuiper Airborne Observatory. By this time, evidence for rings had also been seen at Jupiter, intensifying similar searches at Neptune. Tantalisingly, observations from Chile in the early 1980s pointed to 'ring-arcs', extending part of the way around the planet.

But the mysteries didn't end there. Around all four giants were large retinues of moons, ranging from Jupiter's four 'Galilean' satellites to two-toned Iapetus and planet-sized Titan at Saturn. In 1944, spectroscopy revealed Titan as the first natural satellite known to possess a substantial atmosphere. About the rest, far less was known. Neptune's large moon Triton didn't even have an official name until the last century and, despite evidence of nitrogen ice on its surface, its exact mass was uncertain.

Much of this uncertainty vanished overnight when the Voyager probes arrived. Their whistle-stop tours of the giants opened the floodgates of human knowledge, unleashing an unprecedented torrent of data about these far-off worlds. Our entire understanding of Jupiter, Saturn, Uranus and Neptune would be revolutionised, though the probes would raise as many questions as they'd answer. V

▷ It soon became evident to observers that families of moons orbited both Jupiter and Saturn. In this telescopic image the four Gallilean moons of Jupiter are easily seen



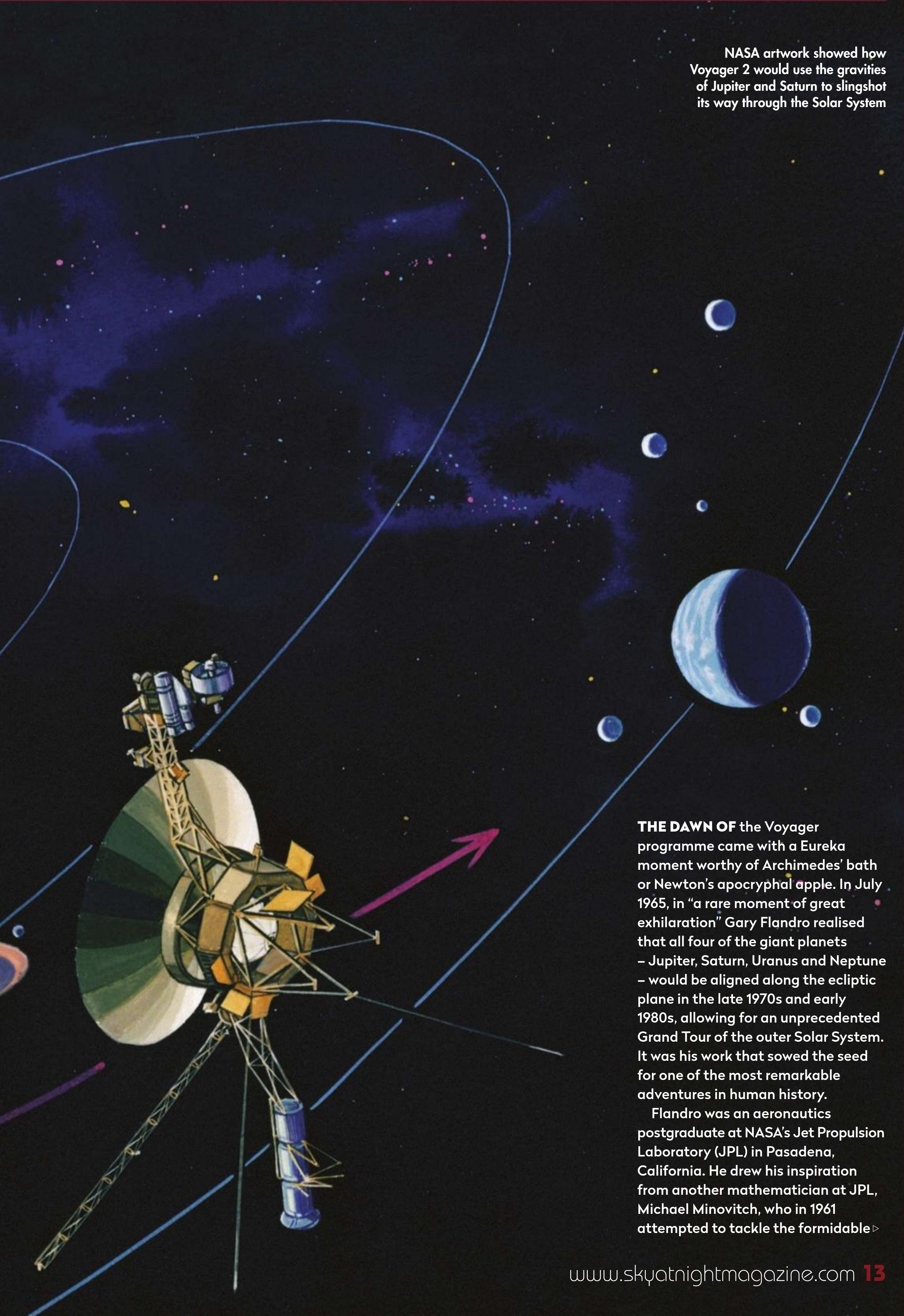
Jupiter's colossal magnetic field is the largest (relative to the planet's size) and strongest in the Solar System

The chance of three lifetimes

Words: Ben Evans

The project first dubbed the 'Grand Tour' grew from the accidental discovery of a cosmic alignment that would not be repeated for another 176 years. After surviving budget cuts, naysayers and conflicting agendas it became the mission we now know as Voyager

NASA/SCIENCE PHOTO LIBRARY



NASA artwork showed how Voyager 2 would use the gravities of Jupiter and Saturn to slingshot its way through the Solar System

THE DAWN OF the Voyager programme came with a Eureka moment worthy of Archimedes' bath or Newton's apocryphal apple. In July 1965, in "a rare moment of great exhilaration" Gary Flandro realised that all four of the giant planets – Jupiter, Saturn, Uranus and Neptune – would be aligned along the ecliptic plane in the late 1970s and early 1980s, allowing for an unprecedented Grand Tour of the outer Solar System. It was his work that sowed the seed for one of the most remarkable adventures in human history.

Flandro was an aeronautics postgraduate at NASA's Jet Propulsion Laboratory (JPL) in Pasadena, California. He drew his inspiration from another mathematician at JPL, Michael Minovitch, who in 1961 attempted to tackle the formidable ▹

▹ 'three-body problem'. This 300-year-old conundrum sought to predict exactly how the gravitational influences of the Sun and a given planet would perturb the trajectory of a third object, such as a natural satellite, an asteroid or a comet. Working mainly at night, Minovitch noticed that planetary gravitational fields could be used to adjust the course of an incoming spacecraft, relative to the Sun. The craft could then be redirected to another destination, yielding substantial savings in launch energy and overall flight duration.

His work laid to rest several misconceptions about 'gravity-assist' (or 'gravity-thrust', as Minovitch called it) marking a paradigm shift at the dawn of the Space Age. Energy requirements to travel beyond the asteroid belt were prohibitively high and early missions focused instead on visiting the closer, terrestrial planets Mercury, Venus and Mars. Many engineers suspected that there would be no net change in a spacecraft's energy and gravity-assist would carry it outside its direct trajectory, taking more time (rather than less) to reach its destination. What wasn't fully understood was the fact that planets themselves lose small amounts of energy as they accelerate passing spacecraft.

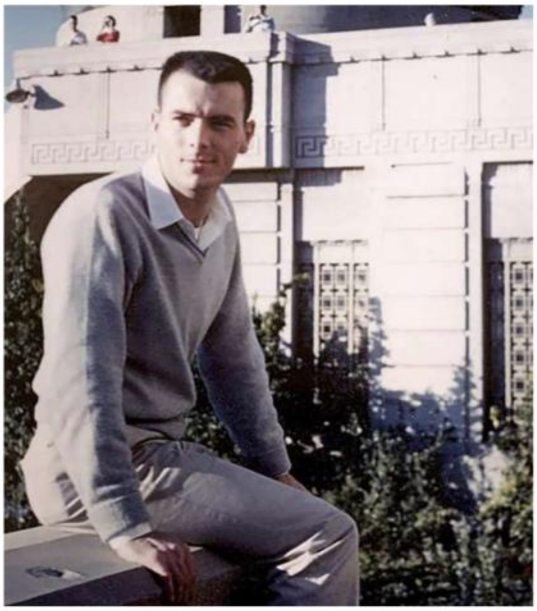
A route is revealed

Minovitch realised that launches between 1962-1966 and 1976-1980 could achieve rendezvous with multiple planets in the outer Solar System. A few years after this revelation, Flandro modified the calculations, mapping hundreds of potential trajectories and noting that a launch in 1976-1978 could employ Jupiter's immense gravity to reach Saturn, Uranus and Neptune in less than a decade.

This was hugely significant. Flying direct to the outer planets demanded huge launch energies, together with lengthy flight times: two and a half years to Jupiter, six years to Saturn, 16 years to Uranus and 30 years to Neptune. But by launching in the summer of 1977, a spacecraft could reach Jupiter in early 1979, then be accelerated by 11 km/s and have its trajectory deflected by 97° to rendezvous with Saturn in 1980, Uranus in 1984 and Neptune in 1986. "I studied a whole range of trajectories and flight times," Flandro explained, "but my favourite was the one that took you out to Neptune in about eight years." In his mind, Jupiter was "the best energy supply station" and a crucial key in unlocking the secrets of the giant planets.

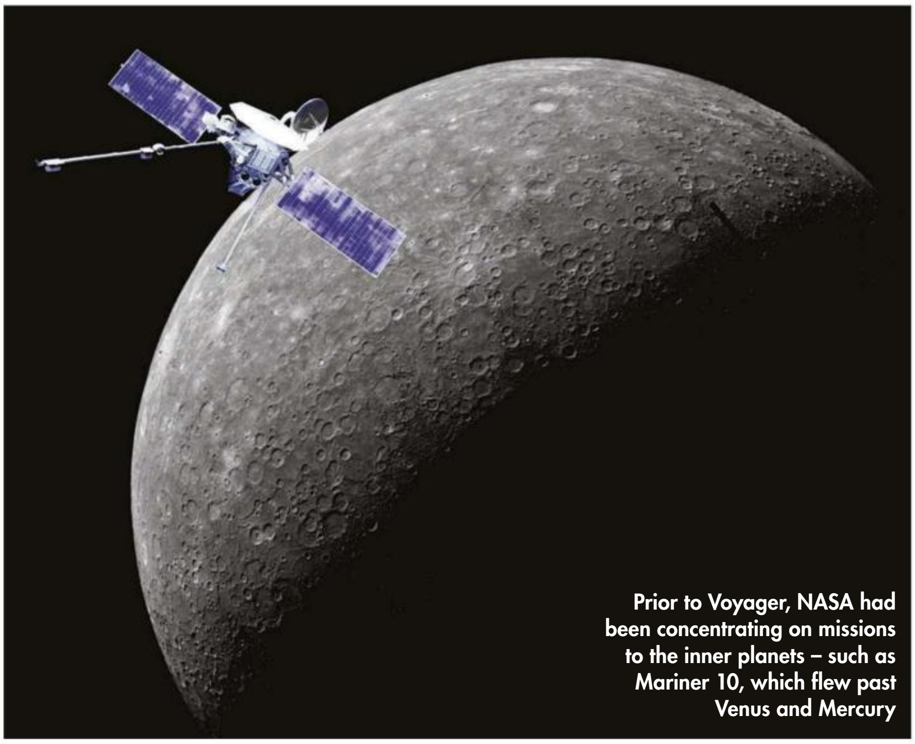
If they made efficient use of these potential gravitational gains, the time needed to visit Jupiter and Saturn could be halved, while Uranus and Neptune became reachable in a third of the time needed via the direct route. Flandro suggested that launch dates in September 1977, October 1978 and November 1979 were ideal to reach differing combinations of the outer planets, including the distant dwarf Pluto.

Then came the bombshell. After exhaustively plotting the heliocentric longitudes, he observed that during the 1980s



△ Gary Flandro realised the outer planets would fall into a rare alignment during an internship at NASA in 1965

△ Michael Minovitch's work showed how planetary gravitational fields could be used to steer spacecraft



Prior to Voyager, NASA had been concentrating on missions to the inner planets – such as Mariner 10, which flew past Venus and Mercury

GARY FLANDRO/SUUNEWS, NASA/JPL/USGS X 2, NASA/JPL they would be on the same side of the Sun and in relative proximity to one another. This opened the possibility of visiting them all, within the bounds of one or two missions. Such a favourable celestial alignment of the outer planets arose only once every 176 years. The last time it occurred was during the Napoleonic Wars, half a century before the discovery of Neptune. To Flandro, it was a chance of not one, but three lifetimes.

"SUCH A FAVOURABLE CELESTIAL ALIGNMENT OF THE OUTER PLANETS AROSE ONLY ONCE EVERY 176 YEARS"

Added motivation

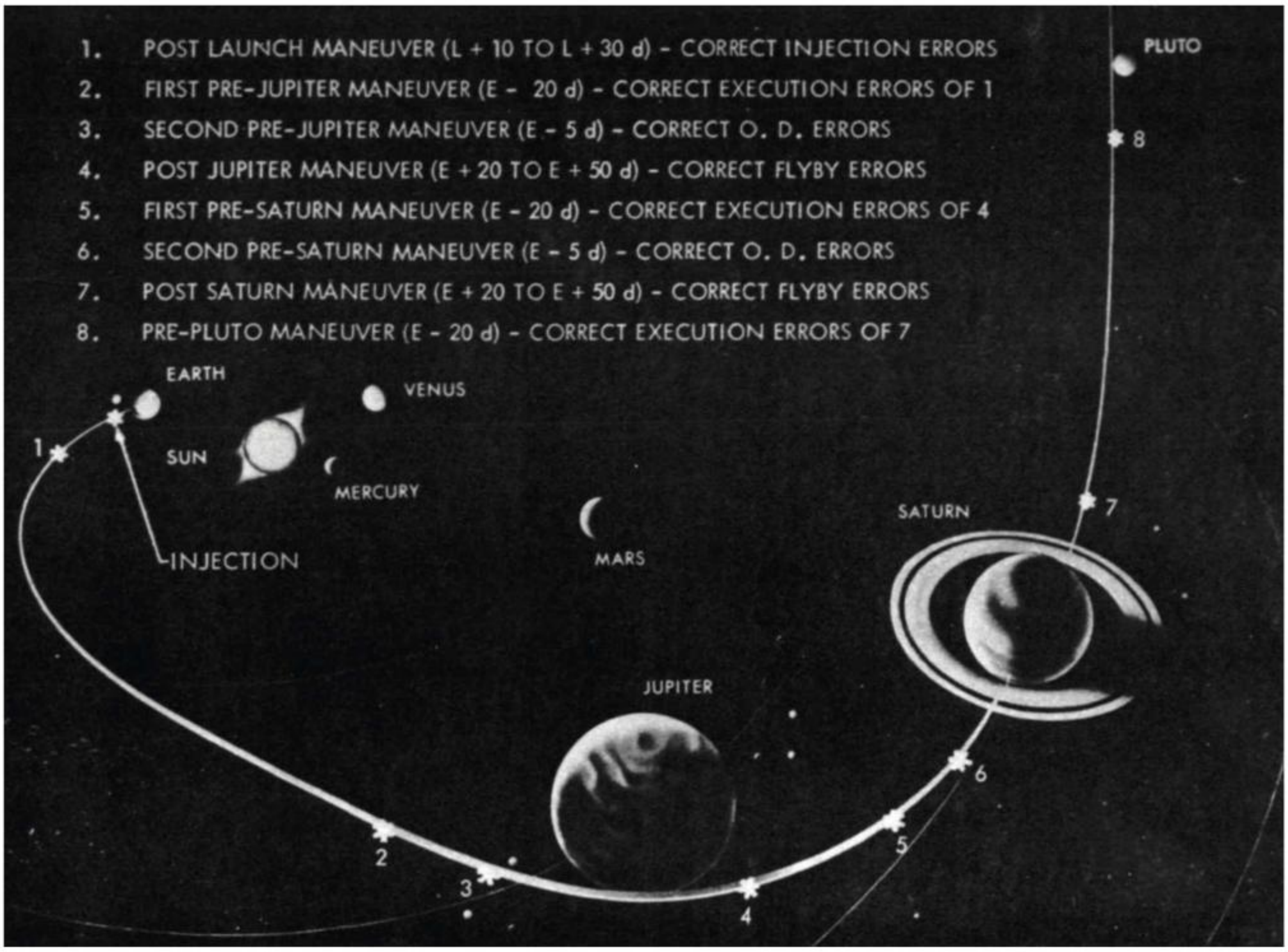
He doubted that the US's slow-paced planetary exploration effort could be galvanised in just a decade to support such an ambitious mission, but wrote that the "motivation supplied by a goal like this one could have a real impact on progress".

The proposal drew criticism – some scientists poured scorn on the likelihood of building a sufficiently long-lived spacecraft, while a tongue-in-cheek hippy group protested that the mission might damage Jupiter's orbit. But the idea drew warm support from Flandro's supervisor, Elliot 'Joe' Cutting, and from Homer Joe Stewart, head of JPL's advanced concepts group.

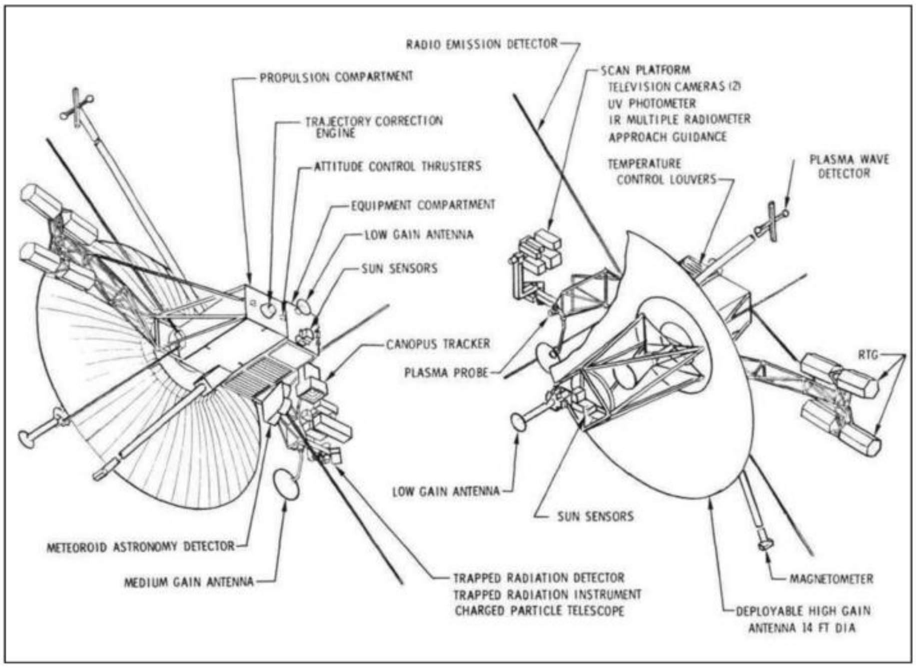
Almost immediately, a mission design phase was initiated. Stewart labelled it 'Grand Tour', deriving the name from one used a decade earlier by Gaetano Crocco to describe a gravity-assisted Earth-Mars-Venus voyage. The major obstacle facing the mission, however, was the need to travel perilously close to Saturn's rings to gain sufficient impetus for a slingshot to Uranus. "To make a fast flight, a very close passage of Saturn was required," wrote Flandro, "with the trajectory passing between the planet's upper cloud layers and the rings to achieve the extra gravity-assisted boost."

Back-up plans

The risk of particulate ring material impacting the spacecraft was a very real hazard. So much so that in 1966, JPL engineer James Long devised a conservative plan for two Grand Tour flights, directed well clear of the rings. The first, GT-1, would launch in August 1977, reaching Jupiter in March 1979 and Saturn in August 1980, then receiving a boost of 25° out of the ecliptic to encounter Pluto in December 1985. Meanwhile, GT-2 would begin in November 1979 and the energy afforded by a 1981 Jovian flyby would enable it to survey Uranus in 1985 and Neptune in 1988. Long argued that the 1977-1979 window was best for the launches, ▷



▽ NASA's plans for GT-1 would have seen it travel to Pluto via Jupiter and Saturn



△ **The TOPS technology developed for the Grand Tour proved to be too ambitious and expensive**

△ **TOPS prototypes had already entered development when the project was scaled back**

▹ as it offered the greatest reduction in flight times.

Concurrently, the National Academy of Sciences advocated a pair of exploration roadmaps, with opinion polarised between planetary flybys or an intensive study of Jupiter with orbiters and atmospheric probes. In readiness for such missions, JPL began a three-year Thermoelectric Outer Planet Spacecraft (TOPS) advanced systems technology project in July 1968. Although not a 'mission' in itself, TOPS helped to identify future requirements and allowed for "realistic estimates of performance, cost, reliability and scheduling".

This included the fabrication of long-duration subsystems and the integration of a nuclear power source. Since the amount of incident sunlight at Jupiter was recognised to be a mere fraction of that available in Earth orbit, a TOPS-based spacecraft would carry four plutonium-fed radioisotope thermoelectric generators (RTGs) on deployable booms, well away from the scientific payload.

These RTGs would produce 550 Watts of electricity at the beginning of the mission and around 439 Watts at its end. Other TOPS technologies included a 4.3m furlable X/S-band high-gain antenna – capable of a 131kbps data downlink from Jupiter, decreasing to 2,000b/s from Neptune – and a highly fault-tolerant Self-Testing and Repair (STAR) computer.

Due to the enormous distances travelled and the multi-hour time lag between commands being issued from Earth and received aboard the spacecraft, it was imperative that TOPS technologies were self-reliant. In case of problems, messages generated by faulty components were deliberately 'corrupted', with a three-string Test and Repair Processor isolating failed units and switching to backups. It was hoped that the system could even periodically health-check itself, but its size, reliability and the perceived weakness of 'who tests the tester' proved to be STAR's downfall.

Budget cuts were an ever-present companion that ultimately sounded the death-knell for missions of TOPS's complexity. When NASA formed an Outer Planets Working Group in early 1969, the Grand Tour was called "a technological tour-de-force of heroic dimensions", but such attitudes were not reflected by an increasingly conservative White House. Space exploration was no longer a tool of competition with the Soviet Union, and with the end of the Vietnam War and 'Great Society' reforms at the top of President Richard Nixon's agenda, the NASA budget declined precipitously.

"THE GRAND TOUR PROGRAMME BALLOONED FROM AN IDEA FOR A HANDFUL OF FLYBY MISSIONS INTO A BLOATED FLEET OF ORBITERS"

Costs escalate

The Grand Tour programme didn't help itself, ballooning from an idea for a handful of flyby missions into a bloated fleet of complex orbiters and atmospheric-entry probes. Its cost peaked at almost $750 million – plus a further $106 million for launch vehicles – while its payload weight correspondingly dropped from 90kg to 60kg. By mid-1971, planetary exploration funding had been slashed and NASA


With President Nixon backing the Space Shuttle, NASA administrator James Fletcher (left) was forced to stop developing TOPS

NASA/JPL X 4, ISTOCK X 2, NASA

administrator James Fletcher's assertion to Congress that the programme would trigger "great popular interest" proved a hollow statement, backdropped as it was by a scientific community torn between flyby and orbiter missions. In December, President Nixon indicated his intent to fund the Space Shuttle and Fletcher had little choice but to abandon a TOPS-based Grand Tour.

Yet all was not lost. TOPS had established an experience base to understand the necessary capabilities for future missions to the outer Solar System. In January 1972, Fletcher unveiled a less costly Mariner-Jupiter-Saturn (MJS) venture, featuring a pair of identical spacecraft. The Grand Tour programme, he explained, had ended due to a "less than enthusiastic response from certain elements of the scientific community, particularly and, to some extent, Congress". The new MJS would draw on tried-and-tested Mariner spacecraft hardware and was "warmly endorsed" by the Space Sciences Board in February.

To minimise the financial risks, MJS received a budgetary cap of $250 million and NASA opted for 'in-house' design and construction at JPL to further drive down costs. It was estimated that half of the technologies that arose from TOPS would be used by the new mission. Others, including STAR and the furlable high-gain ▷

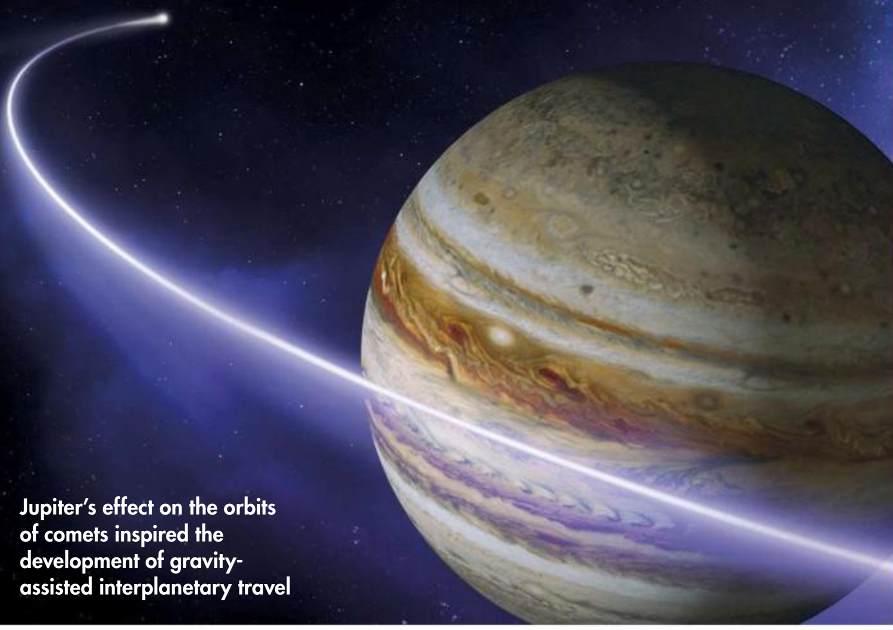
THE BIG CHALLENGE: GRAVITY ASSISTS

Mathematicians first observed the perturbative effect of planets on cometary orbits 300 years ago –specifically, the powerful ability of Jupiter to modify such objects' trajectories. Yet it was not until the early 20th century that an understanding grew regarding the usefulness of multiple-planet rendezvous to execute missions deep into the Solar System.

In 1925, Germany's Walter Hohmann demonstrated that placing a spacecraft into an ellipse tangential to the orbits of Earth and a 'destination' planet could theoretically get the craft to travel between the two planets using the least amount of energy. Thirty years later, Derek Lawden described the amount of velocity change afforded by 'gravity-assist' and Krafft Ehricke, another German rocket scientist, identified the importance of hyperbolic encounters with planets as a means of decreasing or increasing the orbital parameters of a passing spacecraft.

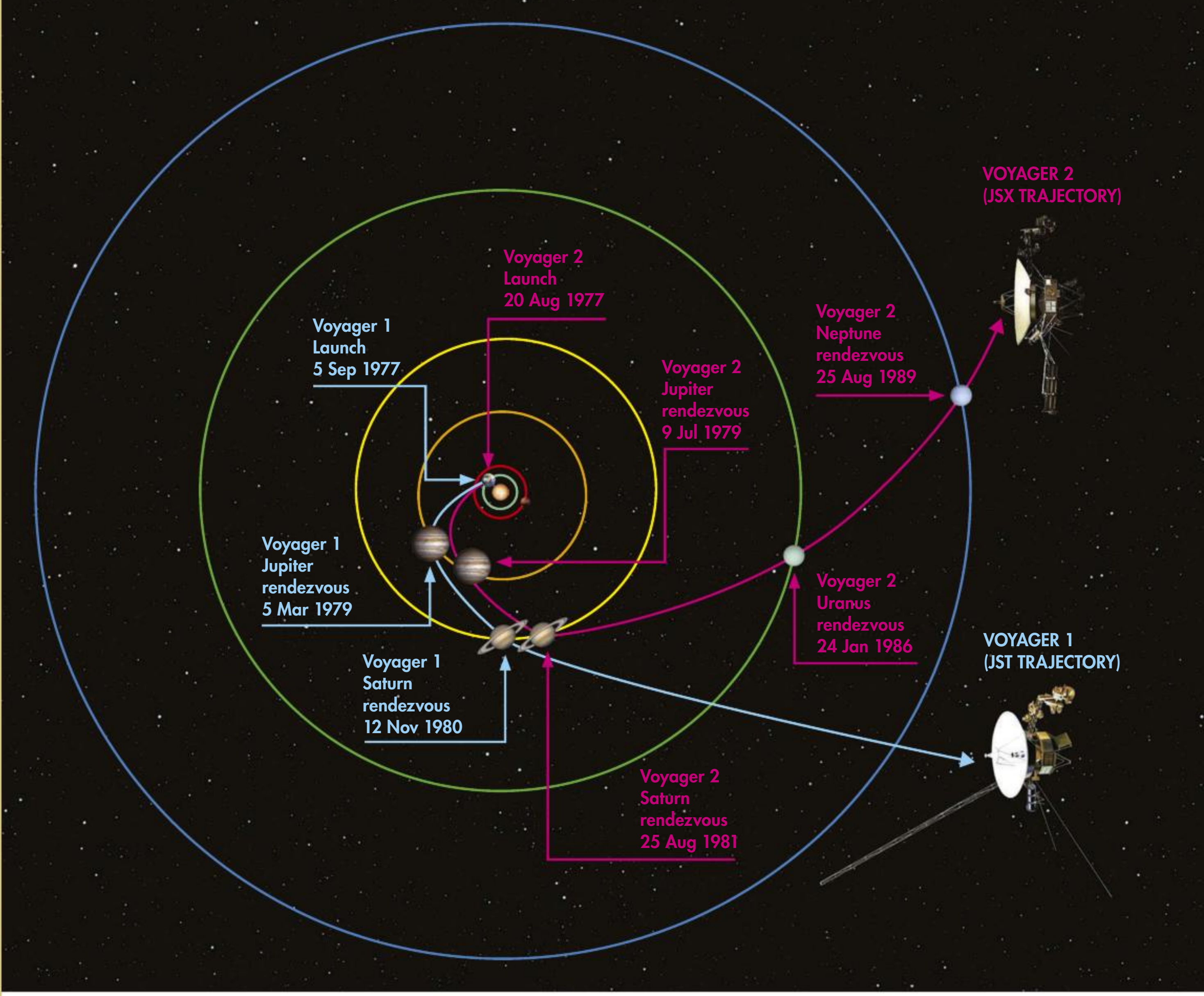
"The greater the planet's mass," he wrote, "the greater the energy saving." Ehricke showed that the shape and orientation of a spacecraft's trajectory could be adjusted and explained that if approach conditions were carefully selected, "the perturbative force can be utilised for astronautical benefits".

But although gravity-assist clearly offered energy-saving benefits, it was widely believed that rendezvous with 'intermediate' planets would yield longer (rather than shorter) overall flight durations. Theoretical mission plans to Mercury, Venus and Mars, studied by Hohmann and later by Gaetano Crocco in the mid-1950s, seemed to reinforce this notion. It wasn't until the early 1960s that we learnt that careful application of the energy gained in a properly configured encounter could seriously reduce travel times to the outer planets.


Jupiter's effect on the orbits of comets inspired the development of gravity-assisted interplanetary travel

A TALE OF TWO TRAJECTORIES

These are the final two trajectories for the Voyager spacecraft. Voyager 1, on a course dubbed 'JST', was bound for Jupiter, Saturn and then Titan, after which it would leave the plane of the planets entirely. Voyager 2's path, called JSX, would take it to Jupiter, Saturn and then – if a mission extension was granted – on to Uranus and Neptune. Oddly, Voyager 2 launched first: that's because its trajectory was the slower of the two. Voyager 1 would overtake it in the asteroid belt.



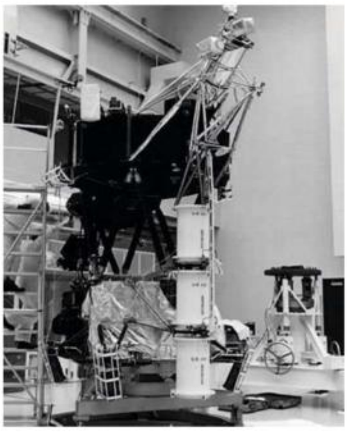
▷ antenna, were discontinued. An initial announcement of opportunity for scientific payloads in April 1972 received responses from over 200 scientists scattered around the globe, including the US, France, Sweden, West Germany and the UK. By July, 77 proposals for MJS payloads had been formally submitted. These were whittled down to 28 finalists, a handful of which were selected to build actual instruments, with the remaining finalists participating in observations.

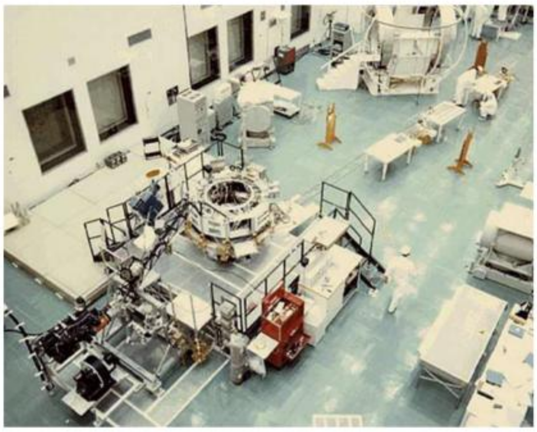
"NAVIGATOR WAS A POTENTIAL NEW NAME, BUT A NASA-RUN COMPETITION IN MARCH 1977 CAME OUT IN FAVOUR OF VOYAGER"

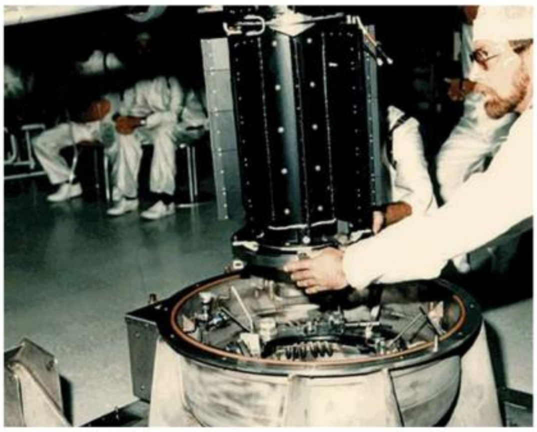
Each of the 10-sided MJS spacecraft would be dominated by a 3.7m high-gain antenna, capable of a 115.2kb/s downlink from Jupiter, dropping to 14.4kb/s at Neptune. In addition, both of the probes would be equipped with three deployable booms and a pair of whip antennas that would be bristling with 10 scientific instruments and the all-important radioisotope thermoelectric generators.

A name change

Targeted to launch in August-September 1977 – precisely in line with the optimum Grand Tour opportunities identified by Flandro – the MJS twins quickly evolved far beyond the capabilities of the Mariner





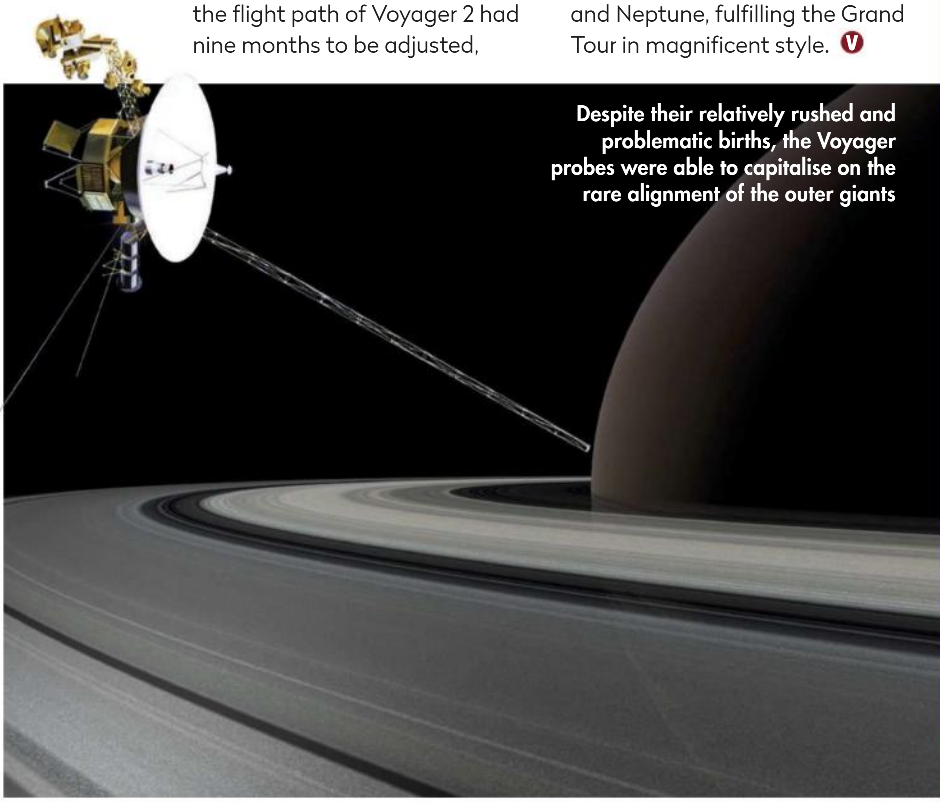


△ **NASA's experience with TOPS enabled the development of Voyager 'in-house'**

spacecraft. JPL director William Pickering had already suggested 'Navigator' as a potential new name, but a NASA-run competition in March 1977 came out in favour of 'Voyager'. It was originally the name of an unrealised Mars mission and seemed entirely fitting for an expedition to the very edge of human knowledge.

In spite of the name change, Voyager remained tied to Jupiter and Saturn, although it was hoped that changing political and budgetary winds might see the Uranus and Neptune flybys restored. The original Grand Tour was still possible, but at the expense of getting close views of Jupiter's moon Io and Saturn's moon Titan. If Voyager 1 flew close to Io, its velocity would be increased so much by Jupiter's gravity that it would reach Saturn too early to achieve a suitable rendezvous with Uranus. Conversely, if it flew close to Titan, it would depart the Saturnian system in the wrong direction to encounter Uranus.

But if Voyager 1 relinquished any chance to go to Uranus and Neptune and instead undertook both the Io and Titan encounters – adopting a Jupiter-Saturn-Titan (JST) trajectory – then Voyager 2 could conceivably visit the two outer planets. Should Voyager 1 fail at Saturn, the flight path of Voyager 2 had nine months to be adjusted, in order to complete the JST trajectory in its stead. But if Voyager 1 succeeded, its twin could execute a unique mission of exploration, dubbed 'JSX'. If realised, JSX promised to carry Voyager 2 from Saturn to Uranus and Neptune, fulfilling the Grand Tour in magnificent style. V



Despite their relatively rushed and problematic births, the Voyager probes were able to capitalise on the rare alignment of the outer giants

NASA, NASA/JPL X 7, ISTOCK

A nuclear-powered marvel

In the spring of 1977, 12 years after Flandro's revelation and several trips back to the drawing board, the twin Voyager spacecraft were nearing completion

Words: Ben Evans

THE VOYAGER PROBES are identical, nuclear-powered twins, each about the size of a small car and weighing 722kg. At each spacecraft's core is a 10-sided 'bus' that's 47cm high and 1.8m in diameter. Dominating each structure is the 3.7m-wide dish of the high-gain antenna, which is kept pointing towards Earth thanks to 16 small thrusters.

The two probes contain technology that was cutting-edge in 1977 but is now very much outdated. For instance, data is stored on an eight-track tape recorder while the crafts' computer systems have a measly 68KB of memory – around 240,000 times less than the average smartphone or approximately enough for an average jpeg image.

Sprouting out of the probes' buses are three deployable booms – one long (12m) and two short (2.4m) – as well as a pair of whip antennas. Most of the science instruments are mounted on one of the short booms to keep them as far away as possible from the 'atomic batteries' attached to the other short boom.

The long boom holds two pairs of magnetometers, which are used to explore a planet's magnetic field and how it interacts with the solar wind. The short boom that doesn't carry the atomic batteries is known as the scan platform and includes a low-res wide-angle camera and a high-res narrow-angle camera. The spectacular images of the Solar System that these cameras produced is ultimately what sold Voyager to the public.

△ **NASA engineers test the scan platform to see how well it stands up to acoustic and pyro shocks**

"THE PROBES' COMPUTER SYSTEMS HAVE A MEASLY 68KB OF MEMORY – AROUND 240,000 TIMES LESS THAN THE AVERAGE SMARTPHONE"

The scan platform also carries an ultraviolet spectrometer and a 'three-in-one' infrared radiometer, interferometer and spectrometer to examine planetary temperatures, chemical constituents and radiated heat. Particle abundances in atmospheres and near moons are observed by a photopolarimeter, while low-energy charged particle and cosmic-ray detectors, and plasma investigation systems constitute the spacecrafts' fields-and-particles suite.

The two whip antennas are used for planetary radio astronomy. They record electron densities when they're near enough to a planet in the hope of gaining deeper insights into its magnetospheric dynamics. The Voyagers' radio signals are also employed to examine the planets' atmospheric composition, gravitational fields, masses and densities, as well as any rings that might be present.

The whip antennas also house the plasma-wave subsystem to investigate wave-particle interactions at other planets. The system was a last-minute addition following NASA's decision to delete a micrometeoroid detector and ultraviolet photopolarimeter from the mission.

Going nuclear

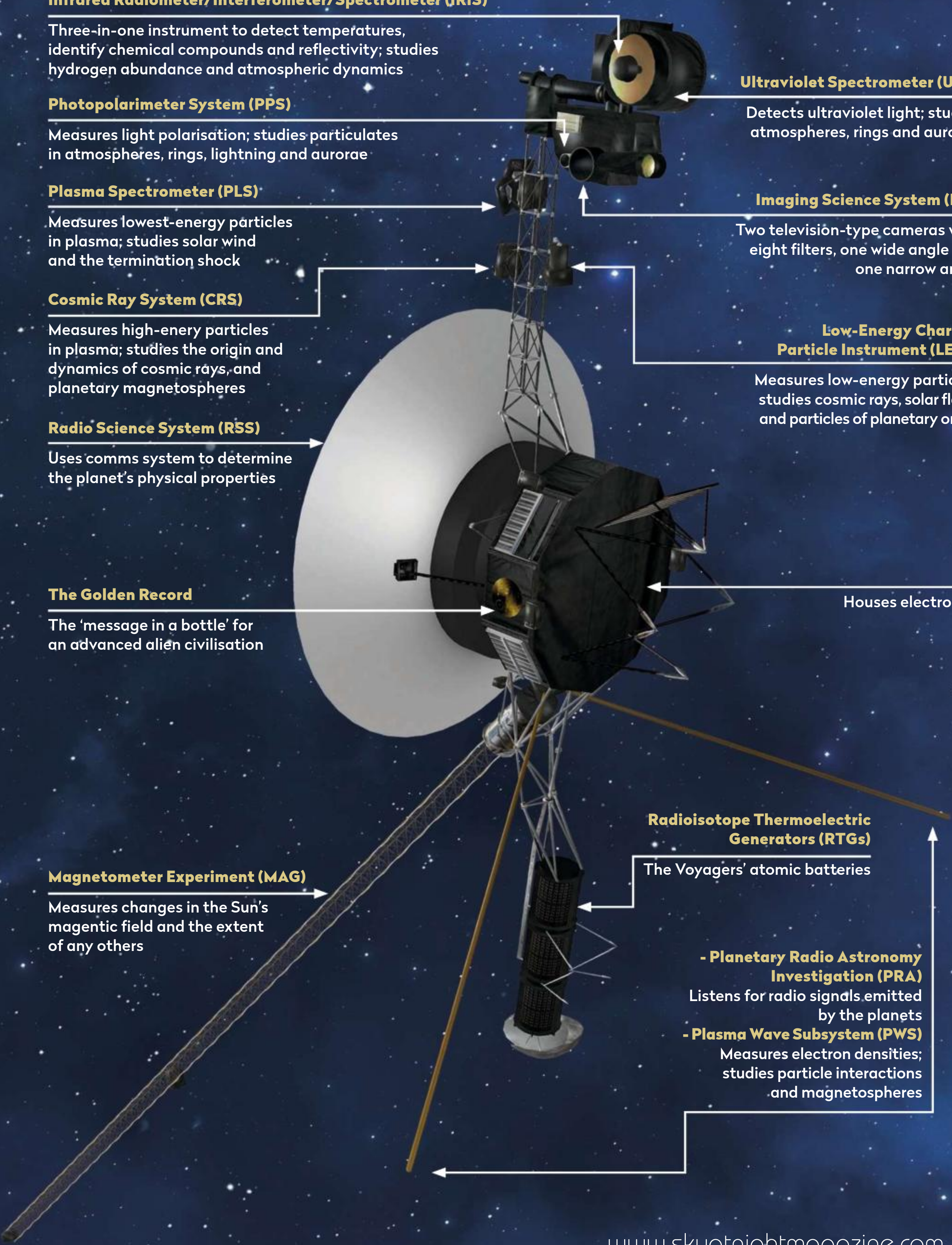
Given that the Voyagers would be travelling to Jupiter (778 million km from the Sun) and one of them would hopefully make it to Neptune (4.5 billion km from the Sun) solar energy wasn't an option as a power source for the two spacecraft. The amount of sunlight that falls on solar panels at Jupiter's distance is barely four per cent of sunlight available in Earth's orbit.

So each Voyager probe is outfitted with three multi-hundred-Watt radioisotope thermoelectric generators, each containing 4.5kg of fissionable plutonium-238 oxide in pressed pellets. These decay to produce heat, which is converted to electricity by thermocouples. V

NASA/JPL-CALTECH, ILLUSTRATION BY MARK GARLICK

THE VOYAGER INSTRUMENT SUITE

The Voyagers launched with an armada of instruments capable of examining atmospheric chemistry, mapping magnetic fields, detecting aurorae and more. Some of them could even analyse changes in space itself, in order to tell us where the solar wind gives way to interstellar space



The Voyagers' bumpy rides

Both spacecraft were successfully launched just weeks apart from Florida's Cape Canaveral. But the beginning of the Voyager mission was a frantic period of close calls and high drama

Words: Ben Evans

ON 20 AUGUST 1977, as Voyager 2 and its Titan IIIE-Centaur rocket sat on the launchpad, few would have gambled that a multi-decade mission to explore four giant planets, dozens of their moons and take us beyond the Solar System could be a success.

There were so many unknowns that the fear of failure was acutely real. No spacecraft had ever flown so far; no spacecraft had ever survived for so long. Yet people were preoccupied with another question on that sweltering Saturday morning at Cape Canaveral's Launch Complex 41: why was Voyager 2 launching before Voyager 1?

The answer is because of the different trajectories the probes would be following. Voyager 1 was set for a short, fast course that would see it arrive at Jupiter in March 1979 and Saturn in November 1980, before then sailing away from the plane of the planets. The path Voyager 2 was on would take longer, but allow it to continue out towards Uranus and Neptune. The earlier launch date would put the probe on the best trajectory to reach those outermost giants.

So why not simply renumber the Voyagers in response to the reversed launch order? Because, while the faster-moving Voyager 1 would set off 16 days later, it overtake its twin in December 1977 and reach Jupiter and Saturn sooner. In NASA's grand scheme, being first to launch was irrelevant; being first to arrive at Jupiter was the main prize.

At 10.29am local time, the Titan IIIE-Centaur's two solid-rocket motors ignited, pushing the 48m-tall booster into the crystal-clear Florida skies with a combined thrust of 1.1 million kg. After 112 seconds, the dual engines of the first stage – part of the rocket's central core, fed by a half-and-half mixture

LAUNCH PROFILE

LIFT OFF 20 August 1977 (Voyager 2), 5 September 1977 (Voyager 1)
LAUNCH VEHICLE Titan IIIE-Centaur
FROM Cape Canaveral, Florida

Despite problems before and after launch, Voyager 2 was able to continue its mission almost as planned of Aerozine-50 and nitrogen tetroxide – roared into life, punching out almost 500,000kg of propulsive yield.

At two minutes, the solid rocket motors were discarded and the vehicle continued to climb under the impulse of its core, until that too was jettisoned a little over four minutes after lift-off. The turn then came for the core's second stage, whose single engine burned for 210 seconds.

Eight minutes into the mission, the second stage separated and the high-energy Centaur upper stage prepared for a pair of burns to heave Voyager 2 out of Earth orbit and onto a course for Jupiter. Fuelled by liquid oxygen and hydrogen at very low cryogenic temperatures, the 9.6m-tall Centaur was wider than the Titan IIIE core and so required a tapering inter-stage adapter to connect them.

Problems arise

The Centaur's initial burn established a temporary 'parking orbit' and demonstrated that Voyager 2 could support a lengthy period of coasting to maximise performance. Its second burn lasted five and a half minutes and accelerated the spacecraft to over 14km/s, well beyond escape velocity.

The mission was only minutes old but already it was running into problems. The probe had suffered a double computer failure on the launchpad, but during its ascent another glitch saw its fault-protection system report unexpected readings, described by some as 'robotic vertigo'. The glitch turned out to be the fault-protection system itself, which hadn't been programmed to recognise the launch conditions and reported an issue even though everything was proceeding as expected.

After the jettisoning the Centaur, Voyager 2's Star-37E solid-fuelled motor burned for 45 seconds to add 1.9km/s onto its Jupiter-bound velocity. The spent motor was then discarded and the 23-month trek to Jupiter could begin, but there would be a few more bumps along the way.

One of the bumps was a sensor that erroneously indicated the boom carrying Voyager 2's scan platform had not deployed, another was a manoeuvring thruster that ended up pointing the wrong way and spraying propellant onto the spacecraft, causing it to drift slightly off-course. The infrared radiometer, interferometer and spectrometer – a crucial element of Voyager 2's imaging suite – also suffered a period of degraded sensitivity. This was caused by the crystallisation of some bonding material, which led to the mirrors inside the spectrometer becoming warped and misaligned. Fortunately, the spacecraft's flash-off heater reversed this problem and returned the instrument to its pre-launch levels of sensitivity.

Although these obstacles were overcome, it wasn't possible for engineers at the Jet Propulsion Laboratory (JPL) in California to fully rectify a potentially catastrophic situation that occurred in April 1978. A series of minor headaches culminated in Voyager 2 permanently losing its main radio receiver. The problem began rather innocuously, when the onboard seven-day timer – a safety mechanism designed ▷

△ **Voyager 2, encased in its launch capsule, is winched into position atop the Titan IIIE-Centaur rocket**

"IN NASA'S GRAND SCHEME, BEING FIRST TO LAUNCH WAS IRRELEVANT; BEING FIRST TO ARRIVE AT JUPITER WAS THE MAIN PRIZE"

NASA/JPL X 2, NASA/JPL-CALTECH/KSC

TITAN IIIE-CENTAUR: SUCCESS AND SHORTSIGHTEDNESS

The wide-bodied Centaur rocket (top) links to the Titan IIIE booster (below) with a tapering inter-stage adaptor

Following the cancellation of the Saturn V rocket, the Titan IIIE-Centaur became the most powerful launch vehicle in the US's inventory. Standing 16 storeys tall, it was capable of firing 'Earth-escape' missions, weighing up to 3,700kg, deep into the Solar System. These included both of the billion-dollar Viking orbiters and landers sent to Mars in 1975. But the Titan rocket had run into difficulties even before its development was finished. The Space Shuttle was widely expected to replace all expendable launch vehicles and by the time the Titan IIIE-Centaur was being readied for its maiden voyage on 11 February 1974 its death knell had already sounded. It flew only seven times, with the two Voyager probes being its swansong.

Voyager 1 lifted off after Voyager 2, to follow a different but quicker path to Jupiter

▷ to guard against loss of contact with Earth – ran down to zero, without receiving a reset command from ground control. Voyager 2 responded by assuming the main receiver had failed and switched to its back-up. But an electrical short had caused a circuit to fail in the back-up receiver, leaving it tone-deaf and forcing JPL engineers to transmit at precisely the right frequency in order to communicate with the probe.

The difficulty in finding the correct frequency was complicated by Earth's rotation and motion around the Sun, as well as Voyager 2's own movements and fluctuating deep-space temperatures that caused the frequency to slip by as much as 96Hz. At length, a solution was found and efforts were undertaken to return the main receiver to back full functionality and take the back-up receiver offline.

During this switching process, an electrical short blew both fuses in the main receiver, effectively killing it. Only months after launch, the team was left with just the back-up receiver to support the entire mission. Remarkably, for the rest of its operational lifetime – four decades and counting – Voyager 2's scientific data would be relayed home by a flawed, yet workable back-up receiver.

One follows two

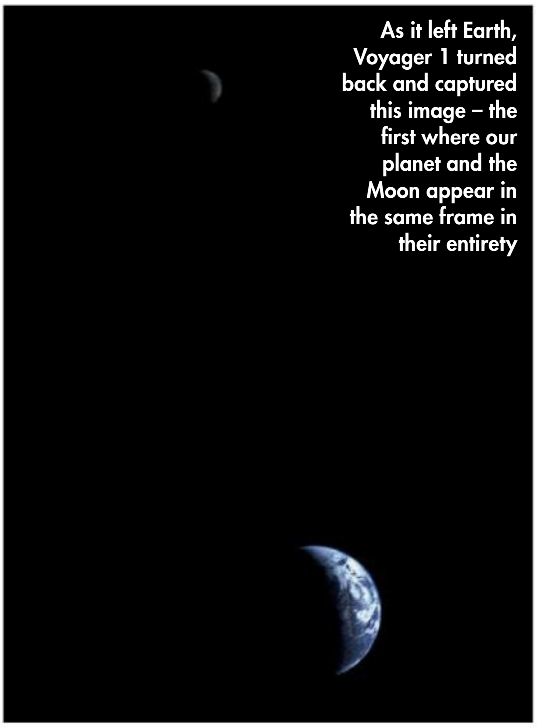
At 8.56am local time on 5 September, 16 days after Voyager 2 left Earth, Voyager 1 rose from Launch Complex 41 atop the final Titan IIIE-Centaur. But Voyager 1 was in for a rough ride. Although the early phase of ascent appeared to proceed normally, a failure in the Titan hardware left more than 540kg of propellant unburned. The result was that Voyager 1 and its Centaur were not travelling fast enough. Fortunately, the Centaur's onboard computer saved the day by compensating for the shortfall and burning its own engines for slightly longer.

It was a nail-biting time. When the Centaur finally shut down, it had only 3.4 seconds of burn-time remaining. "Wow," remarked JPL Director Bruce Murray, with an air of understatement. "That was pretty close!"

Had a similar malfunction occurred with Voyager 2, whose trajectory had a smaller margin for error, even the Centaur couldn't have rescued it. Voyager 2 would have ended its mission a few hours after launch by falling into the Pacific Ocean.

Despite the early problems they encountered, both Voyager probes barrelled away from the Earth on their missions to explore the outer Solar System.

Thirteen days after launch, and having already weathered its own issue with a jammed scan platform, Voyager 1 acquired a remarkable image of Earth and the Moon (below). Never before had our world and its only natural satellite (both crescents at the time) been seen together in their entirety. It served as a final farewell as the two Voyagers left their place of origin behind, never to return. V



As it left Earth, Voyager 1 turned back and captured this image – the first where our planet and the Moon appear in the same frame in their entirety

NASA/JPL X 2

Voyager's great milestones

Words: Kev Lochun

The highlights from a mission that has lasted for two-thirds of the entire Space Age and could continue for another decade

20 AUGUST 1977
Voyager 2 launches from Cape Canaveral in Florida at 14:29:00 UT atop a Titan IIIE-Centaur, ahead of Voyager 1 owing to its slower trajectory.

5 SEPTEMBER 1977
Voyager 1 follows its sister spacecraft skyward, launching from Cape Canaveral at 12:56:00 UT.

18 SEPTEMBER 1977
As Voyager 1 leaves Earth, it photographs its home planet from 11.7 million km away. It's the first time Earth and the Moon have been seen in a single frame shot from a spacecraft.

19 DECEMBER 1977
Voyager 1 overtakes Voyager 2, passing its twin in the asteroid belt.

6 JANUARY 1979
Voyager 1 snaps the first photo of the mission's first planetary encounter, a portrait of Jupiter from 57.6 million km away.

5 MARCH 1979
Voyager 1 makes its closest approach to Jupiter, 206,700km over the planet's cloud tops. The gas giant is unexpectedly found to have faint, slender and dusty rings.

9 MARCH 1979
Volcanism is discovered on the Galilean moon Io, from a photo only taken to navigate the spacecraft. It's the first time volcanism has been seen beyond Earth.

9 JULY 1979
Voyager 2 makes its closest approach to Jupiter, at a much greater distance of 570,000km.

12 NOVEMBER 1980
Voyager 1 makes its pass of Titan, only 4,000km above its clouds. The atmosphere is too thick for the probe to see the moon's surface, but it's atmosphere is intriguing.

12 NOVEMBER 1980
Voyager 1 also passes within 64,200km of Saturn's cloud tops. The probe reveals new rings, new 'gaps' between the rings and spots the first shepherd moons.

14 DECEMBER 1980
Voyager 1's Saturn encounter comes to an end with observations of the moon Hyperion. The spacecraft now begins moving away from the plane of the planets.

25 AUGUST 1981
Voyager 2 arrives at Saturn and passes closer to the planet than its twin, coming with 41,000km.

24 JANUARY 1986
Voyager 2 has the first-ever encounter with Uranus. It discovers 11 new moons and two rings, plus reveals Miranda to be the weirdest moon in the Solar System.

25 AUGUST 1989
Neptune is photographed up close for the first time, by Voyager 2 from 5,000km. The spacecraft records ferocious winds and a massive storm system – the Great Dark Spot.

14 FEBRUARY 1990
Voyager 1 acquires the final images of the mission, a 'family portrait' of our Solar System; among them is the Pale Blue Dot, in which Earth appears as a speck trapped in a sunbeam.

17 FEBRUARY 1998
Voyager 1 overtakes Pioneer 10 to become the most distant human-made object in space; it is 69 AU from Earth at this time.

17 DECEMBER 2004
Voyager 1 passes the termination shock, where the intensity of the solar wind starts to diminish. It enters a boundary zone called the heliosheath.

30 AUGUST 2007
Voyager 2 passes the termination shock and enters the heliosheath.

13 AUGUST 2012
Voyager 2 gains the title of longest-operating spacecraft, breaking the 12,758-day record previously set by Pioneer 6 in December 2000.

25 AUGUST 2012
Voyager 1 enters interstellar space. NASA is only able to confirm this 13 months later, after a coronal mass ejection from the Sun catches up with the spacecraft.

WITHIN FIVE YEARS
Voyager 2 is expected to reach interstellar space.

BY 2025
Both Voyagers are expected to have exhausted their plutonium batteries and all its instruments will have been shutdown.

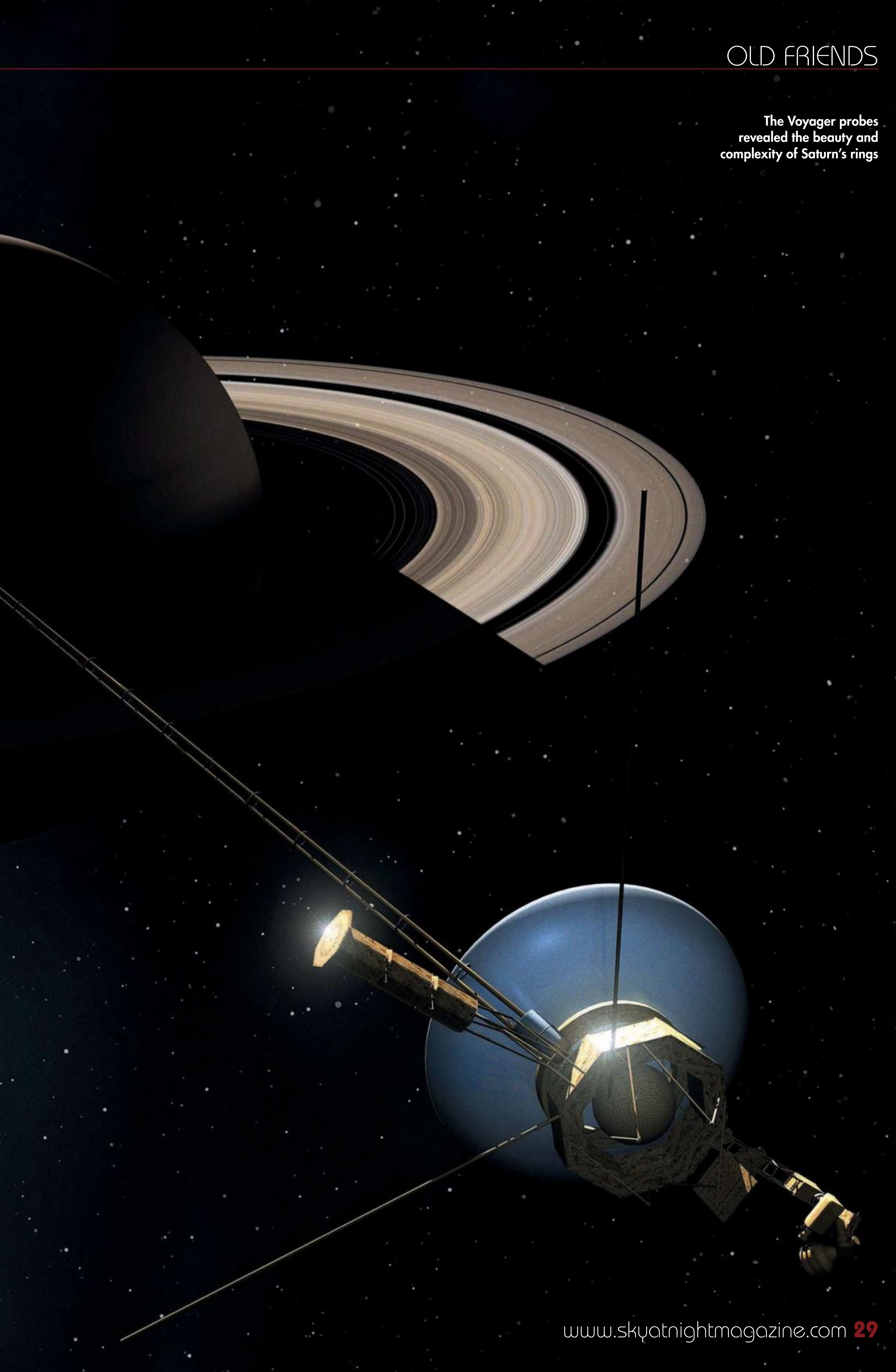
300 YEARS' TIME
Voyager 1 is expected to reach the Oort Cloud. It could take 40,000 years to pass through it.

40,000 YEARS' TIME
The Voyagers pass close to other stars. Voyager 1 will sail within 1.6 lightyears of Gliese 445, while Voyager 2 will travel within 1.7 lightyears of Ross 248. V

MARK GARLICK

PHASE II
OLD FRIENDS

The first stops for the Voyagers were the two gas giants known to humankind since antiquity: mighty Jupiter, largest planet of them all, and the majestic ringed world Saturn. They sent back close-up images of Jupiter's swirling belts of cloud, its surging storms and, of course, its Great Red Spot – an anticyclone large enough to swallow several Earths. They revealed that Saturn's rings were far more complex than we had realised and that Jupiter's magnetosphere was more enormous than we ever imagined. But it was these planets' moons that really surprised. Instead of finding dead, barren husks like our own, the Voyagers encountered a broad cast of characters with all manner of quirks – satellites with cracks and stripes, icy crusts and active lava floes. The rewriting of the textbooks, so often credited to the Voyager probes, began here.



The Voyager probes revealed the beauty and complexity of Saturn's rings

Secrets erupt from Jupiter

In January 1979, after a journey of 15 months, Voyager 1 began to photograph the first planet on its Grand Tour, the gas giant Jupiter. Voyager 2 followed a few months later, and together they rewrote almost everything we thought we knew about the Jovian system – not least the fact that volcanism exists beyond Earth

Words: Ben Evans

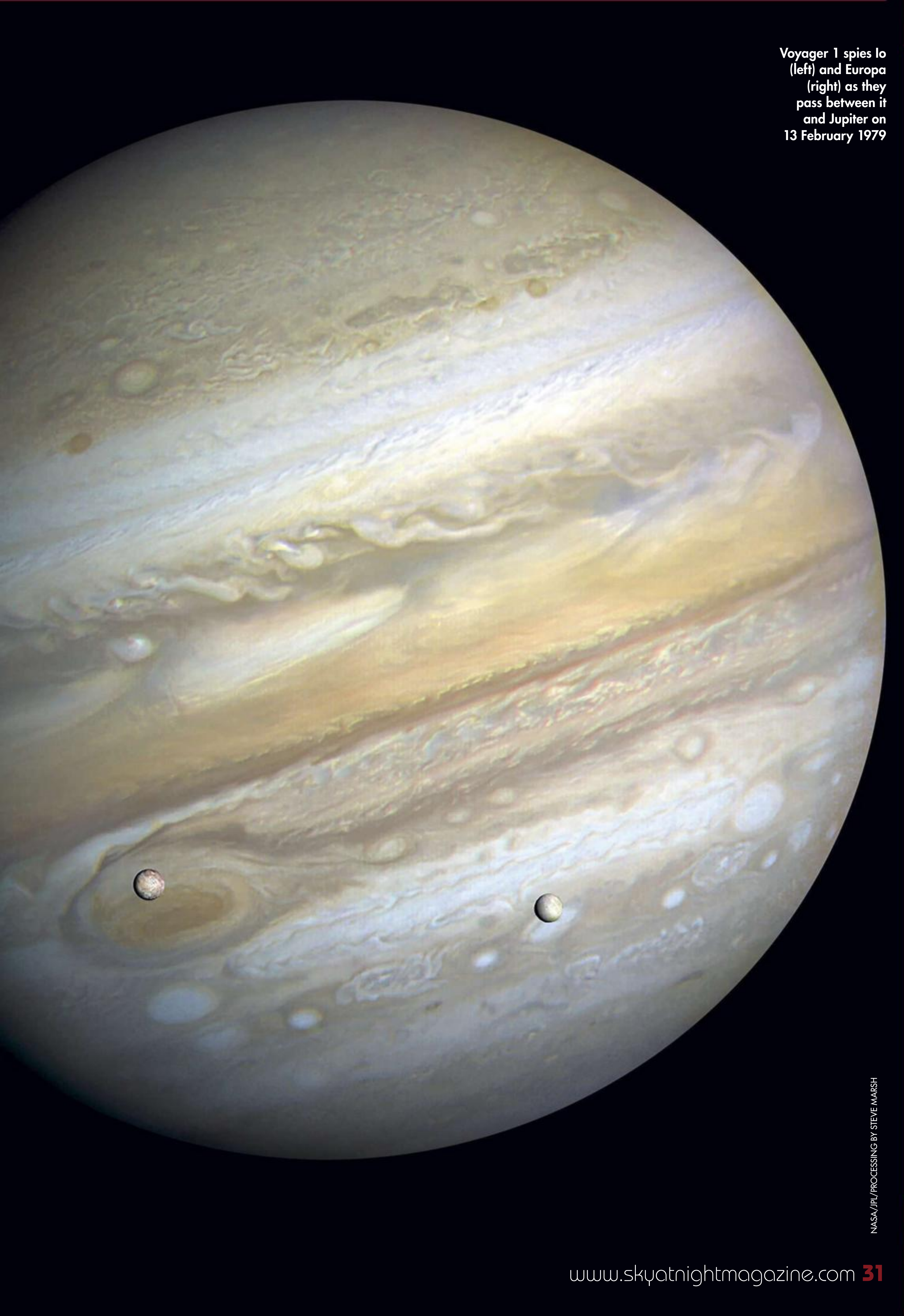
AT FIRST GLANCE, it resembled nothing more than a blemish on Voyager 1's lens. But as 26-year-old engineer Linda Morabito peered closer at the image of Jupiter's moon, Io, she realised she was looking at something extraordinary. The blemish was actually a faint, bluish crescent that was protruding from beyond the moon's limb.

This all occurred on 9 March 1979, four days after the probe had made its closest pass – 349,000km – of the broiling Jovian cloudtops. Morabito was part of the optical navigation team, plotting Voyager 1's trajectory to Saturn, three-quarters of a billion kilometres and 20 months away. She had just made the most significant discovery of the entire mission.

The long-exposure shot, taken a day earlier, viewed Io from a parting distance of 4.5 million km. Analysis revealed the crescent to be a plume – rising over 280km into space – from a volcano. Later named 'Pele' after the Hawaiian goddess of volcanoes, it was the first of hundreds of such features to be found on Io. As the days wore on, infrared data pinpointed regions rich in sulphur dioxide, where temperatures soared up to 200°C higher than the surrounding terrain. Four months later, on 9 July, Voyager 2 revealed that Pele had fallen dormant, although several other volcanoes remained active.

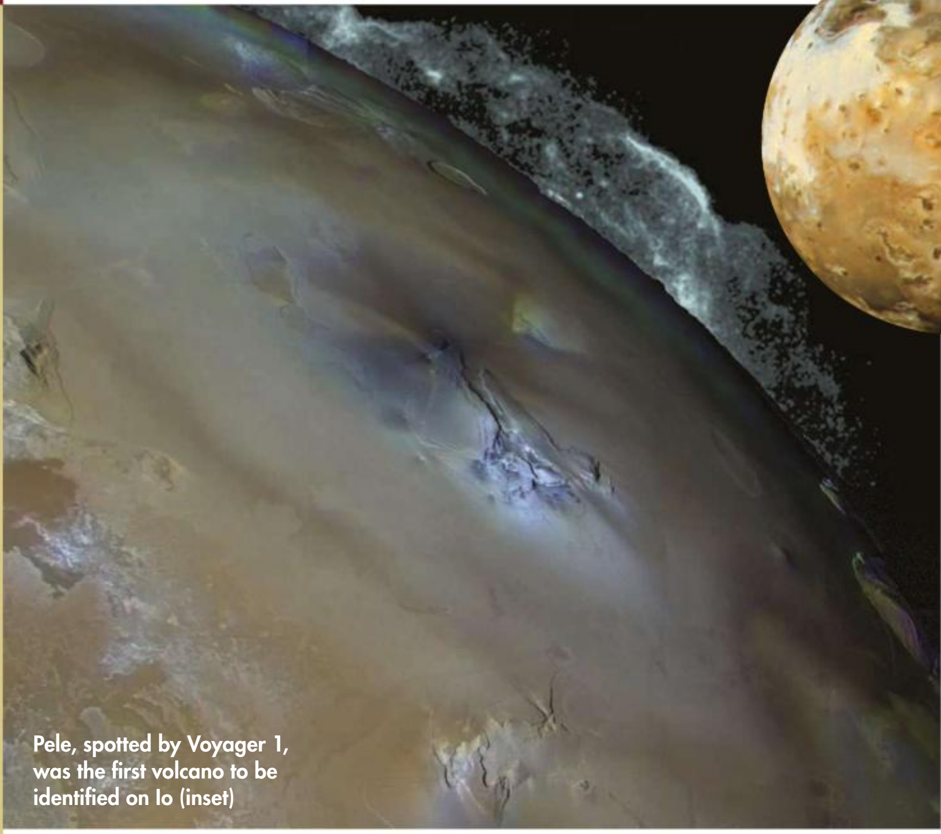
Big surprises

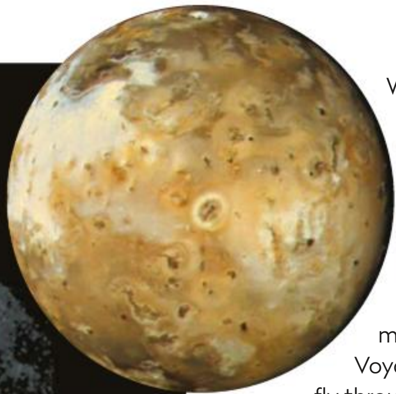
It was a big surprise on a natural satellite with a size and density roughly equal to that of our geologically inactive Moon. Io's proximity to its giant host (it orbits just 421,800km from Jupiter's centre) forces it to bear the brunt of a punishing magnetic field. This is hundreds ▹



Voyager 1 spies Io (left) and Europa (right) as they pass between it and Jupiter on 13 February 1979

NASA/JPL/PROCESSING BY STEVE MARSH





Pele, spotted by Voyager 1, was the first volcano to be identified on Io (inset)

▷ of times stronger than Earth's and 'co-rotates' with Jupiter's interior every 10 hours, transporting vast quantities of energetic plasma back and forth along magnetic field lines. The field is inflated at the magnetic equator, pushing the plasma outwards in a huge, tilted 'sheet' that rises and falls, flopping north then south, during each rotation period.

The relationship between Jupiter and Io is a complex one. As Jupiter's magnetic field sweeps past Io it strips 1,000kg of mass from the moon every second. This forms a doughnut-shaped 'torus' of charged particles, the existence and extent of which was first inferred by Pioneer 10. Ground-based observations also identified a neutral sodium cloud around Io, formed by atmospheric sputtering, as well as the spectroscopic fingerprints of sulphur dioxide.

Not until the discovery of Io's volcanism did the process of how this torus was maintained begin to make sense. Under Voyager 1's gaze, twice-ionised oxygen and sodium atoms glowed brightly at ultraviolet wavelengths. To achieve such intensities, electron temperatures have to surpass 100,000°C and radiate a trillion Watts – double the power-generating potential of the entire US – along a 'flux-tube' into Jupiter's magnetosphere. Voyager 1 tried to fly through this flux-tube, but missed its centre by around 5,000km.

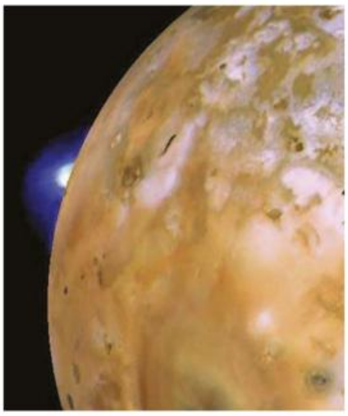
Lava lakes and lights

Morabito's chance discovery identified Io as the most volcanically active place in the Solar System. It yields twice as much energy as all of Earth's volcanoes combined, despite having a fifth as many hotspots and being only a third of the size of our planet.

Voyager 1 found virtually no impact craters on its young and dynamic surface, just a few per cent of which was pockmarked with dark-centred volcanoes. From these snaked red and orange lava flows, some fanning out in wide arcs, others forming

▽ **Tiny Io hangs in front of Jupiter's cloud belts**

△ **Streams of lava snake out from the volcanoes on Io's surface**



△ **Voyager 1 catches a plume erupting from Ionian volcano Loki**

△ **Io's plains are vivid in colours, thought to be the result of layers of sulphur, sulphur-dioxide frost and basalt**

NASA/JPL X 7, NASA/JPL/PROCESSING BY STEVE MARSH a series of twisting tentacles. Pele was surrounded by a hoofprint-shaped lake of sulphur dioxide, while 200km-wide Loki – more powerful than all of Earth's volcanoes, put together – had increased in magnitude and evolved into a two-plume eruption by the time Voyager 2 was able to observe it.

Jupiter's torus offered a contributing reservoir of energetic particles, which spiralled along magnetic-field lines to fuel the planet's spectacular aurorae. One display extended 30,000km across its north polar region and generated extraordinary 'whistling' radio emissions. The Voyager 1 image that confirmed the existence of the 'Jovian Lights' also picked out massive electrical discharges from 19 lightning 'superbolts', while Voyager 2 went on to locate eight additional flashes.

Jupiter's magnetosphere is a truly colossal powerhouse. The Pioneer probes revealed its sunward extent and raised speculation of a bullet-like 'magnetotail' in its wake.

△ Voyager 1 took this picture on 5 March 1979; lightning can be seen in the centre of the image, as can aurorae on Jupiter's limb

Voyager data confirmed the tail's existence and showed that it extended 740 million km beyond the planet, as far as Saturn's orbit. Increased solar activity since 1974 had compressed the sunward boundary and a continuous push-pull dynamic saw both spacecraft repeatedly enter, exit, then re-enter the magnetosphere – Voyager 2 recorded 11 boundary crossings. This showed the variability of the magnetosphere's size, as the boundary rhythmically flashed in and out in response to solar wind pressure.

"VOYAGER CONFIRMED JUPITER'S MAGNETOSPHERE EXTENDED 740 MILLION KM BEYOND THE PLANET, AS FAR AS SATURN'S ORBIT"

Moving pictures

The two Voyagers spent months examining Jupiter, both before and after their closest passes. From January until April 1979, Voyager 1 transmitted data across the 778-million-km gulf to Earth, while Voyager 2 did likewise between April and August. Pictures received during those periods showing how the differential rotation of Jupiter's atmosphere produces a colourful latitudinal display of bright 'belts' and dark 'bands', prompted comparisons to the work of Vincent van Gogh.

Movies made with overlapping photos of Jupiter's rotation showed clouds swirling around the edge of the planet's famous Great Red Spot and clipping along at 100m/s. Twice the size of Earth and observed telescopically since the 17th century, the spot inhabits the southern hemisphere and rotates ▷

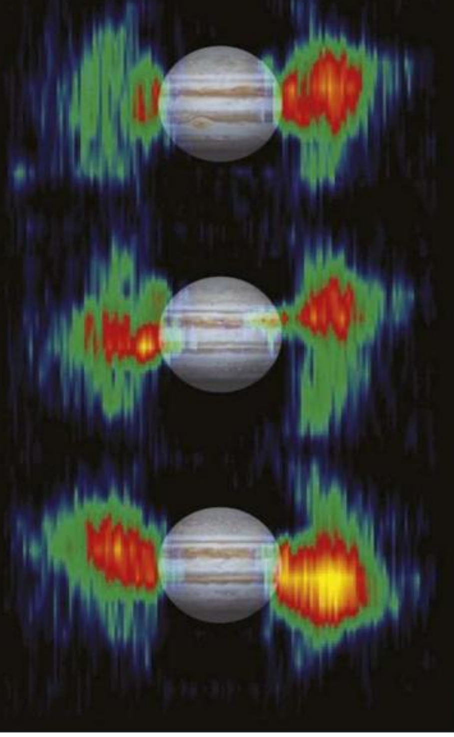
THE RADIATION PROBLEM

Before 1970, it was theorised that large quantities of abrasive dust might endanger a spacecraft as it attempted to pass through the asteroid belt between Mars and Jupiter. Several years later, when the Pioneer probes crossed the belt, they showed the dust was no danger. But upon their arrival at Jupiter, a new problem emerged: the Pioneers' circuits had been fried and their optics darkened by the savage Jovian radiation belts. They'd endured 1,000 times the human-lethal dose of high-energy protons and electrons.

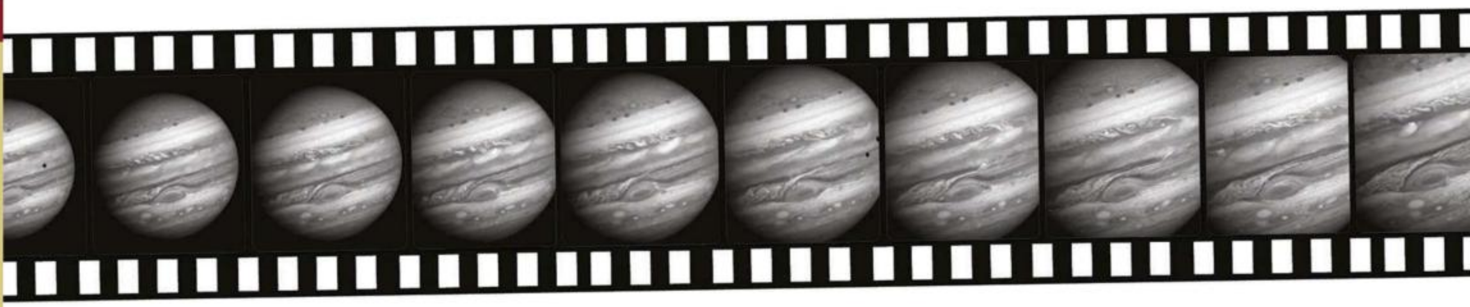
As well as building a plasma-wave instrument to analyse this environment, engineers worked to toughen the Voyager probes' electronics ahead of their visits to Jupiter and Saturn. Radiation-resistant materials, including tantalum, were tested to maximise their reliability, before being added into each of the spacecraft. Particularly sensitive areas received additional spot-shielding.

The Voyagers made it through the radiation belt but not wholly unscathed. Voyager 1 experienced a 'timing offset', which caused its onboard clock to slow down. Moreover, its two computers drifted out of synchronisation with each other and the flight data systems. These glitches led to some photographs being taken 40 seconds too early, which induced blurring and the loss of high-resolution images of Io and Ganymede.

Fortunately, Voyager 2 passed Jupiter at a much wider distance than its twin so its problems were correspondingly lessened. Its computer had also been reprogrammed to synchronise automatically, every hour. In this fashion, the complications of image-smear by the high radiation levels were largely avoided.



▷ Images taken by the Cassini spacecraft years later revealed the variable nature of Jupiter's radiation belts



△ The movements of Jupiter's cloud bands could be seen when pictures of the planet were stitched together to make short movies

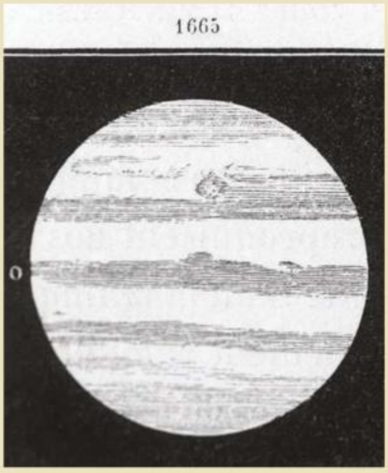
▷ anticyclonically, bearing many hallmarks of a high-pressure region. With no solid surface or continents to anchor pressure waves, Jupiter's storms can (and do) endure for centuries. The Pioneer probes saw uniform colour within the spot and its attendant clouds, but by 1979 south temperate latitudes had altered considerably, producing complex turbulence. In July, Voyager 2 hurtled past at a distance of 576,000km and revealed a notable 'thinning' of bands at the spot's southern rim, a spreading-out of clouds to the east and a greater evenness of colour. Three oval-shaped white spots, first seen four decades earlier and each the size of our Moon, had also worked their way steadily eastwards.

A ring is revealed

At 1,300 times the size of Earth, Jupiter is the biggest and most massive planet in the Solar System. Infrared data from Voyager pegged its composition at 87 per cent hydrogen and 11 per cent helium, with trace amounts of methane, water, ammonia and rock. A seething mass of clouds, storms and eddies within its bands and belts moved crisply across its disc, indicating that the motion of material, rather than energy, was at work deep in the interior. Westward-blowing zonal winds extended at least 60° north and south, far closer to the poles than expected. But the surprises didn't end there.

Before 1979, only Saturn and Uranus were known to have rings; theoretical models of

A FRESH GLIMPSE OF AN OLD GREAT



△ Giovanni Cassini sketched the Great Red Spot while observing Jupiter in 1665

Measuring 26,000km in its east-west diameter and half as much north-south, the enigmatic Great Red Spot lies 22° south of Jupiter's equator and has been observed telescopically for more than three centuries. Its discovery is usually attributed either to the English scientist Robert Hooke or the Franco-Italian astronomer Giovanni Cassini, both of whom are believed to have seen and recorded it between 1664 and 1665. Writing in the *Philosophical Transactions of the Royal Society*, Hooke identified the feature's presence "in the largest of the three observed belts of Jupiter" and noted that "its diameter is one-tenth of Jupiter".

The spot was seen intermittently up until 1713, before seemingly vanishing. Heinrich Schwabe saw it again in 1831. Since then, it has changed both in size and colour: ranging from an extraordinary brick-red hue to a more mellow ruddy brown and swelling at one stage to 40,000km in diameter. Voyager observations revealed it to be a high-pressure region, significantly colder at the cloud-tops, although the reason for its colour remains a mystery.

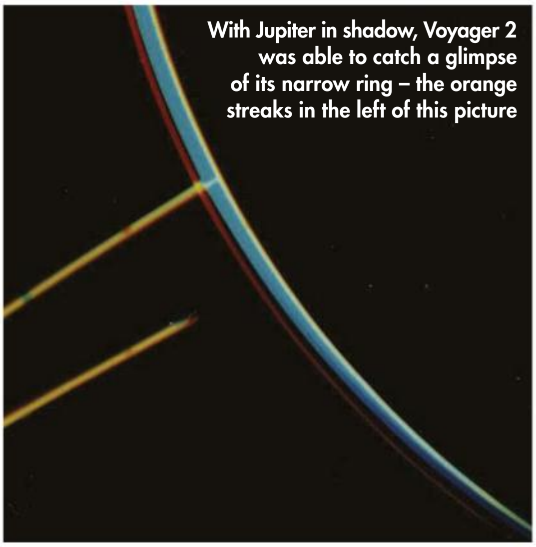
Due to the lack of solid surfaces on the giant planets, long-lived storms of this type have been identified on Saturn and Neptune, although not in the same league as the Great Red Spot. It's possible that such features draw energy from the sides or below, or perhaps that they accrue their size simply by gobbling other smaller spots and eddies. It seems that thanks to the immense depth of the atmosphere and the absence of continents to dissipate the storm's energy, the Great Red Spot has settled into a semi-stable state.

The Great Red Spot is a violent and long-lived storm big enough to engulf Earth several times over

△ Among the myriad atmospheric features were brown oval 'barges' like this one (left) and an array of white storms close to the Great Red Spot (right)

△ Different meteorological characteristics persist at different latitudes on Jupiter, which lead to the formation of the planet's distinctive bands

△ The storm responsible for producing the Great Red Spot is believed to have been raging for over 150 years

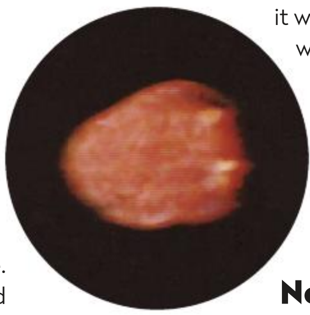


With Jupiter in shadow, Voyager 2 was able to catch a glimpse of its narrow ring – the orange streaks in the left of this picture

"JUPITER'S MAIN RING MIGHT HAVE EVOLVED FROM AN ANCIENT MOON, TORN APART BY TIDAL FORCES"

long-term stability had not predicted any to exist at Jupiter. That prediction was proven wrong just 17 hours after Voyager 1 made its closest approach, when a photo taken to search for new moons picked out a tenuous ring only 30km wide.

It was intrinsically dark and composed of tiny, rocky grains, with a reddish hue similar to the surfaces of the newly found moons Thebe, Metis and Adrastea. Long-range imagery also revealed a red surface on the elongated and cratered moon Amalthea. This prompted speculation that the ring might have evolved from an ancient moon torn apart by tidal forces and it was argued that Adrastea could provide a suitable reservoir of material for it.



△ Amalthea, known to exist since 1892, was found to be extremely red

NASA/JPL X 8

Voyager 2 revealed the ring to be quite narrow – one scientist called it "ribbon-like" – and its proximity to Jupiter implied that it was quite young. Its main body was joined by an interior 'halo' of dust and an outer 'gossamer' ring, which petered out into the background darkness, 180,000km above the planet's cloud tops.

New view, new details

The Voyager probes unveiled the Jovian system in its entirety for the first time and showed us the vast differences between the four Galilean moons. Even the finest telescopes of the era were only capable of showing Io, Ganymede, Europa and Callisto as tiny, dancing points of light. The two Voyager spacecraft revealed them to be four distinct worlds that varied in size from smaller than our Moon to almost as big as Mars.

Giant Ganymede is the largest planetary satellite in the Solar System, with an equatorial diameter of 5,270km, slightly pipping Saturn's moon Titan. Voyager 1 uncovered the presence of a thin atmosphere on Ganymede with a pressure equivalent to just one billionth of the sea-level pressure on Earth. Images taken by the probe showed a terrain split between dark, heavily cratered ancient areas and brighter, more youthful patches intersected by ridges and furrows.

The dominant feature on Ganymede's surface is the Galileo Regio, a 4,000km-wide ▹

Ganymede's crust contrasts dramatically, with dark, old regions standing out from the newer, lighter ones

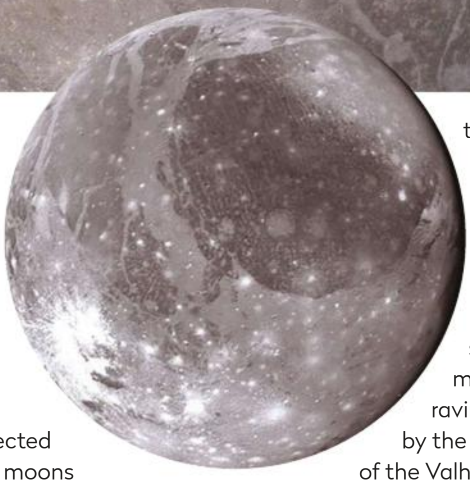
▹ dark patch big enough to cover the 48 adjoining US states. This vast oval-shaped remnant of Ganymede's primordial crust is punctuated by craters nicknamed 'palimpsests', after pieces of reused medieval parchment that allow the original, partly erased work to show through the new writing. The region and its craters offer a tantalising glimpse of Ganymede's past tectonic upheavals. Elsewhere, younger craters exhibit dark rays, extending for hundreds of kilometres across the surface.

An old moon

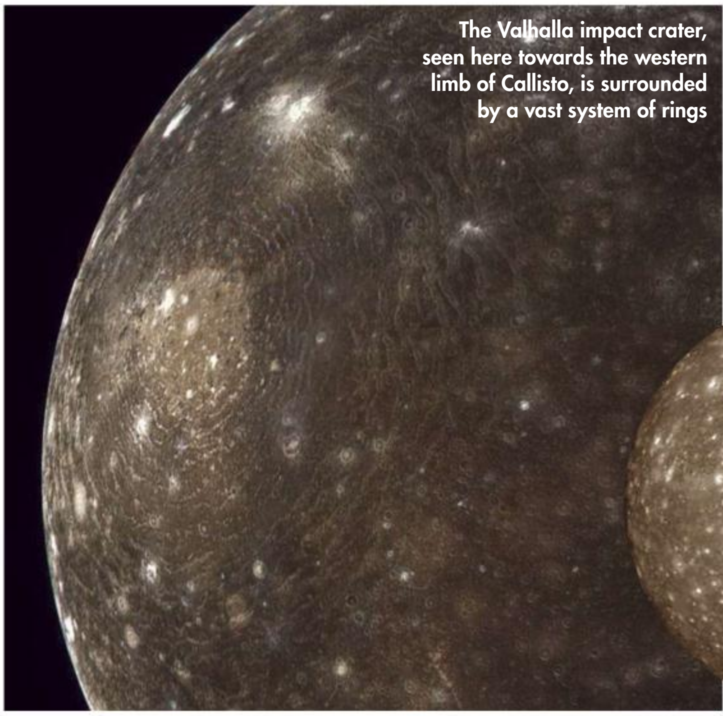
Callisto, although eight per cent smaller in equatorial diameter than Ganymede, was expected to be similar, as both moons are approximately half-water and half-rock and, unlike Io, are far enough from Jupiter to escape serious magnetospheric bombardment. Voyager 1 saw Callisto on the outward leg of its journey and found a surface without high mountains or deep ravines but dominated by the 600km-wide bullseye of the Valhalla impact crater and its surrounding array of concentric rings.

Vast tracts of heavily pitted terrain revealed a world whose origin may stretch as far back as the accretional stages of the giant planets themselves, some 4.5 billion years ago. 'Large' craters, exceeding 150km in diameter, were conspicuously absent, however, leading to theories that Callisto's ice-rock composition had somehow altered the ability of its thin crust to support them. Even at the time of the Voyager encounters, it was argued that ice floes over millions of years probably filled and obliterated craters of this size.

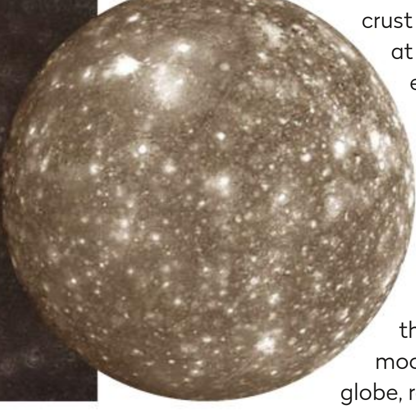
As for Europa, the two spacecraft saw the smallest Galilean moon as a highly reflective globe, reminiscent of a



△ The craters in Ganymede's huge Galileo Regio provide a window onto the moon's tectonic history



The Valhalla impact crater, seen here towards the western limb of Callisto, is surrounded by a vast system of rings



▽ The small number of craters on Callisto suggests a lack of tectonic activity

"string-wrapped baseball". It was a description inspired by the moon's striking linear features, from its scalloped ridges to meandering dark stripes that crisscrossed the surface for thousands of kilometres, while mysterious 'triple bands' made up of two parallel ridges, separated by a depressed central gorge. One of the few craters on Europa is 26km-wide Pwyll, which is surrounded by bright rays of ejecta that run for hundreds of kilometres out from its central basin.

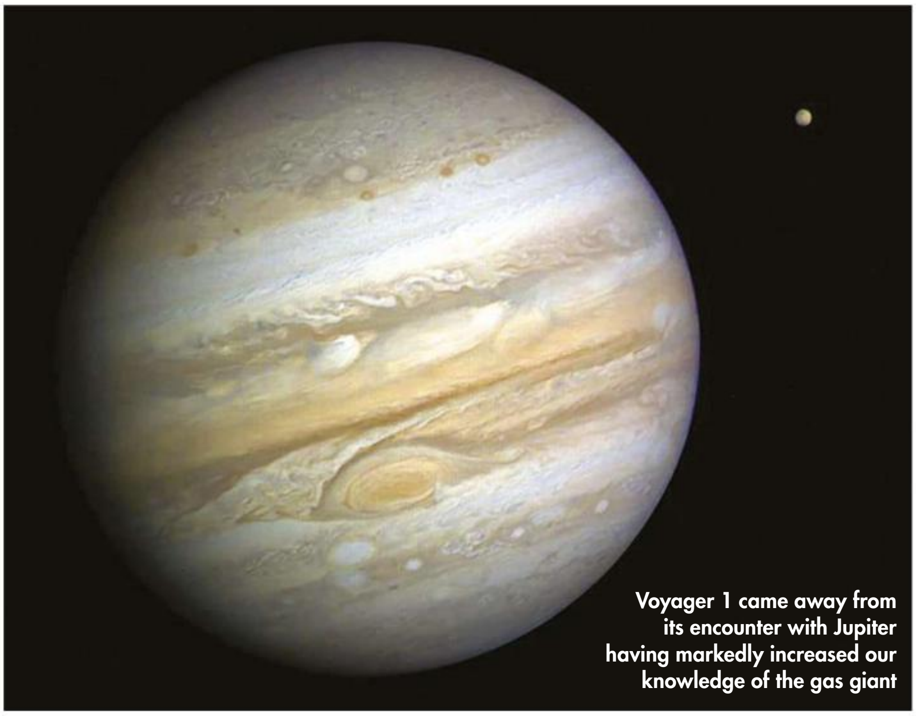
Interestingly, the Pwyll impact seemed to have occurred on a particularly thin portion of the crust, for iceberg-shaped chunks of subsurface material protruded from its floor. Dark areas, nicknamed 'maculae', were identified as potential upwellings from deep within Europa's interior, while the side of the moon, which faces away from Jupiter was characterised by huge, wedge-shaped bands, many kilometres long.

More to discover

The Voyagers' discoveries at Jupiter underlined the unpredictability of planetary exploration, for the largest planet in the Solar System had begrudgingly surrendered only a handful of the mysteries it held. For the Voyager scientists, it had been a once-in-a-lifetime experience. NASA's associate administrator for space science Thomas Mutch likened it to "being in the crow's nest of a ship during landfall and passage through an archipelago of strange islands". Volcanism on Io, colossal polar aurorae, along with unknown and unseen rings and moons could never have been confidently predicted before we turned our knowledge-gathering capabilities over to the Voyager robots, millions of kilometres from home; robots whose findings rewrote the textbooks on Jupiter for the next quarter of a century. V

△ **Europa from afar (inset) and up close (above); the heavily scored surface is riddled with stress fractures**

"THE VOYAGERS' DISCOVERIES AT JUPITER UNDERLINED THE UNPREDICTABILITY OF PLANETARY EXPLORATION"



Voyager 1 came away from its encounter with Jupiter having markedly increased our knowledge of the gas giant

NASA/JPL X 7

THE VOICES OF VOYAGER

Linda Morabito

Linda Morabito joined the Voyager mission as an engineer in the navigation team. In the days after Voyager 1's Jupiter encounter she made the mission's most famous discovery: a plume that revealed the Galilean moon Io was volcanically active

Interviewed by: Iain Todd

I was part of a team dedicated to working out the exact locations of stars and the moons of Jupiter, using a computer that filled a good-sized room.
We needed to know the locations of the centres of those bodies in the images we had taken to sub-pixel accuracy. This was asking quite a bit at the time, but it was certainly doable! Back then the camera was a Vidicon, which is really harkening back to technology from long ago.

To work out the locations we needed a new star catalogue.
We need accurate star positions to determine a spacecraft's position relative to the moons. For that you need a star catalogue dated to a particular epoch, then you apply proper motions because we move relative to the stars and they move relative to us. There wasn't a single star catalogue in existence that could provide us with the accuracy we needed to accomplish our task. A colleague and I had to go to the Lick Observatory in northern California to assist in creating a star catalogue so that we knew the true positions to the highest accuracy possible. It was very exciting!

We didn't get much sleep prior to the Jupiter encounter.
Our job was to make sure that no-one ever heard of us or knew the work we were doing. We just wanted to navigate that spacecraft flawlessly and that is exactly what I was privileged to do.

> "I BELIEVED WHAT I WAS SEEING WAS REAL... SO I JUST KEPT ASKING MYSELF 'WHAT IS THAT?' OVER AND OVER AGAIN"

I suspect that any laptop of reasonable quality today has far more computing power than my mini computer.
It took up an entire room and had to be cooled, so there was an enormous amount of noise coming from its fans at all times. Every time I had to step inside the navigation team's little bullpen area I had to put on extra layers of clothing!

We had a runner to bring us Voyager data from the Goldstone Deep Space Communications Complex across the street, where it had been received.
There were actually a few final manoeuvres that needed to be made prior to the Jupiter encounter to ensure that we were in exactly the right place to view the satellites and capture images of them. I recall waiting for the runner with the rest of the navigation team. The data was somewhat late in coming, although not because of any errors. But when you're counting every second and you need that data to be combined with Earth-based data, the seconds going by make everybody extremely nervous. All these years later, I still haven't forgotten looking at my manager and my manager looking at me and everyone else while we were waiting for the data so that the trajectory direction could happen when it was supposed to.

Science-fiction writers do an amazing job of describing things we haven't seen yet, but the appearance of Jupiter at the level of detail that we saw was beyond imagination.

LINDA MORABITO, NASA

△ **Linda with colleagues in the navigation team's image processing room, where the discovery of active volcanism on Io took place**

As navigators, our images weren't in colour, but I remember during the very brief periods of time that I did go home and sleep I had the opportunity to see the fruits of our labour. I'd been working so hard that I hadn't had a chance to view the images of Io up close, but then finally I saw them during a press conference somewhere in the laboratory – the sight of that moon took my breath away. I almost couldn't believe what I was seeing: what appeared to be one of the strangest objects humanity has ever seen in the Solar System. I'll never forget it. The colours of Io, caused by sulphur dioxide at various temperatures, range from black to orange to yellow to blue. The way scientists described it – and the way we described it at the time – caught on very quickly: it looked like a mouldy pizza.

Seeing Io – a world we had never seen before – was incredible.
This is an object that's a moon, that's about the same size of our own and that's about the same distance from Jupiter as the Moon is from Earth. So you'd think you would know what to expect. From what I had read, scientists were pretty confident that we would see an object with craters that could be somewhat geologically dead, much like Earth's Moon. But that's not what we found.

The images I had were designed to show me only what I needed to see for the high-accuracy centre-finding. To be honest, they had a very low priority.
I think nearly every member of the imaging team had left and returned to their home institutions at that point. By then everybody really thought that the wonders Voyager had revealed of Jupiter were pretty much behind us!

I came in and displayed the pictures, and I was astonished because the phase angle didn't result in fully lit satellites, so Io appeared as a crescent. The software I was using was based on having a fully-lit satellite, so I knew that the high-accuracy centre-finding wasn't going to happen. I made the decision that the images were useless in terms of the purpose for which they had been taken, but I began processing them anyway.

I performed what's known as a linear stretch on the images to bring out the contrast and pick out small variations in brightness. At that moment, a gigantic object appeared off the limb of the moon.
I believed what I was seeing was real, in the sense that it belonged to my data, so I just kept asking myself "what is that?", over and over again. I think I thought that if I asked myself that question enough, the answer would finally occur to me! But, of course, I had no idea what it was and I was very short on sleep.

The object had a phase angle associated with it, so it actually had its own crescent and its own illuminated dark portion. There was an offset in the orientation of this crescent compared to Io's crescent. And the object was huge, it was about a quarter of the size of the crescent in the image. It was also umbrella-shaped and raining back down. Of course, now we know that it was a plume rising about 270km above the surface of Io.

One after another, I contacted the people who I thought could give me the answer on the spot, because I felt I didn't have a lot of time and I wanted to know what I was looking at.
I began making educated guesses, one after the other, and started contacting people who were familiar with the camera systems and artefacts. There were blemishes in most images, things that weren't real, and so I had to eliminate that possibility. I also had to eliminate the possibility that it was a newly discovered satellite because that's what it looked like.

By the end of the day, we had the answer to the extent that project scientist Ed Stone sent commands to one of the instruments to detect further possible evidence that this was a volcanic plume. I had to find out the latitude and longitude ▷

Linda's computer displays the image in which Io's volcanic plume was revealed

▷ on Io directly beneath the spacecraft and then had to extrapolate based upon the appearance of the cloud, because I didn't know whether it was behind the limb or not. But once you have the spacecraft latitude and longitude, it's just takes a simple addition and subtraction to position the object. It landed just about on top of the large heart-shaped volcanic feature on Io. I don't think I'll ever forget the moment the latitude and longitude of what I was seeing lined up with that feature.

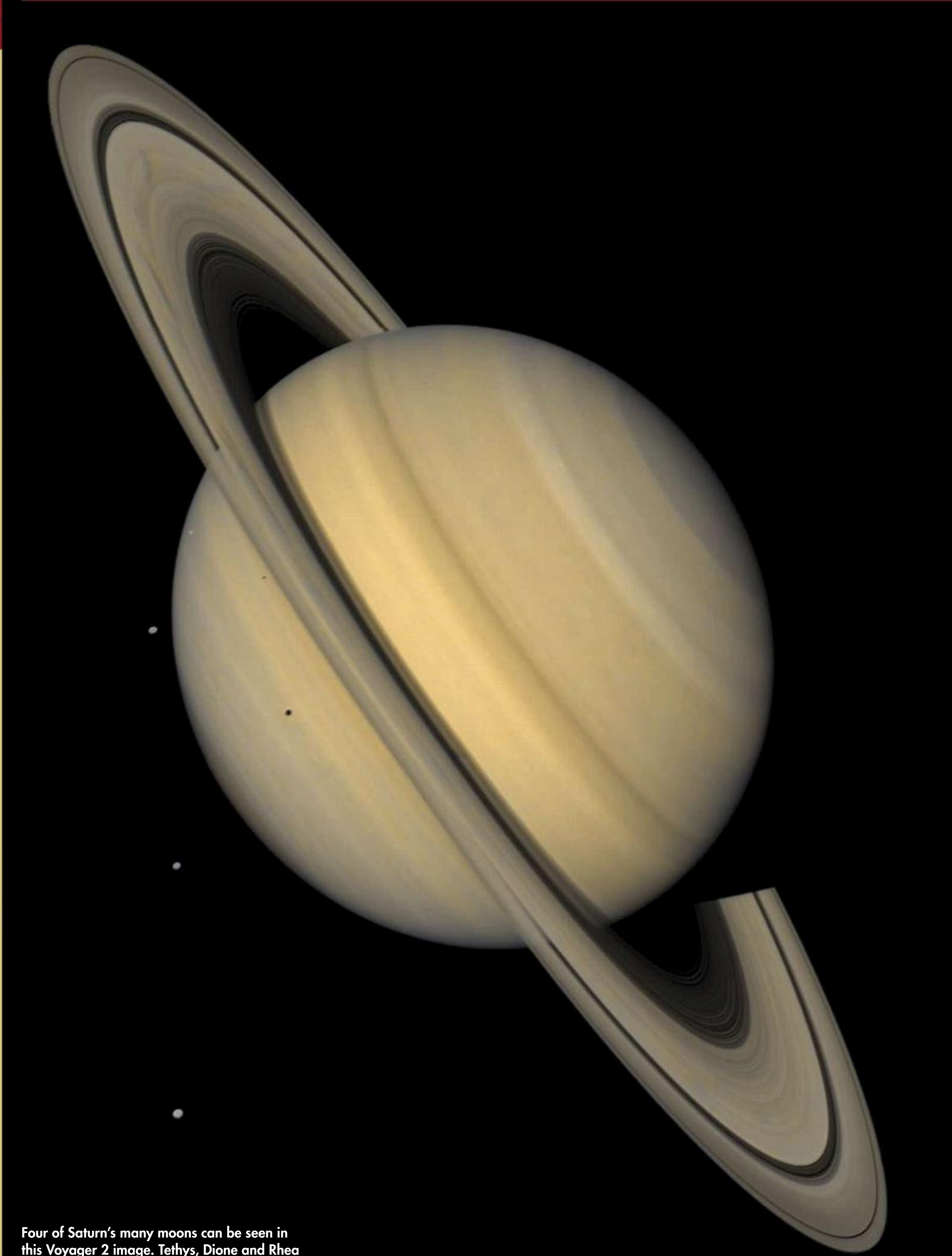
The most memorable part came when I began making those initial enquiries and I had a few moments alone with the image.
Those moments very early in the morning were the only ones that belonged to me in terms of this discovery, because the science is more important than any one individual. It was the stuff of dreams, because I knew I was seeing something that, in all likelihood, no human being had ever seen before.

I didn't realise it, but there had been a prediction of volcanism on Io before Voyager 1 arrived.
Just before the encounter, Stanton Peale from the University of California, Santa Barbara had published a paper predicting that Io was being heated through tidal dissipation. He anticipated what we were seeing at Io. I was unaware of Stan's paper at the time, but there were a lot of people, including Ed Stone, who were looking for any possible evidence to back up the prediction. When Stone was called in, you could see it in his eyes: he knew in a heartbeat what he was seeing.

▽ Linda sits in front of a model of Voyager 1, the probe that snapped this revelatory photo

These were moments of incredible opportunity.
They often say we rewrote the textbooks. Yes, we did. A good portion of the course I now teach is on tidal forces, an amazing way to make worlds generate internal heat and come alive. This was the first time we saw it happening. Voyager had so many firsts that I was so privileged to part of. Those were my dreams: to somehow move humanity forward. Ⓥ

BILL PETERS/WWW.BILLPETERS.CA, NASA



Four of Saturn's many moons can be seen in this Voyager 2 image. Tethys, Dione and Rhea float in space while Mimas hangs just below the rings, near the planet's western limb

Titanic discoveries at Saturn

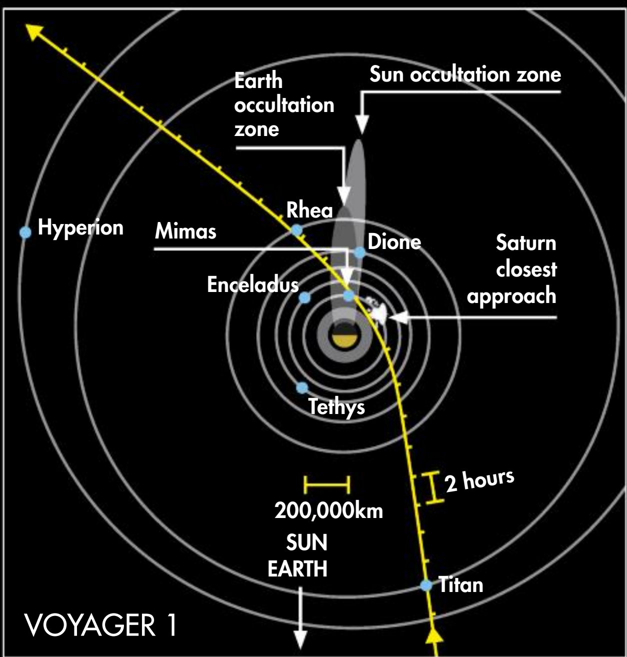
Words: Ben Evans

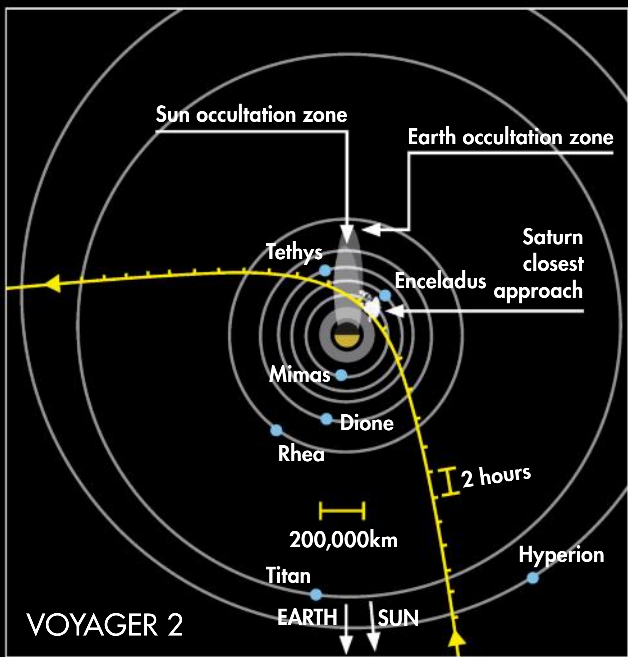
Long regarded as the 'wow' planet of the Solar System, Saturn proved more magnificent than anyone had imagined. While it was in the neighbourhood, Voyager 1 skimmed past Titan, still the only moon we know of with a thick atmosphere

ON THE EVENING of 6 November 1980, less than a week before reaching Saturn, Voyager 1 fell abruptly, though not unexpectedly, silent. Bruce Murray, then serving as director of the Jet Propulsion Laboratory (JPL) in Pasadena, California, was not alone in having expressed consternation over the hazardous manoeuvre that was about to take place.

After all, the tiny spacecraft was three years into an epic mission of exploration that had already rewritten the textbooks on Jupiter. Now, more than 1.4 billion km from Earth, it was having its critical communications link with Earth intentionally severed so the craft could be turned towards Titan.

"Isn't it risky," Murray asked at one of the last pre-Saturn meetings, "to break communications, so close to encounter?" It was indeed a dauntingly bold move, but there was a clear rationale for it. Voyager 1 was following a route known as 'Jupiter-Saturn-Titan' so it could observe, at close quarters, the only natural satellite in the Solar System definitively known to possess a dense atmosphere. ▷

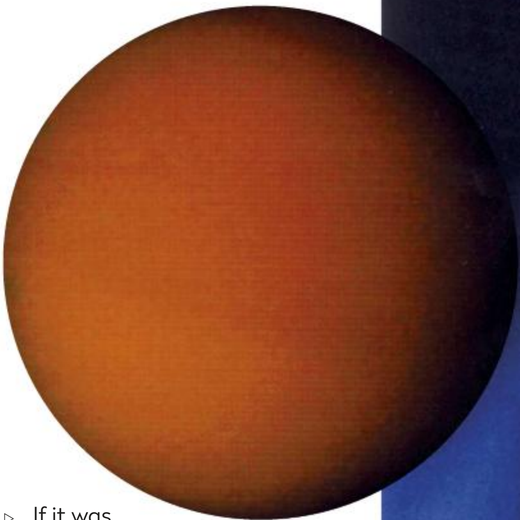




▽ The probes' paths through the Saturnian system saw Voyager 1 (below left) pass much closer to Titan than Voyager 2 (below right)

NASA/JPL

THE STORY OF VOYAGER



▷ If it was to fly within 3,900km of Titan's soup-like canopy of gases and particulate haze, a trajectory-correcting firing of the spacecraft's thrusters was needed. And to accomplish that, Voyager 1 had to reposition itself a quarter-turn away from its lock on Earth.

The Deep Space Network's tracking station in Goldstone, California, duly transmitted the requisite commands up to the spacecraft. It took 84 minutes, travelling at the speed of light, for those commands to cross the immense gulf between Earth and the Saturnian system.

Voyager 1 responded crisply, rotating its high-gain antenna away from Earth. Its hydrazine-fuelled thrusters hissed for almost 12 minutes, affording it a slight sideways nudge for the Titan flyby. The probe then realigned itself with our world. To everyone's immense relief, communications were restored 84 minutes later.

Investigations begin

The first dividend was paid soon after. Early on 11 November, the spacecraft's radio signal passed through Titan's thick orange clouds, gradually faded and then vanished, reappearing after 13 minutes. The signal's 'occultation' allowed investigators to show that Titan's atmosphere – first detected spectroscopically in the 1940s – was far more substantial than anticipated. Later analysis of the signal data revealed the existence of a solid surface with a temperature of –180°C.

The radio signal also showed the moon to have an equatorial diameter of around 5,150km. This was a significant find as, until 1980, the unknown size of Titan's opaque veil had spawned the erroneous assumption that it was the biggest natural satellite in the Solar System, larger even than Jupiter's moon Ganymede. An occultation of our Moon, seen from Earth a few years earlier, suggested an optical size of 5,800km, but this figure was biased by a lack of precise detail regarding the thickness of Titan's clouds. With Voyager 1's data, it was possible to ascertain that Ganymede is marginally the larger of the two, and that both moons are bigger than the Solar System's innermost planet, Mercury.

Titan's equatorial tilt causes distinct seasons and Voyager 1 was able to show that gases and particulates migrate from one

△ Voyager 2 imaged Titan's featureless blob from afar (inset); Voyager 1's closer, false-colour shot (above) shows the layers of haze that shroud the moon

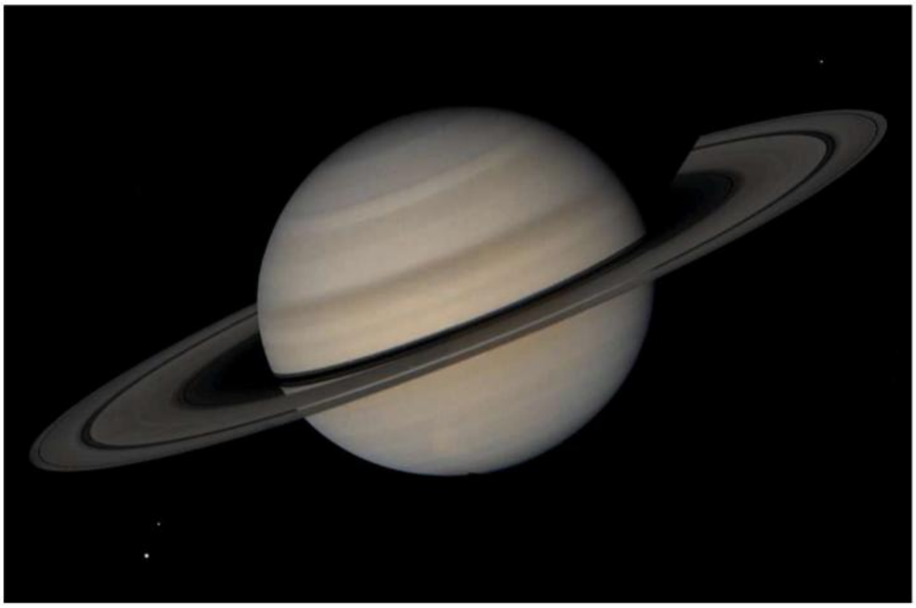
hemisphere to the other. Along with the sheer density of the atmosphere, this highlighted broad differences in albedo. Neither Voyager 1 nor Voyager 2, which swept 907,000km past Titan in August 1981, saw any trace of a solid surface through the murk, but they did identify a dark brown 'hood' of detached haze over the north pole. This contrasted starkly with the far brighter south and provided a glimpse of the seasonal variation – at the time it was spring in the north and autumn in the south.

"THE EXISTENCE OF HYDROCARBON LAKES AND SEAS ON TITAN WAS PLAUSIBLY CONSIDERED FOR THE FIRST TIME"

The moon's atmosphere was known to contain methane long before the Voyager probes arrived, although it turns out that methane only accounts for a few per cent. In fact, protons from Saturn's fierce magnetosphere and ultraviolet photons from the solar wind separate molecules of nitrogen and methane. Their atoms recombine into a raft of trace constituents, including hydrogen cyanide and acetylene, many of which were detectable to the Voyagers' infrared instruments. Hydrogen cyanide plays an important role in the synthesis of amino acids and its discovery at Titan triggered early theories that the moon might harbour the building blocks for complex organic chemistry. Indeed, it may even mirror conditions on the infant Earth, as it was billions of years before life evolved here.

A complicated picture

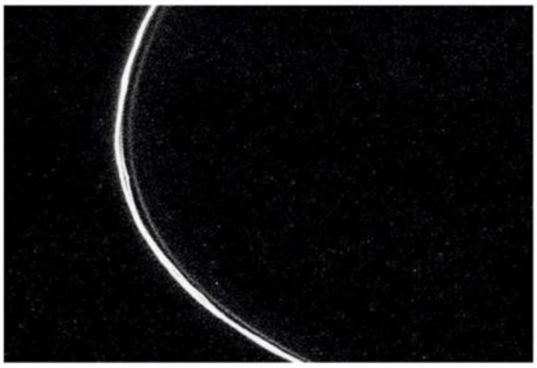
During their rapid transits, the Voyagers observed cooler temperatures nearer the moon's and warmer ones in the high troposphere, a phenomenon known as 'temperature inversion'. It's driven primarily by ultraviolet sunlight and contributes to Titan's already complicated photochemical picture, which is dominated by a dense layer of hydrocarbon 'smog', 200km thick, whose particulates vary in size from 0.2µm to 1µm. Even in 1980, it was argued that these particulates could 'snow' onto Titan's surface, and so the existence of hydrocarbon lakes and seas was plausibly considered for the first time.

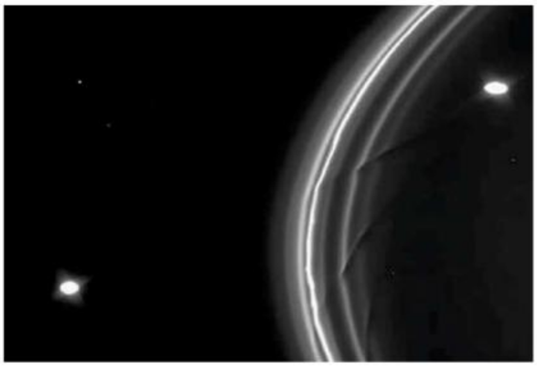


△ Tethys, Enceladus and Mimas are visible around ringed Saturn in this mosaic, made from images taken 18 million km away

Eighteen hours after leaving Titan, Voyager 1 hurtled 64,200km past the sickly yellow cloud-tops of Saturn, the Solar System's most visually spectacular planet. Its intricate rings, which so puzzled Galileo in 1610, before they were correctly described and identified by Christiaan Huygens in 1655, have a radial breadth of 282,000km, equivalent to three-quarters of the distance but are believed to be no more than 1.4km thick.

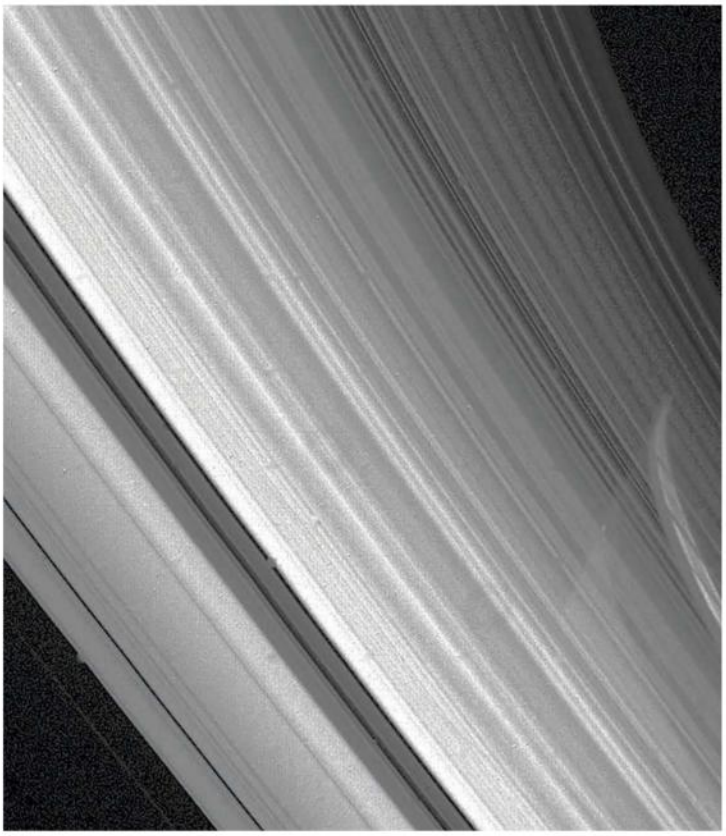
Three rings, dubbed A, B and C, together with the 4,800km-wide Cassini Division, were known to astronomers long before the dawn of the Space Age. In September 1979, Pioneer 11 found the F ring, which resembled a contorted tangle of ▷



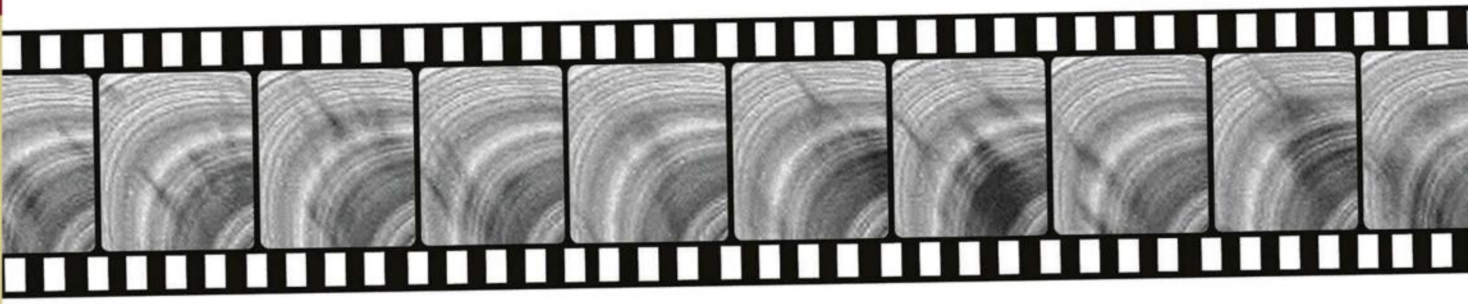


△ Voyager 1 spotted kinks in Saturn's F Ring (top), which suggested that moonlets were responsible for 'shepherding' ring material. In 2010, the Cassini spacecraft allowed scientists to see how Prometheus and Pandora (also discovered by Voyager) do just that

NASA/JPL X 5, NASA/JPL-CALTECH/SPACE SCIENCE INSTITUTE



△ The rings as seen by Voyager 2 from 3.3 million km; Saturn's limb can just be seen through the C ring and inner part of the B ring, in the lower right



narrow strands. Moreover, its data hinted strongly at the possible existence of tiny 'moonlets', which somehow anchored, or 'shepherded', the ring material along its million-kilometre-long tracks. A year later, Voyager 1 discovered the moonlets Prometheus and Pandora, both of which straddled and possibly influenced the structure of the F ring. Unfortunately, a defective photopolarimeter meant that the probe was unable to examine them in great detail.

Still, Voyager 1 managed to locate the dusty D ring and the exceptionally slender G ring. Nine months later, Voyager 2 encountered Saturn with a fully functioning photopolarimeter and managed to resolve groups of hitherto-unseen 'ringlets', showing that very few gaps existed anywhere in the rings.

Even the notionally 'empty' Cassini Division, the broad, dark band of which separates the bright A and B rings, turned out to be populated by a vast mass of dust and rocky fragments. Radio-science measurements confirmed that the most closely spaced particles ranged in size from under 1cm to 10m or more.

The rings' origins

The principal constituent of the rings is water-ice. It makes up 99.9 per cent of the rings and is what makes them so dazzlingly reflective, although both Voyagers saw discolouration in places, perhaps due to the presence of impurities such as tholins or silicates. Until 1980, scientific consensus favoured gravitational forces as the driving force behind the rings' formation. Yet the Voyager probes uncovered radial features, including spokes and kinks, that are inconsistent with gravitational orbital mechanics.

Voyager 1 took a sequence of images during one of Saturn's rotations that revealed the spokes' formation and dissipation lifecycles. The images showed them to be

△ Sequences of Voyager images revealed the 'spokes' that traverse Saturn's rings

WHY DOES SATURN HAVE SUCH GRAND RINGS?

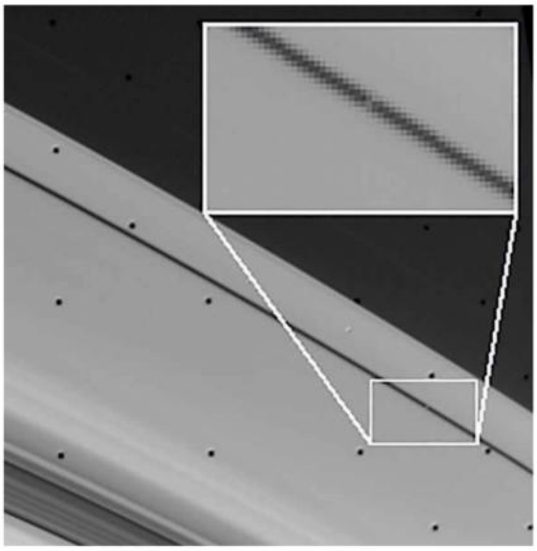
For over three centuries, from the earliest observations by Galileo Galilei and Christiaan Huygens, Saturn was believed to be the only planet to have rings. More recently, its three giant cousins have revealed their own assemblages of dust and rocky grains. Despite being far less grandiose than those of Saturn, the creation and endurance of ring systems was a mystery it was hoped the Voyagers could help solve.

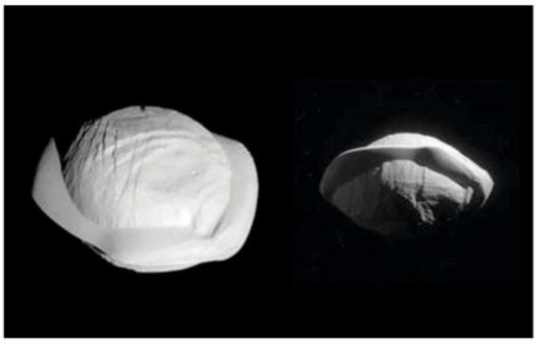
Two main theories took centre-stage before 1980. The first, by Edouard Roche, postulated that small moons residing at specific distances from a given planet would be torn apart by tidal forces and the debris might settle into rings. The second, by Pierre Laplace and Immanuel Kant, argued that the rings formed at the same time as Saturn, in a process similar to how the Solar System formed from a large disc.

As viewed by the Voyager probes, discrete particles in the rings were so bright and pristine – formed almost wholly water-ice, with some trace contaminants – that they seemed no older than a few hundred million years. Some particles are so small (from car-sized boulders to sand-like grains) that they would have been pulled into the atmosphere if they were much older than this. Furthermore, the Voyagers revealed exceptionally low levels of ambient radiation at Saturn, implying that the rings have thrived in a relatively benign environment.

This contributed to early theories that Jupiter, Uranus and Neptune lost their primordial gaseous discs quite early in their evolution, leaving mainly volatiles from which to assemble their far darker and less expansive ring systems. Saturn, on the other hand, cooled sufficiently early for water vapour to condense and eventually produce far more brilliant rings. During their encounters, the Voyagers also uncovered much more intricate detail, from spokes and kinks to ringlets and shepherd moons, than had been expected.

The outer edge of the A ring; it's thought that the linear features parallel to the ring edge are maintained by shepherd moons





△ A tiny speck in a Voyager 2 image (top) was later revealed to be moon Pan. Investigations performed by the Cassini probe showed it to be walnut-shaped (above)

"THE VOYAGER PROBES UNCOVERED RADIAL FEATURES, INCLUDING SPOKES AND KINKS, THAT ARE INCONSISTENT WITH GRAVITATIONAL ORBITAL MECHANICS"

charged particles that levitated above the rings.

It had been argued that divisions within the rings were formed by the process of orbital 'resonance', whereby particles were confined to specific regions by the gravitational attraction of neighbouring shepherd moons. The discovery of Prometheus and Pandora lent credence to this idea, and particles bordering the Cassini Division are thought to be influenced by the presence of the moon Mimas.

Elsewhere, particles near the edge of the A ring are 'sharpened' by the moonlet Atlas – its astonishing equatorial ridge might represent a deposit of swept-up ring material – and by the co-orbiting moonlets Epimetheus and Janus.

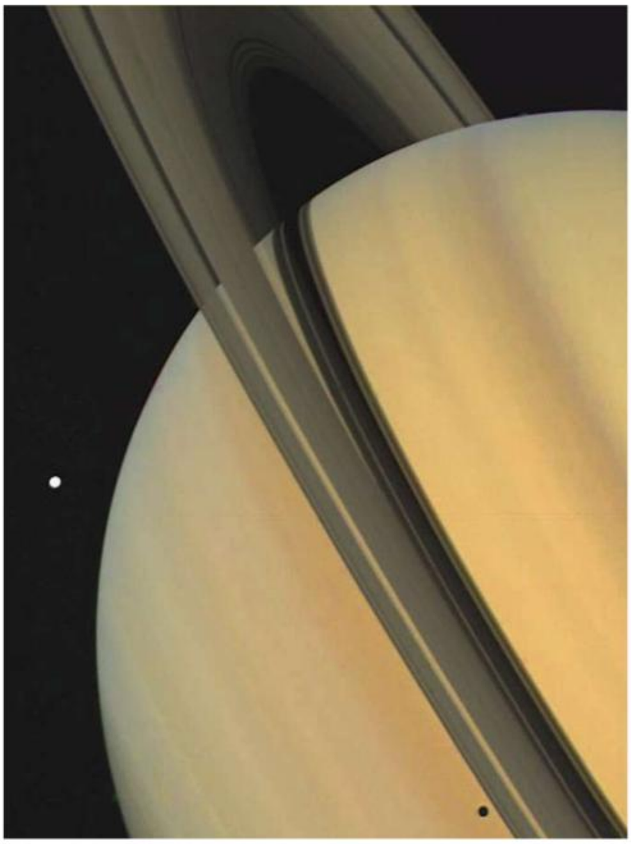
Another moonlet, the walnut-shaped Pan, was found in 1990, following an analysis of old Voyager 2 images. It's thought to be responsible for 'scalloping' the edges of the 325km-wide Encke Gap in the A ring and keeping it free of particles. Still other openings in the rings – including the Cassini Division and the narrower Huygens Gap – are thought to be controlled in part by the influence of Mimas. Another gap, measuring 42km in diameter and named in honour of astronomer James Keeler, was detected by the Voyagers deep within the A ring.

Giant storms

Unexpectedly, the composition of Saturn's atmosphere was quite distinct from Jupiter, with smaller helium abundances and a larger relative share of hydrogen – about 96 per cent, compared to the Jovian 87 per cent. Like its larger cousin, Saturn was shown to radiate ▷

△ Ribbon-like wave structures were seen in Saturn's clouds

△ Saturn has its own red spot, albeit smaller than Jupiter's



△ The rings and moons were seen casting shadows on the planet

NASA/JPL X 17, NASA/JPL-CALTECH/SPACE SCIENCE INSTITUTE

▷ more heat into space than it absorbed from incident sunlight and it rotates rapidly upon its axis, generating the polar flattening and outwardly bulging equator that's a curious characteristic of all four giants.

In a further contrast to Jupiter, Saturn is 30 per cent less massive, leading to the famous idiom that if a sufficiently large bathtub could be found, it might float on the water. Its latitudinal banding is also much less obvious. But the world whose name pays homage to the fabled father of Jupiter and Bringer of Old Age is by no means an inactive place. Half a century before the Voyagers visits, comedian and amateur astronomer Will Hay observed an elliptical white spot near Saturn's equator, one of several periodic sightings of large-scale storms at work.

"SATURN'S LATITUDINAL BANDING IS LESS OBVIOUS THAN JUPITER'S, BUT IT'S BY NO MEANS AN INACTIVE PLACE"

When Voyager 2 flew past the planet on 25 August 1981, it revealed eastward-gusting jetstreams, which peaked at 1,800km/h – five times faster than those on Earth. Marginally greater winds were also clocked at higher latitudes. Data from both spacecraft uncovered powerful polar aurorae at latitudes above 65°N, together

A GROWING MOON MENAGERIE

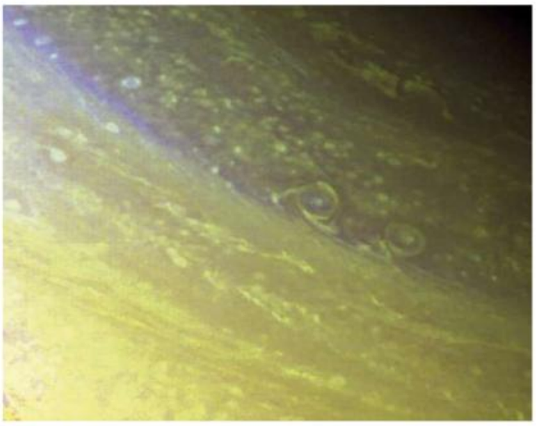
△ The two Voyager probes provided our best shots of Saturn's moons until the Cassini spacecraft

Around a dozen moons were known to orbit Saturn before the Voyagers visited, the largest among them being the planet-sized Titan. Next largest was rocky Rhea, one-third the size at 1,530km in diameter.

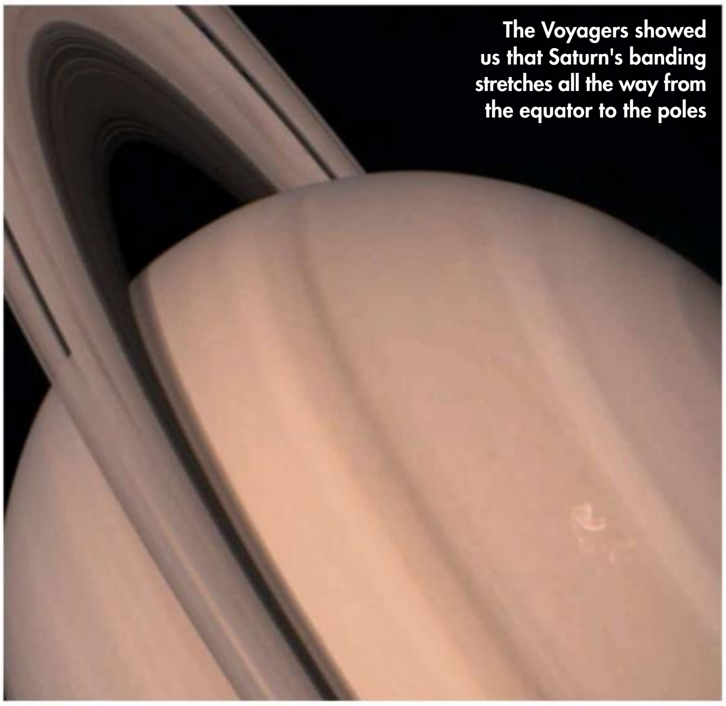
It was Rhea – stripped of a 'sensible' atmosphere, globally crater-scarred and seen only from a great distance by both Voyager craft – that had endured two savage epochs of meteoroid bombardment in its youth.Those epochs are thought to have generated many craters on Saturn's other moons. Most intriguing are Tethys and Mimas, both predominantly water-ice, which showcase the biggest craters in proportion to their size ever seen. In fact, Mimas's Herschel crater (almost 10km deep and 130km across) covers a third of its diameter, so enormous that its causative impact must have almost broken the moon apart. Tethys boasts a shallower, more ancient feature, called Odysseus, which also spans a wide fraction of its terrain.

Then there's enigmatic Iapetus, which a bewildered Giovanni Cassini identified as 'two-toned' – bright on one face, dark on the other. The Voyagers revealed a meandering, 300km-wide transitional zone between the two halves, suggesting that preferential bombardment of Iapetus's leading hemisphere by darkened material could be responsible. Elsewhere, icy Enceladus reflects virtually all incident sunlight, rendering it the brightest-known natural satellite and raising early suspicions of 'cryovolcanism'. Rugged Dione was shown to possess a co-orbital companion moon, while potato-shaped Hyperion might be the remnant of an ancient collision and blob-like Phoebe could represent a seized asteroid.

With the Voyagers' close-range observations of Janus and Epimetheus, the floodgates opened. Three more moons (Atlas, Prometheus and Pandora) were found by the Voyagers and later Earth-based work on their imagery led to the detection of others, including Pan. Today, it's known that more than five dozen moons with confirmed orbits exist at Saturn, but the presence of innumerable particles within the rings– from grains to moonlets – could carry this figure into the thousands or beyond.



△ Saturn's north polar region was seen to be littered with bright, small-scale cloud spots



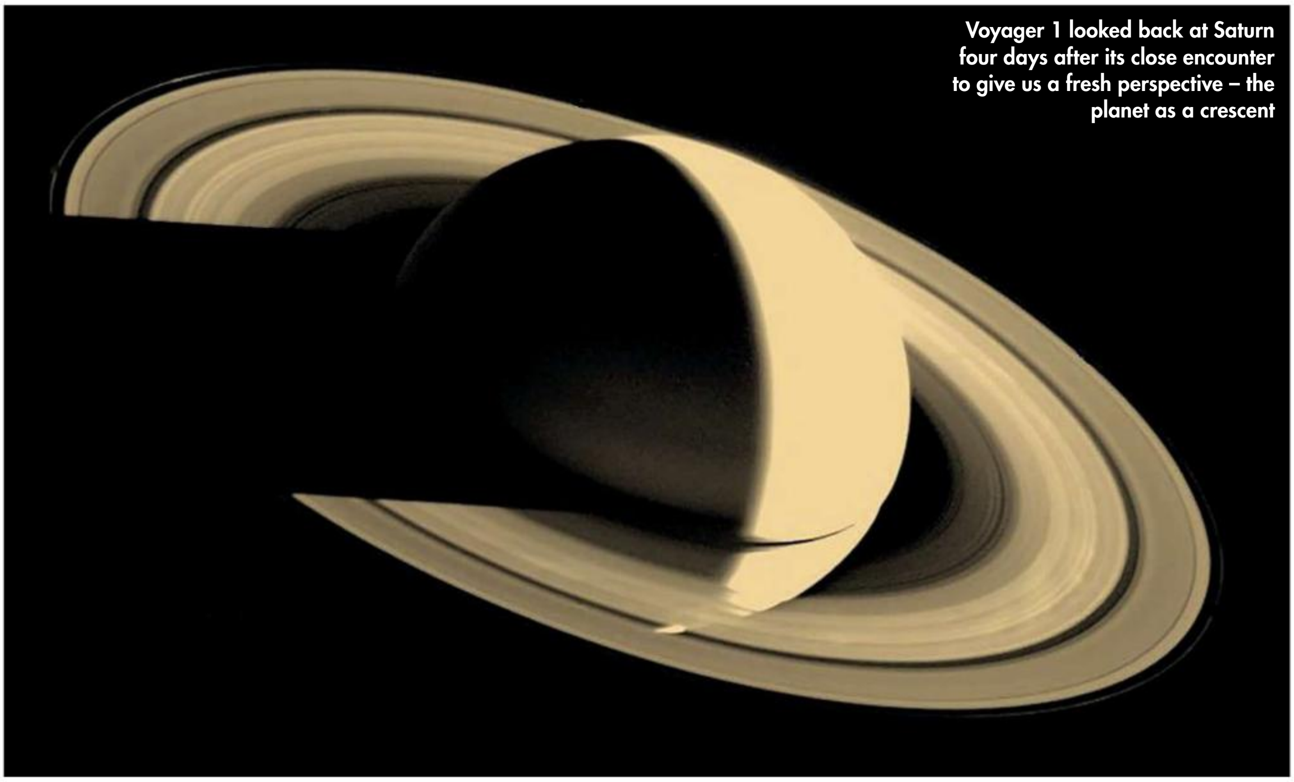
The Voyagers showed us that Saturn's banding stretches all the way from the equator to the poles

with ultraviolet emissions of hydrogen at mid-latitudes.

A parting gift

It was Pioneer 11 that first detected the unusual alignment of Saturn's magnetic field, which is tilted by less than 1° with respect to its rotational poles, while the Voyagers observed a strange 'torus' of positively charged hydrogen and oxygen ions about 400,000km above the cloud tops. The strong emissions associated with this torus were measured by the fields-and-particles instruments, revealed a million-kilometre-wide 'sheet' of plasma, perhaps supplied by atmospheric material from Saturn and Titan. The planet's magnetosphere is much smaller than the enormous cavity that encapsulates Jupiter, but was still shown to span over two million km by Voyager 1. Nine months later, when Voyager 2 arrived, solar wind pressures had heightened and markedly compressed the sunward boundary. Then, as the spacecraft departed Saturn on the outward leg of its journey, its instruments detected a sudden drop in solar wind pressure and the magnetosphere rapidly ballooned outwards in less than six hours.

It was a final parting gift. Then Voyager 2's instruments were deactivated and the spacecraft entered hibernation for its lonely, five-year trek to Uranus; the timing had almost been poetic. It seemed as if Saturn was bidding its visitors farewell, by offering up one more mystery to perplex and astound us. V



Voyager 1 looked back at Saturn four days after its close encounter to give us a fresh perspective – the planet as a crescent

NASA/JPL X 13

THE VOICES OF VOYAGER

Carolyn Porco

The imaging team leader for the Cassini mission at Saturn looks back on her days spent analysing photographs from the Voyager mission, work that led to her discovering the spokes that lie within the gas giant's rings

Interviewed by: Iain Todd

I was a graduate student when Voyager passed by Saturn. One of the people in the academic department where I was studying was a member of the Voyager imaging team. Through him I got to work on some of the images that the probe was sending back. There was so much information that none of the Voyager science teams had enough people to analyse it all. Some nice topics fell into my hands to do my thesis on and that's how I got on the Voyager project.

I did my thesis on Saturn's rings and as soon as I graduated I was added to Voyager's imaging team. I was helping to prepare for the Uranus flyby in three years' time. I had done my thesis on the exact type of rings that were eventually found around Uranus, so I was the team's expert. By the time Voyager got to Neptune, I was leading the small group within the imaging team that was responsible for all the observations made of the planet's rings.

Voyager was like a Homeric epic. It was like spending three years in a boat rowing to get to our destination, then it was conquest and triumph, before getting back in the boat for more years of paddling until we reached the next port of call. We would spend years getting to our destination and then there was a crazy week or two when the probe was gathering data and making observations continually. During the years between encounters is we'd be analysing the images and the data that we'd got from the previous encounter, as well as planning the next one.

We weren't all together in a room doing nothing but Voyager analysis and planning each day. We would be called together maybe three times a year for planning meetings and to discuss the science and so on. Cassini was entirely different. On Cassini, it was like being asked to sprint for the duration of a marathon. It was like taking the two-week long Voyager

▽ Carolyn and Brad Smith, Voyager's imaging team leader, prepare to appear on US TV to discuss Voyager's data

encounters and making them last continuously for 13 years!

All eyes are on the images when you're presenting results to the public.
That's still the case, very much to the resentment of other scientists. During the Voyager days, there wasn't really any attempt to get the pictures looking the best they could by worrying about the colours, putting red, green and blue images together, aligning them so they could sit on top of one another and framing the picture so that it looks like a work of art. Nothing like that was done when we were processing images during the Voyager mission, so it was one of my cardinal goals when I was made the imaging team leader on Cassini.

△ **Carolyn (centre) joins scientists including Carl Sagan (seated on the desk) and Ed Stone (seated, far right) to analyse images of Neptune's moon Triton**

CAROLYN PORCO X 2, CORBIS/CONTRIBUTOR

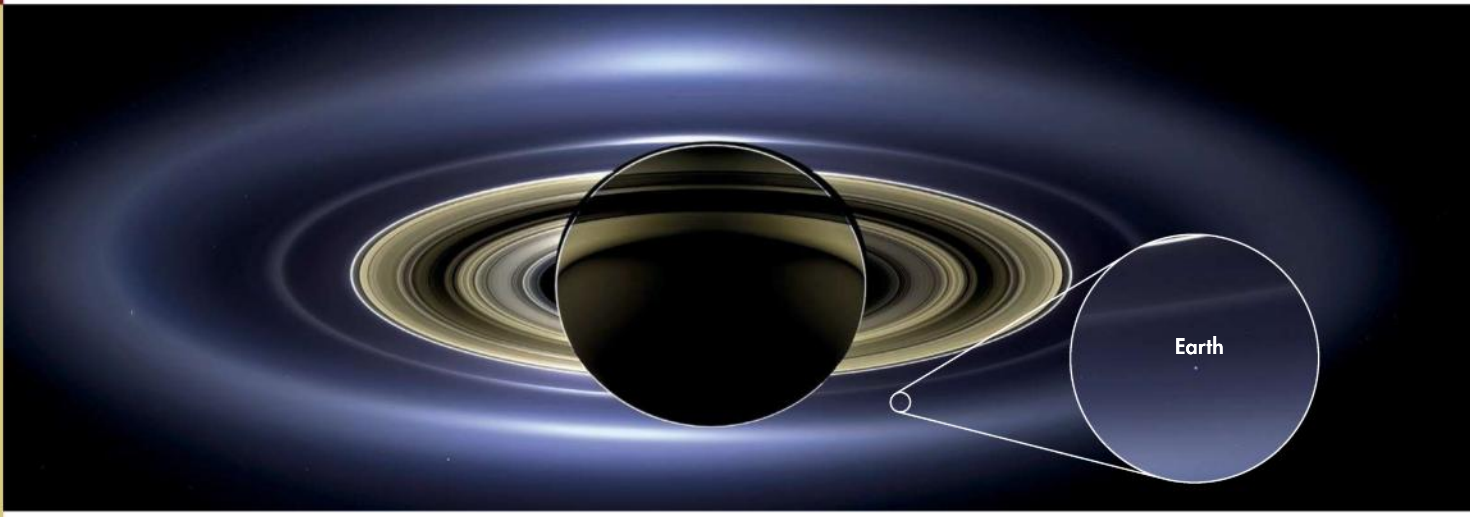
We actually lost the chance to take some images during the Saturn encounter.
Voyager 1's scan platform got stuck during the flyby, so we had to work out how to fix it. Because of that glitch there were some sequences of images that never got taken, one of which was a sequence of the southern hemisphere of Saturn's moon Enceladus. So we might have seen the tiger stripe fractures sooner with Voyager but, as it turned out, they were left for Cassini to discover.

"VOYAGER 1'S SCAN PLATFORM GOT STUCK DURING THE SATURN FLYBY, SO WE HAD TO WORK OUT HOW TO FIX IT."

In the days of Voyager, we were dealing with hard-copy images.
JPL put out these small, 4x4-inch glossy prints that were made of every image the Voyagers took. I somehow got my hands on them and they were contrast-enhanced enough that you could see what was in them. Back then it was the only format in which I could look at hundreds of images at once.

I noticed how Saturn's ring spokes changed in their intensity and number.
So I decided to categorise them, putting images with very few spokes in a pile on the left and images with lots of spokes in a pile on the right. And then I had two intermediate piles in between, giving me four categories, which I numbered.

Every picture had a time stamp, so I decided to a spectral analysis.
Out of that popped an obvious periodicity showing the spokes coming and going in their intensity and their aerial coverage on the rings. They were coming and going in a period that was equal to the magnetic field period. This was my first genuine discovery. ▹



NASA/JPL-CALTECH/SSI

△ **Cassini reimagined the Pale Blue Dot with this image: The Day the Earth Smiled**

▷ **It was just one of those Eureka moments that scientists live for.**
There's a time before you tell other people, when you know that you're the only person on the planet who knows anything about it. Nothing can be as heady as that! You can imagine lots of things that would give you a thrill, but this was the kind of thrill that comes from knowing something about mother nature. You feel like a high priestess who's just uncovered a fundamental truth about the Universe and for a brief period you're the only one who knows it.

I wouldn't say the discovery of the spokes was my biggest scientific contribution.
I know in the eyes of the public, when they think about me and Voyager, they think of that discovery. But I'd say my biggest contribution was actually studying the rings within the Saturn system that were the kissing cousins of the rings around Uranus.

Voyager was the opening act in showing everyone what the Solar System was like.
It allowed us to survey what was out there and gave us a picture of the Solar System that we looked fondly at for 23 years before, in the case of Saturn, we got there with Cassini. It left us with a very keen sense that we needed to go back; a feeling that we'd just scratched the surface and that there was so much more to learn… and not just about things that were particular to one planetary system. In the case of Saturn, for example, there were scientific issues that had tremendous, far-reaching implications. What we studied said a lot about what was happening everywhere throughout the cosmos in the past, in the future and now.

Saturn has certainly played a special role in my life.
It's the most phenomenally rich planetary system in our Solar System because it's got everything all the other planetary systems have. It's got the biggest set of rings. Its atmosphere is as interesting, if not as ornate, as Jupiter's. It's got a very large and diverse collection of moons. No other moon in the Solar System has an atmosphere like Titan's. I really lucked out in initially studying Saturn and then a few months after Voyager was over we learned that we were going to go back there with Cassini.

Cassini and Voyager are very different projects.
Cassini has been a sumptuous immersion in the promised land, so to speak, but Voyager was like an odyssey. Voyager redefined humanity; that's how I think of it. It made us interstellar explorers. It was us reaching out not only across space but also into the future, because it will outlive us. It carries that wonderful message to the cosmos. If anybody ever picks it up, there's a bit of all of us on it and Voyager will carry it for billions of years. It's a beautiful gesture, which you wouldn't say about Cassini. But it's a symbol of our longing to communicate and to connect with the Universe around us.

It was Carl Sagan who turned the 'Pale Blue Dot' image into an allegory for the human condition.
With the 'Pale Blue Dot', I was thinking of how it would look to see the Solar System from very far away, with all the planets dramatising the isolation and the blackness of space. But Carl Sagan saw the image from a more human perspective, noting that on this mote of dust was everyone you know and everyone you love. That was pure Carl; he was the master at finding that emotional hook to get people to pay attention to what we were doing and the exploration of the Solar System.

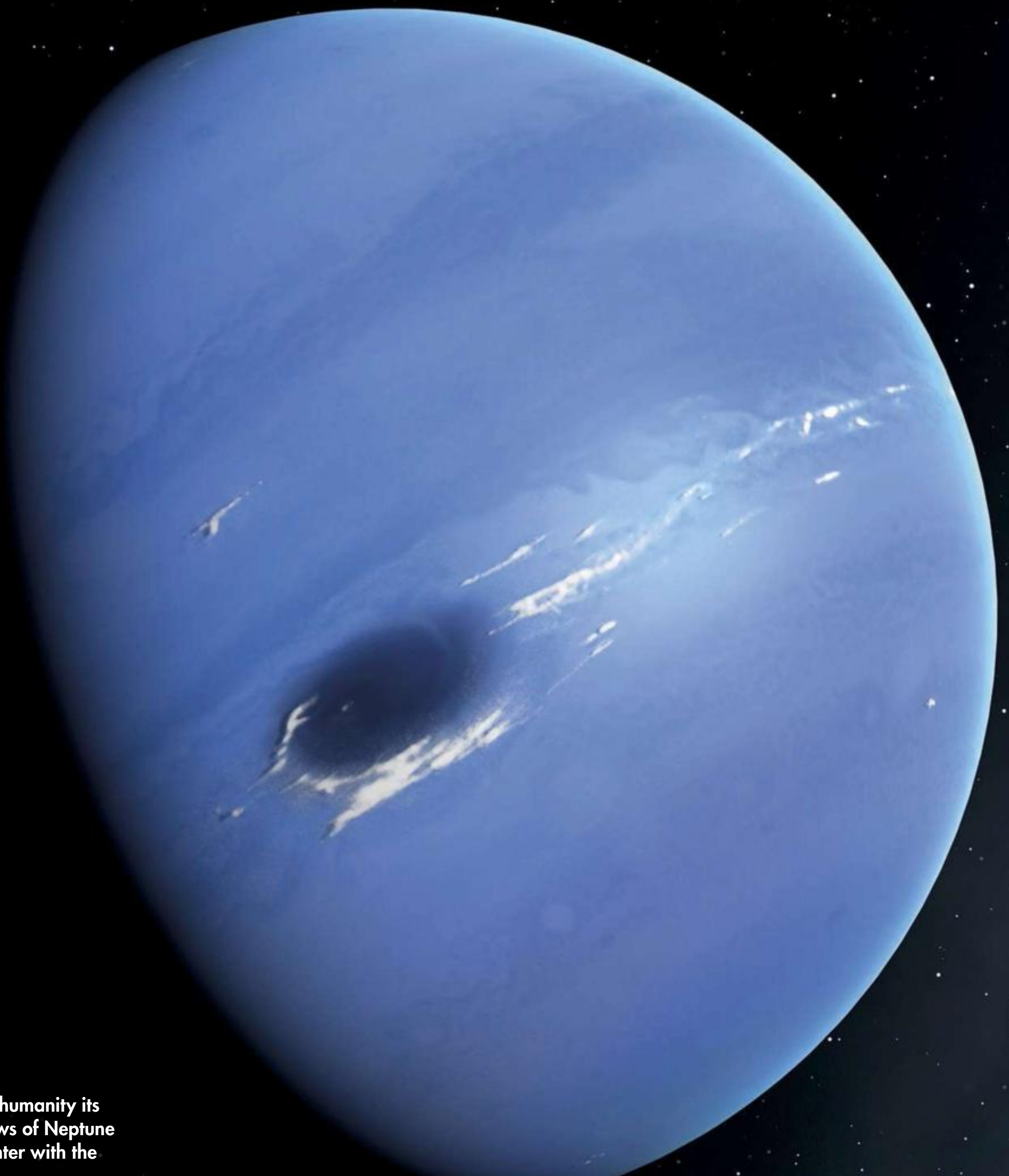
'The Day The Earth Smiled' image [above] from Cassini is what Sagan had originally envisioned.
He was hoping that the Voyager 'Pale Blue Dot' picture would be a picture of the Earth awash in a "sea of stars". He put that phrase in the proposal for the Voyager project, urging them to take the picture. While we don't see stars in the 'Pale Blue Dot', we do see stars in 'The Day The Earth Smiled'.

NASA/JPL

The Pale Blue Dot

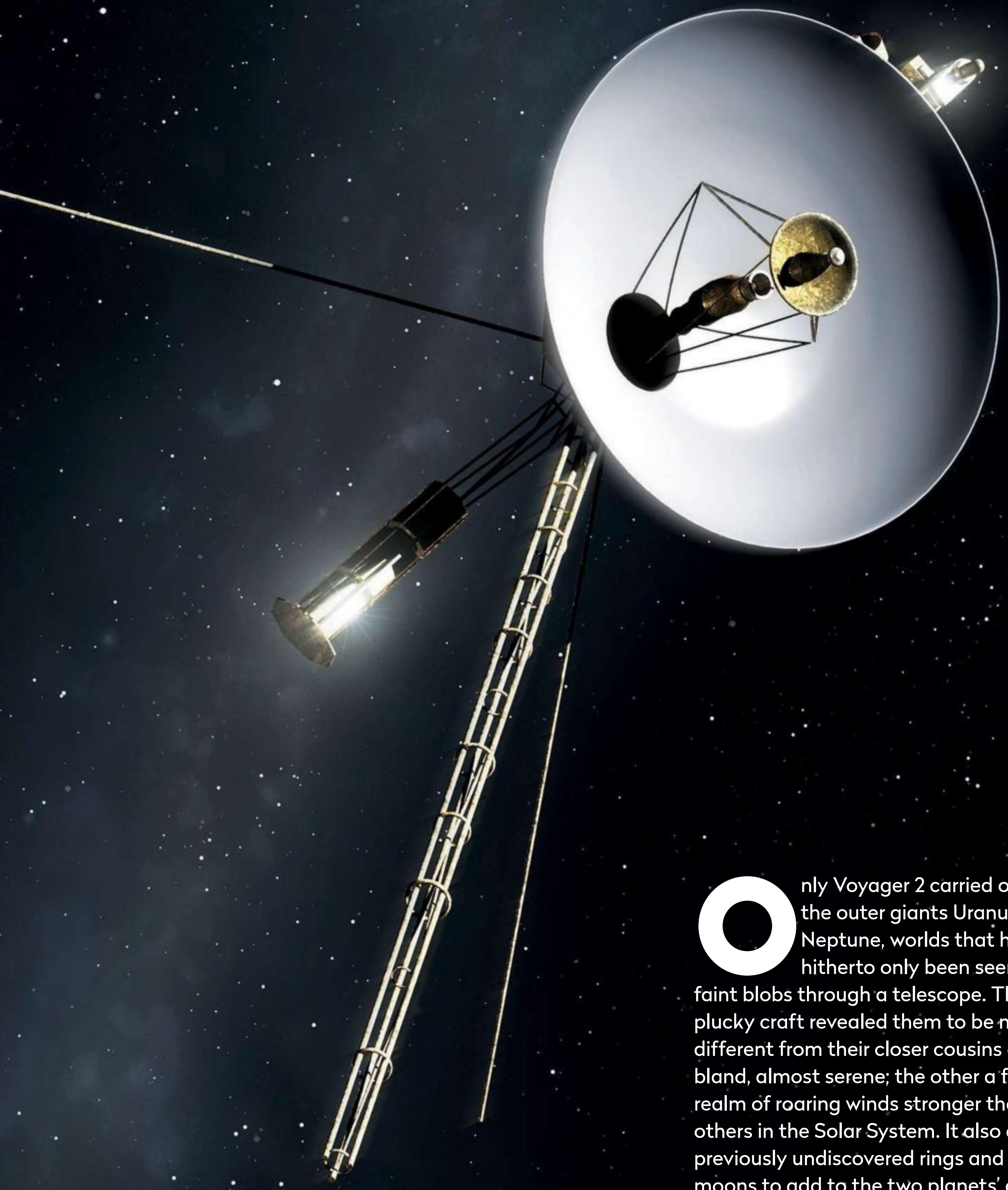
"LOOK AGAIN AT THAT DOT. THAT'S HERE. THAT'S HOME. THAT'S US. ON IT EVERYONE YOU LOVE, EVERYONE YOU KNOW, EVERYONE YOU EVER HEARD OF, EVERY HUMAN BEING WHO EVER WAS ... EVERY SAINT AND SINNER IN THE HISTORY OF OUR SPECIES LIVED THERE – ON A MOTE OF DUST SUSPENDED IN A SUNBEAM." CARL SAGAN, 1994

PHASE III UNCHARTED TERRITORY

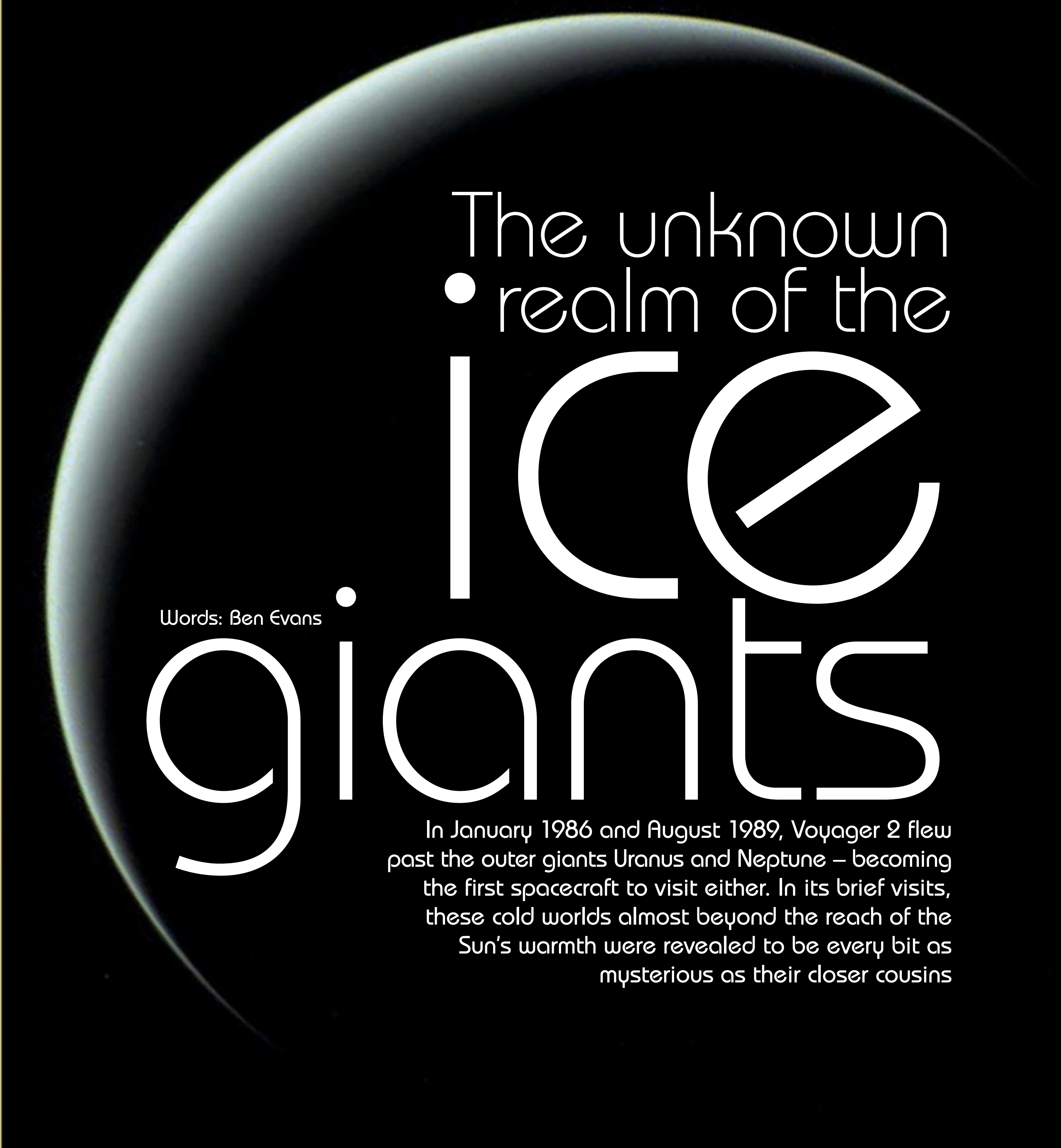


MARK GARLICK

Voyager 2 gave humanity its first close-up views of Neptune during its encounter with the ice giant in 1989



Only Voyager 2 carried on to the outer giants Uranus and Neptune, worlds that had hitherto only been seen as faint blobs through a telescope. The plucky craft revealed them to be markedly different from their closer cousins – one bland, almost serene; the other a frosty realm of roaring winds stronger than any others in the Solar System. It also detected previously undiscovered rings and new moons to add to the two planets' already impressive tallies. Voyager 1, meanwhile, raced away from the plane of the planets, in the hope that it would eventually reach the edge of the heliosphere. In 2012 it did so – becoming the first man-made object to enter interstellar space.

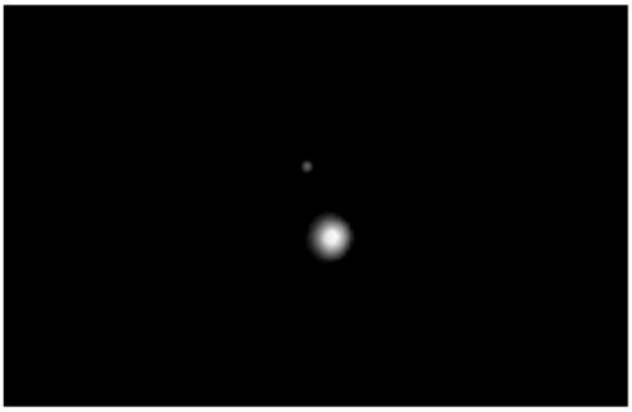


The unknown realm of the ice giants

Words: Ben Evans

In January 1986 and August 1989, Voyager 2 flew past the outer giants Uranus and Neptune – becoming the first spacecraft to visit either. In its brief visits, these cold worlds almost beyond the reach of the Sun's warmth were revealed to be every bit as mysterious as their closer cousins

Having gathered a vast amount of scientific data at Uranus, Voyager 2 took this parting shot of the planet's crescent before heading on to Neptune



△ **Ground-based telescopes had provided our best views of Uranus (left) and Neptune (right) until Voyager 2's visit. Much about these distant worlds remained a mystery as a result, including the number of moons in orbit around them**

PERHAPS THE TOUGHEST kind of exploration is studying a pair of planets about which virtually nothing is known with certainty. In February 1984, several dozen scientists gathered in Pasadena, California, to consider the scant level of knowledge about Uranus and Neptune. These two giants, which reside on the fringe of our planetary system, had only been discovered in the preceding two centuries. And as Voyager 2 journeyed towards them for humanity's first-ever visits, neither had revealed itself as much more than a fuzzy blob in an ocean of emptiness.

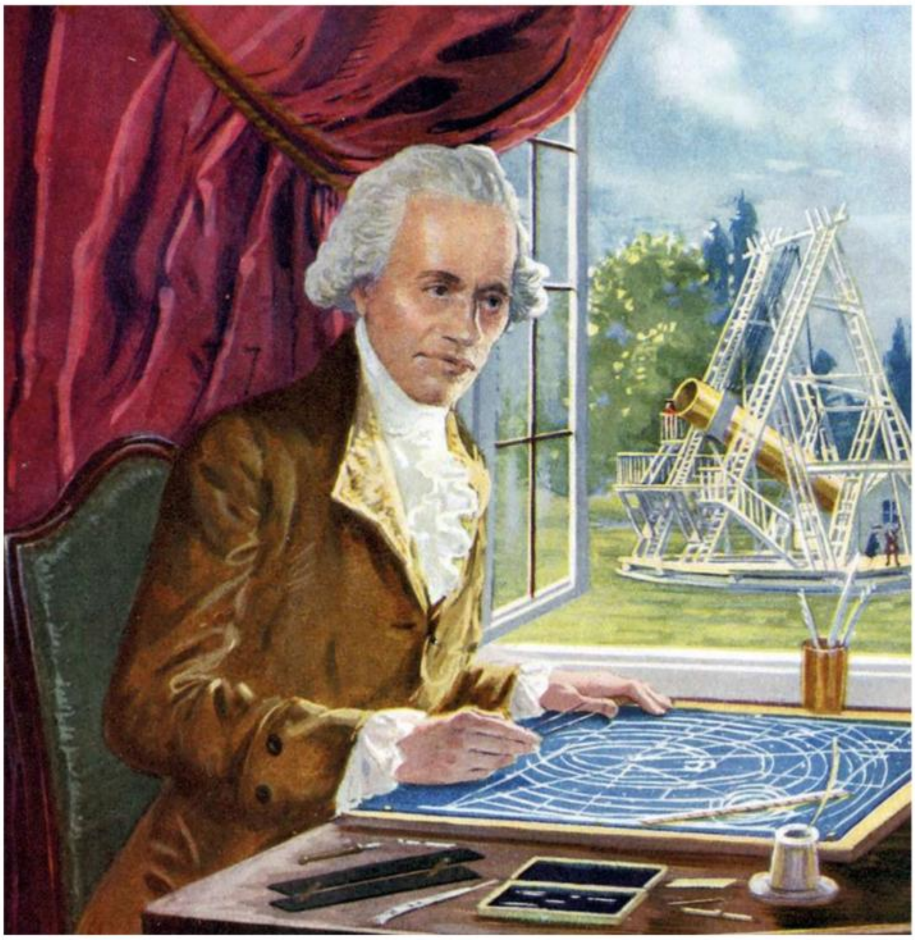
Worth a visit

The desire to travel to Uranus and Neptune originated with NASA's Grand Tour programme, but a subsequent rescoping of the mission led to a revised focus on Jupiter and Saturn. Nevertheless, in 1976 NASA approved an extension to Uranus on the condition that all primary objectives were met. A modified infrared detector was built to achieve the necessary resolution at Uranian distance – 2.6 billion km from Earth – but when the Uranus flyby formally began it did so with a greatly reduced budget and a leaner workforce.

By that time Uranus was known to possess five moons, named after characters from the works of William Shakespeare and Alexander Pope. The first pair, Titania and Oberon, were found in 1787 by Uranus's own discoverer, William Herschel, with Ariel and Umbriel observed by William Lassell in 1851 and tiny Miranda identified by Gerard Kuiper in 1948. Some 1.6 billion km beyond Uranus, Neptune was attended by Triton and Nereid, fittingly named after classical deities of the sea. All were barely detectable with Earth-based instruments before the Voyager 2 probe arrived.

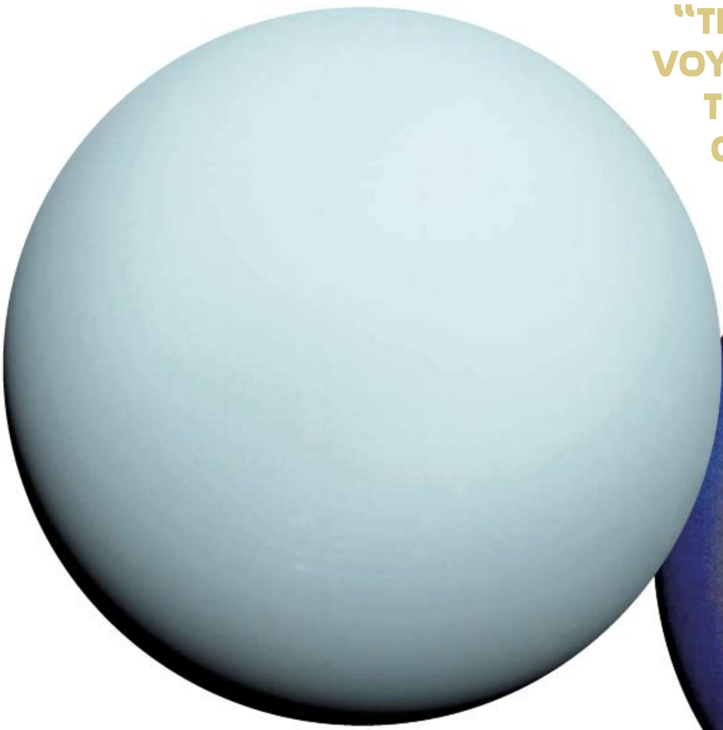
Following Uranus's discovery in 1781 and the finding of Neptune thanks to the mathematical predictions and telescopic observations of Johann Galle, Urbain Le Verrier and John Couch Adams in 1846, there existed only the most general and sweeping awareness of either planet. They were known to be near-twins in size, with equatorial diameters around 50,000km, four times bigger than Earth and over 15 times more massive. The probe confirmed hydrogen and helium as their predominant constituents. Uranus's plain ▷

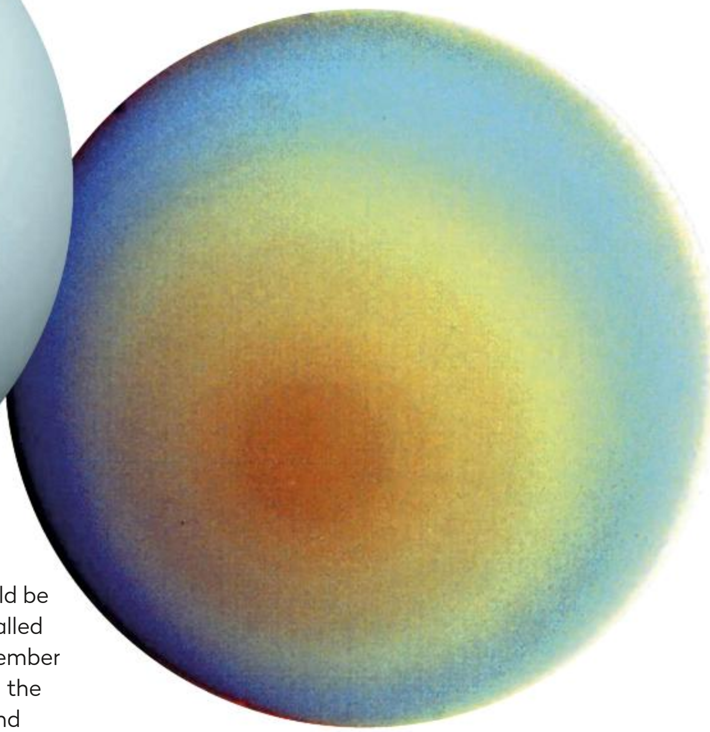
▽ **William Herschel found Uranus in 1781; he also spotted its first known moons Titania and Oberon, in 1787**



ISTOCK, NASA/JPL-CALTECH, SEBASTIAN VOLTMER/CCDGUIDE.COM, ROBERT SCHULZ/CCDGUIDE.COM, WORLD HISTORY ARCHIVE/ALAMY STOCK PHOTO

"TRAVELLING AT 64,000KM/H, VOYAGER 2 HAD ONLY SIX HOURS TO MAKE ITS CLOSE-RANGE OBSERVATIONS OF URANUS"





△ **The blue-green tint in Voyager 2's true-colour images of Uranus (left) is indicative of methane in its atmosphere. False-colour images (right) show an orange spot that might be dense smog over the pole**

▷ aquamarine colour and the richer, sky-blue façade of Neptune also betrayed the presence of ammonia, methane and hydrogen sulphide.

Data gathering

Travelling at 64,000km/h, Voyager 2 had only six hours on 24 January 1986 to make its close-range observations of Uranus. But to maximise the scientific yield of its flyby, the probe took measurements of the planet continually for 16 weeks from November 1985 until February 1986. A similar campaign was adopted at Neptune from June to October 1989. "We had a prediction of where the spacecraft would be at each point in time," recalled Voyager imaging team member Andrew Ingersoll. "We told the engineers what latitude and longitude we wanted to look at and they told the camera to take a picture. These commands had to be worked out and radioed to the probe weeks in advance."

Due to Uranus's 98° axial tilt, Voyager 2 approached the planet's sunward-facing south pole and generated time-lapse movies to track cloud movements and wind speeds. Unlike on Jupiter and Saturn, there was little evidence of storms or latitudinal banding, which led the imaging team to wryly dub themselves 'the imagining team'. However, infrared data revealed clouds beneath a high-altitude layer of hydrocarbons and the probe's radio-science and ultraviolet instruments revealed uniform temperatures throughout the atmosphere of around –216°C.

Theories abounded that this atmosphere might extend more than 3,000km beneath the cloud tops, perhaps terminating in a slushy ocean of water, ammonia

△ **Voyager 2 imaged the varied surfaces of the moons of Uranus. Umbriel (left) is dominated by craters, while canyons and faultlines score the surface of Titania (middle). Oberon (right) has a mix of new and old surface material, which suggests some form of volcanic activity**

△ Giant radio telescope arrays in Canberra (left), Madrid (middle) and California (right) combine to make NASA's Deep Space Network

BEEFING UP THE VOYAGERS FROM THE GROUND

Orbitting billions of kilometres beyond Saturn, the outer giants Uranus and Neptune inhabit a gloomy region of the Solar System, requiring Voyager 2 to examine worlds where high noon is dimmer than dusk on Earth. One scientist likened the problem to photographing a pile of charcoal briquettes lying at the foot of a Christmas tree, lit by a single-Watt bulb.

Stability was crucial, but even turning its tape recorder on and off was enough to induce a disruptive 'nodding' effect in Voyager 2. Its gyroscopes could keep the instruments reasonably steady, but engineers had to halve the duration of thruster firings to allow the probe to settle after manoeuvres. At Neptune, longer exposures of 96 seconds and thruster firings under four milliseconds became necessary. Image motion compensation allowed Voyager 2 to resolve finer detail, but at the expense of picking out irritating optical flaws, including dust on its lenses.

△ The DSS-14 antenna at Goldstone was widened from 64m to 70m in 1989 to help it pick up Voyager 2's weakening signal

Back on Earth, the three tracking stations that make up NASA's Deep Space Network (located in Canberra, Australia, the remote foothills west of Madrid in Spain and in California's Mojave Desert) received a $100 million facelift to boost Voyager 2's ever-weakening signal, which by January 1986 was a billion times fainter than a watch battery. All three stations had their 64m antennas augmented for Uranus, electronically synchronising them to strengthen the signal. Further upgrades to 70m were implemented for Neptune and two additional tracking stations in Japan and New Mexico were called into duty.

Due to the position of Uranus in Earth's skies in the winter of 1985-1986, Canberra was the main tracking station, following Voyager 2 for 12 hours per day and allowing a 21.6kbps downlink rate. In support, a 400km microwave connection was established with the Parkes radio telescope in New South Wales, bolstering it by 25 per cent and allowing up to 50 extra photographs to be returned every day.

and methane, girdling an Earth-sized rocky core. A similar situation is also thought to exist at Neptune. Voyager 2 was unable to prove the existence of such oceans, but did detect radio signals induced by interactions between the solar wind and electrons in the planets' magnetic fields. This enabled its magnetometer to measure Uranus's day at 17.25 hours and Neptune's day at 16.1 hours, which in turn helped provide wind-speed estimates.

▽ Ridges and troughs were seen on the surface of the moon Ariel

NASA/JPL-CALTECH X 10

The dark of the moons

To great surprise, Uranus's magnetic field extended only 600,000km sunward, but wound backwards, like a giant corkscrew, 10 million km beyond the planet. Ultraviolet observations of polar aurorae showed that the field was tilted at 59° to Uranus's rotational axis – a curiosity that, on Earth, would be equivalent to having our north magnetic pole in the Florida Keys – and bore a powerful sting in the guise of trapped, high-energy radiation. This clearly manifested itself on the surfaces of Uranus's moons.

All five moons appeared intrinsically dark, suggesting that radiation had broken down any methane on their surfaces within a few tens of millions of years, darkening them and leaving a thick, charcoal-like dusting. Umbriel is by far the darkest, although it does exhibit a few splotches of bright material, including an enigmatic 'Cheerio' in the crater Wunda at its equator. As for its siblings, Titania – the largest, at 1,580km across – is marred by huge faults and winding canyons, pointing to a violent tectonic past. Oberon revealed bright and dark regions, not unlike our Moon, indicating meteoroid bombardment and perhaps the volcanic extrusion of subsurface material.

But it was Miranda and Ariel to which Voyager 2 devoted ▷

▹the most attention. The latter is the brightest Uranian moon, with an ancient and heavily cratered terrain that features rolling plains, parallel ridges and troughs lying tens of kilometres apart. Miranda, less than 500km in diameter, was the most closely inspected, principally due to the flyby geometry needed by Voyager 2 to reach Neptune.

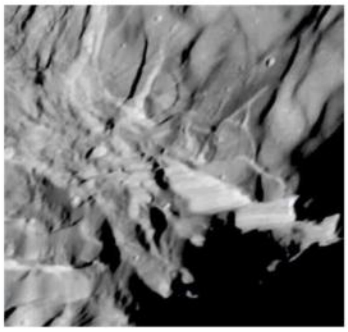
It revealed unmistakable evidence of billions of years of impacts, which tore Miranda apart, then hammered it back together, gouging out 20km-deep canyons, at least three enormous, oval-shaped 'coronae' and broad terraces of old and young, bright and dark, lightly and heavily cratered terrain. One area, the 200km-wide Inverness Corona, showed a bright chevron-like feature between dark layers, possibly a result of reaggregated bits of Miranda's original crust, poking out from the present surface.

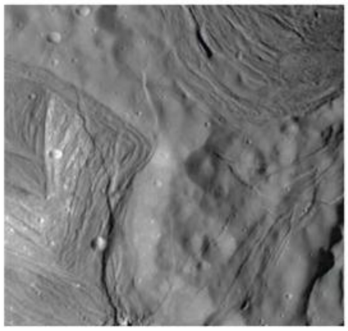
New moons

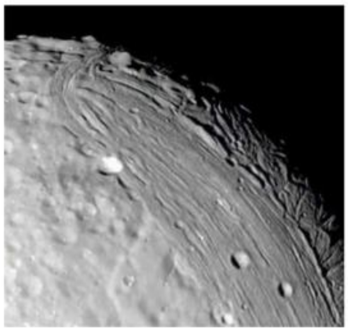
Voyager 2 also found 10 new moons, ranging from 160km-wide Puck to diminutive Cordelia, about an eighth as large. A small subset that share similar orbits, surface colouration and generally elongated shapes was classified as the 'Portia Group' (named for its biggest member). Another object was photographed by the probe, but went unrecognised as a moon until 1999. It was fittingly named 'Perdita', the Latin word for lost.

Something that had already been seen at Saturn was the pivotal role tiny 'shepherd' moons play in anchoring ring material. Several narrow rings had been detected around Uranus by ground-based observers in the 1970s, but Voyager 2 uncovered another pair. The probe revealed the new pair to be relatively insubstantial, although the brighter 'Epsilon ring' achieved a maximum extent of 96km.

Up to 18 shepherd moons were predicted to exist at Uranus, but only two – Cordelia and Ophelia – were detected, lying astride and 'binding' the inner and outer edges of the Epsilon ring. The general darkness of the







△▷ **Miranda's cliffs, canyons and craters (right), hint at a past that saw it smashed to pieces and then reassembled. The Inverness Corona appears as a bright 'tick' (above)**

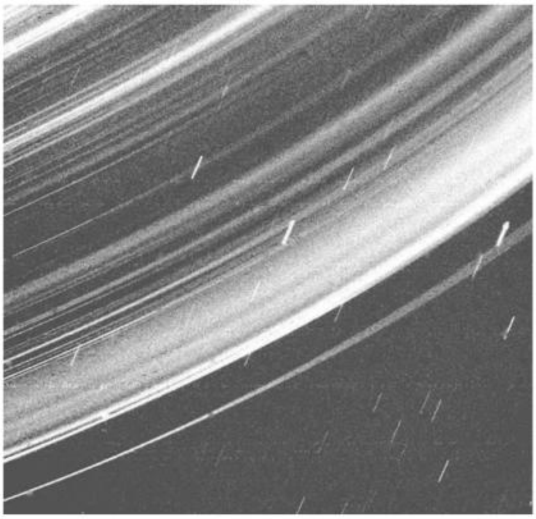
THE BULLSEYE PLANET

Uranus is unique among the planets in our Solar System thanks to its extraordinary rotational tilt of 98° – Uranus presents itself to observers as a world tipped on its side. Its poles lie where its equator should be and receive a correspondingly higher level of incident sunlight. Situated 2.8 billion km from the Sun, Uranus circles its parent star every 84 years, with each pole rhythmically illuminated, before being plunged into frigid darkness, every four decades.

When Voyager 2 viewed the planet only the southern pole was in direct sunlight. Its five main moons orbit their giant host within its equatorial plane, placing their southern halves at the height of Uranian summer in January 1986 and casting their northern extremities into a 21-year-long winter season.

How Uranus's axial tilt came about remains a mystery, although a collision with an Earth-sized impactor has been proposed. The fact that the moons circle within its equatorial plane implies that they formed much later from debris placed into orbit by this impact. Moreover, Uranus radiates hardly any heat into space – its temperatures dip as low as –224°C, giving it the coldest planetary atmosphere in the Solar System – and it's possible that whatever hit the planet caused it to expel much of its primordial heat.

▷ **With its 98° tilt, Uranus is unlike any other planet in the Solar System**



△ **Lanes of dust particles can be seen in this 'close-up' of the Uranian rings, imaged from a distance of 236,000km**

rings underscores their extreme youth, for they are probably no more than 600 million years old. Data from Voyager 2's photopolarimeter and other instruments revealed them to be so sharp that the Epsilon component can't be greater than 150m thick.

Rings were also eagerly anticipated at Neptune, with ground-based studies between 1968 and the early 1980s suggesting that incomplete 'arcs' might run part-way around the planet. Numerous theories postulated that the arcs were held in place by tiny shepherd moons or maybe new rings were in the process of forming. With just two weeks to go until Voyager 2's arrival, their true nature was revealed. A pair of incomplete arcs did appear to exist, with three shepherd moons (Galatea, Larissa and Despina) interacting with them.

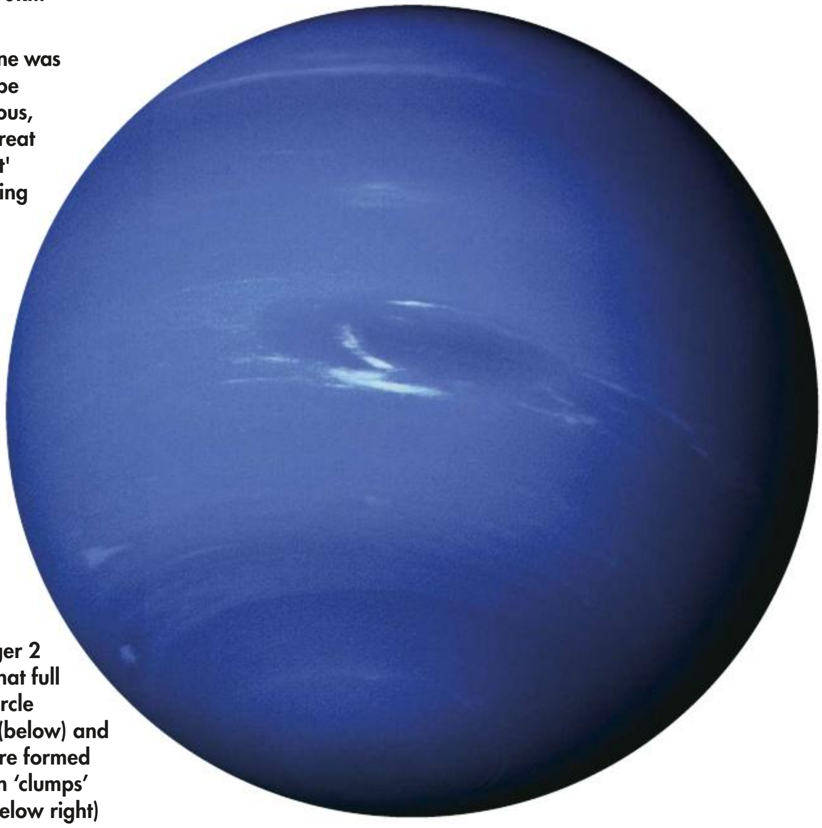
Building rings

As the probe drew nearer, it became apparent that more rings extended around the planet. Their uneven 'clumpiness' and irregularly distributed particles offered an early explanation for why arcs had been suspected for so long. Indeed, Neptune's outermost 'Adams' ring revealed several clods of material, up to 50km wide. It was argued that debris from ancient moons could have contributed to this unequal distribution of mass and a pair of tiny moons, Thalassa and Naiad, could themselves someday be torn apart and incorporated into the system.

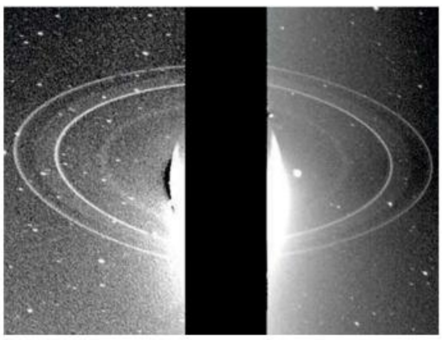
Voyager 2 confirmed the existence of six new moons at Neptune, including potato-shaped and heavily cratered Proteus, which is thought to be almost big enough for gravity to pull it into a spherical shape. Eccentric-orbiting Nereid, discovered by Gerard Kuiper in 1949, was also seen by the probe, but at a distance of 4.7 million km it was still too far away to resolve any surface detail, much less measure its rotational characteristics.

Before it found any rings, it was hoped that Voyager 2 would fly within 10,000km of the planet's largest moon, Triton, which ground-based observations had shown to possess nitrogen ices on its surface. To avoid the risk of colliding with ring particles, the probe's trajectory was altered to carry it 4,950km over Neptune's north pole – the closest ▷

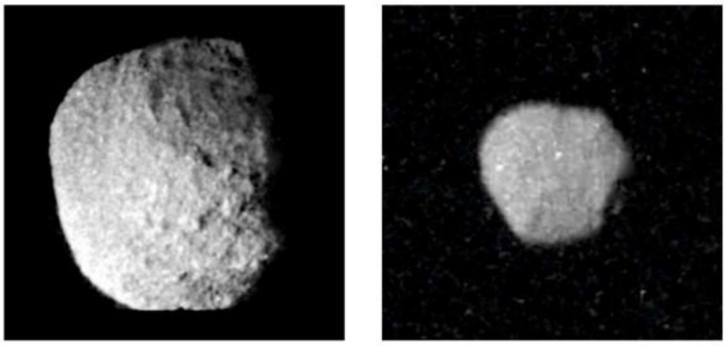
"RINGS WERE EAGERLY ANTICIPATED AT NEPTUNE, WITH GROUND-BASED STUDIES SUGGESTING THAT INCOMPLETE 'ARCS' MIGHT RUN PART-WAY AROUND THE PLANET"



▷ **Neptune was found to be tempestuous, with a 'Great Dark Spot' and howling winds**



▽ **Voyager 2 showed that full rings encircle Neptune (below) and that they're formed by uneven 'clumps' of dust (below right)**



△ **Proteus (left) was among the new moons found by Voyager 2; it's 400km across, bigger than Nereid (right), which had been known of since 1949**

▹ planetary encounter achieved by either Voyager craft – on 25 August 1989. It then plunged south, passing within 39,800km of Triton, five hours later.

Circling Neptune in a highly inclined 'retrograde' orbit, the moon proved smaller than predicted, at just 2,700km across, and a stellar occultation allowed Voyager 2 to measure its 800km-deep atmosphere, all the way down to its surface, the coldest known in the Solar System at a frigid –236°C. In fact, Triton's tenuous mix of gases and particulates is virtually a vacuum, barely capable of supporting thin nitrogen-ice clouds and haze at an altitude of 13km.

Voyager 2 strongly hinted that these constituents originated from the evaporation of surface ices, with winds transporting dust particles up to 50km across its terrain. Triton is the most spectroscopically diverse object in the Solar System, reflecting over 85 per cent of incident sunlight – eight times more than our Moon – and this extreme brightness was a key reason why such a tiny, distant body was found telescopically by William Lassell in October 1846, just weeks after Neptune itself.

Freeze-thaw effect

The probe imaged a third of Triton's surface, uncovering a greenish landscape, nicknamed 'cantaloupe', due to its similarity to the scaly skinned melon. It was crisscrossed with circular depressions, each around 25km wide, and long, interconnecting ridges were thought to be the result of epochs of melting and refreezing. This reinforced the notion of Triton as a captured Kuiper Belt object and that the tidal heating from Neptune's gravity had left its interior fluid for a billion years, underpinning these complex internal processes.

Voyager 2 also revealed a pinkish southern polar cap,

"DARK STREAKS ACROSS TRITON'S SOUTHERN POLAR CAP INDICATED THAT VOLCANISM WAS COMMONPLACE"

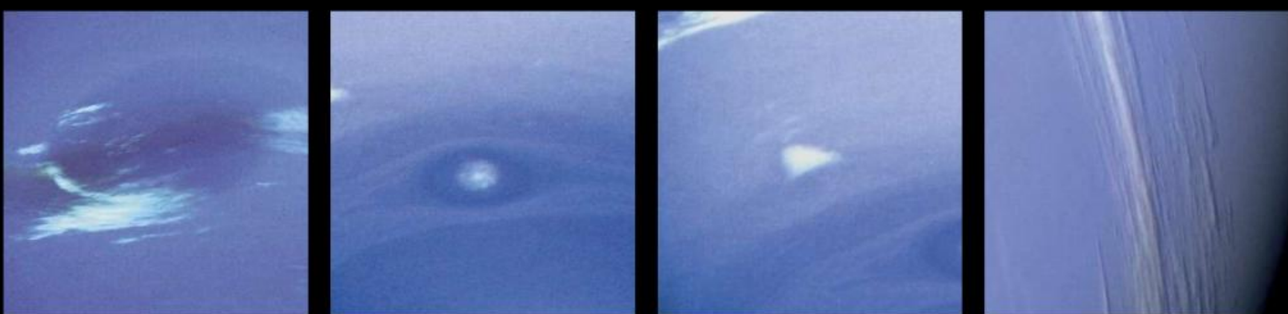
NASA/JPL-CALTECH X 8

A WORLD OF WILD WEATHER

Four-and-a-half billion kilometres from its parent star, recipient of half as much sunlight as gloomy Uranus and with temperatures as low as –218°C, Neptune should be an inactive world. Yet Voyager 2 revealed it to be surprisingly energetic, with the oval-shaped Great Dark Spot observed at a latitude of 22°S. This counter-clockwise-rotating vortex bore many uncanny parallels with Jupiter's Great Red Spot, in terms of relative size, motion and position within the atmosphere.

As the probe drew closer, a second, smaller dark spot was found, together with a chevron-shaped, westward-moving cloud feature, whose rapid 16-hour transit around Neptune's atmosphere generated the nickname of 'Scooter'. The Great Dark Spot, in keeping with its name, was 10 per cent darker than its surroundings and hustled northwards through the atmosphere at 1,100km/h. At its edge was a hovering, shape-shifting 'bright companion' cloud. The spot lay 50km below Neptune's main cloud deck, with the companion at a slightly higher altitude, creating analogies with lenticular cloud formations on Earth.

Elsewhere in the sky-blue atmosphere were cirrus streaks of methane-ice, which cast shadows, tens of kilometres long, on Neptune's cloud deck at low northern latitudes. How such wild weather can manifest itself on such a cold planet must be related to its dense interior and the fact that it emits 2.6 times as much heat as it receives from incident sunlight. It has been suggested that temperature differences between Neptune's internal heat and its cold atmosphere could trigger instabilities and induce large-scale meteorological phenomena.



△ **Tumultuous Neptune up close: its Great Dark Spot; its smaller dark spot; the 'Scooter' cloud pattern; and cirrus-like methane-ice clouds** abutted by a blue-tinged crustal region, indicative of the presence of methane, nitrogen and water ices. And it was from within the polar caps that a moderate greenhouse effect could have been nurtured, forcing exotic ices to 'de-gas' and build pressure, before prompting one of the most surprising discoveries at Triton: erupting geysers.

In August 1989, only Earth and Jupiter's moon, Io, were known to harbour active volcanism, but dark streaks across Triton's southern polar cap indicated that such phenomena were commonplace, even in this far-flung corner of the Solar System. One geyser was observed to hurl carbonaceous material to an altitude of several thousand metres, while other measurements allowed local wind speeds to be clocked at 54km/h, as strong as a moderate gale on Earth.

△ **Voyager 2 took one last shot of Neptune before heading on towards the edge of the Solar System**

Providing a backdrop to these discoveries was magnificent Neptune itself, whose outward similarity to Uranus belied a far more active world. Despite its greater distance from the Sun, infrared data showed it to radiate 2.6 times as much heat from incident sunlight as Uranus. And although the near-twins are thought to have similar compositions, Neptune is marginally more massive, which influences its magnetic field and internal heat. "Wow," exulted one planetary scientist, breathlessly, as Voyager 2 became the only spacecraft in history to visit four planets. "What a way to leave the Solar System!" V

◁ **Dark dust deposits from geyser plumes form streaks across the pink methane-ice on Triton's southern polar cap**

THE VOICES OF VOYAGER

Bonnie Buratti

Bonnie Buratti's storied career has seen her work on NASA's Cassini, New Horizons and Rosetta missions, but she started out on Voyager – and remembers the nerves and excitement of waiting for the Uranus and Neptune flybys all too well

Interviewed by: Iain Todd

I started working on the Voyager data while I was completing my PhD.
My advisor, Joe Veverka, was a member of the Voyager imaging team at the time. He had a project for me, which was to look quantitatively at the light that was coming from some of the icy moons of Jupiter and Saturn. This was the first big research project that I took responsibility for. When I came to NASA's Jet Propulsion Laboratory (JPL), I continued to work on the Voyager mission. But at that stage I was working with the photopolarimeter team and became focused on analysing the data coming from Uranus and Neptune.

My work amounted to doing everything needed to tease the results out of the data.
The thing about research when you're creating new knowledge is that you don't really have a cookbook; you don't really have anything to follow.

We didn't have personal computers back then and the computers we had didn't have data analysis routines built in.
In many ways, it was like we had a more intimate relationship with the data. I was pretty much working about 14 hours a day after walking in from my little apartment to Cornell. I didn't have any kids back then so I just worked all the time! That's pretty typical for graduate students.

During the encounters with the planets you're pretty much working 24/7.
We reached Uranus in 1986 and Neptune in 1989, and when the data first comes in, you just work day and night. It's kind of been that way with Cassini too, especially in the beginning.

When I was working on Voyager, I would receive images and then had to start manipulating them and trying to understand how the light scattered off the surface of the planet.
I'd create models so we could really see what was happening. I did that on a day-to-day basis, and I continued that right up to the time I was working at JPL. In those early stages, I wasn't involved in designing any of the experiments. Later on in my career I became more involved in that aspect; when you have to figure out where to point the spacecraft, how much data volume you can take and how you're going to cooperate with the other instruments on the spacecraft that people want to observe with.

We received data as numbers.
It's basically a bunch of zeros and ones, and then it goes through lots of procedures to decode it. The data comes down to

▽ Computing and data storage at NASA's Jet Propulsion Laboratory relied on magnetic tape during the 1970s and 1980s

BONNIE BURATTI, NASA/JPL-CALTECH, RGB VENTURES/SUPERSTOCK/ALAMY STOCK PHOTO

△ **JPL scientists gather on 25 August 1989 in anticipation of Voyager's close approach to Neptune**

JPL's Deep Space Network and then it goes through computer algorithms, which turn it into a grid of numbers. On Cassini, to give a current example, the imaging camera captures roughly 1,000x1,000 pixels, so there are a million pixels, and each has a number associated with it, telling you how bright it is. This then gets turned into an image by a computer.

Computers have really changed how missions today operate.

When I was working on Voyager, everything was done by phone and you had to photocopy everything and mail it out to people, whereas now we just put everything on a website. Nowadays we can be much more efficient and get much more work done. When you look at the staggering number of flybys and encounters we've had with Cassini, it's more than a hundred times greater. We did one flyby of Enceladus during the Voyager encounter, whereas we had 22 flybys of it during the Cassini encounter, five of Dione and several of all the other major moons.

"IT TAKES HOURS FOR THE DATA TO COME FROM THESE DISTANT PLANETS. YOU'RE SITTING, WAITING, IN SUSPENSE"

The lesson I've learned being involved in these two missions is just because you've been to a place for the first time, doesn't mean you've discovered everything...

Or even that you've discovered the most important things. We didn't discover activity on Enceladus during the Voyager mission and we didn't discover the lakes on Titan either.

The was a great deal of suspense while we waited for the data from Uranus and Neptune to arrive.

First of all, there was a possibility that the encounter hadn't worked out, because there's the light travel time and it takes hours for the data to come from these distant planets. You're sitting, waiting, in suspense. Then when it does come through, it takes a while to put the images together. But then you realise you're seeing something that no human has ever seen before and it makes all the drudgery worthwhile.

For me, the most awesome discovery was that there were at least three active plumes on Triton.

Triton is a massive moon of Neptune and probably a captured Kuiper Belt object. It has this giant polar cap that we think is seasonal and on that cap we saw all these plume deposits and three active plumes of gases being expelled into Triton's thin atmosphere. ▷

▷ Then there was Neptune's 'Scooter', a dark spot similar to the Great Red Spot found on Jupiter.
It amazed us that a body so far from the Sun could still be active. So there's hardly any sunlight but we could see weather systems and convection cells. Neptune seems to be a very active body.

The Uranian moons all appeared to have been active in the past.
One of them, Umbriel, was covered with a mysterious dark dust. When we looked at Miranda, it looked like it had been disrupted and come together again. There were also faults on a lot of the moons. None of that was known and we were the first humans to see it. That's what was so thrilling about it: realising that we were seeing something that had never been seen before. The moons showed us way more than we expected; they weren't just the cratered objects that we'd expected to find out there.

Voyager will go down in history as the reconnaissance mission; as the exploratory mission; as the first.
We were the first to see Uranus and Neptune, and the first to look at the moons of Saturn and Jupiter close up. One of the most amazing discoveries was the first view of volcanoes beyond Earth, on Jupiter's moon Io. Astronomers had observed that when Io came out of Jupiter's shadow, it seemed to brighten. Scientists couldn't figure out why that was. Now we know that it was maybe some sulphur dioxide in the atmosphere that was condensing on the surface. Several days before the encounter, Stanton Peale and his colleagues wrote a paper that predicted the volcanoes. And when we got there, Io and behold, we saw active volcanoes spewing out sulphur dioxide.

Ed Stone said it best after Linda Morabito discovered the volcanoes on Io.
He remarked: "This has been a great mission". I think that summarised what all of the scientists who were involved were thinking. We were making history. Every flyby got a picture on the front page of every newspaper.

This was before the days of the internet and the 24-hour news cycle, remember.
We had to have these lithographs made up showing all the images and you couldn't post them to your website because there was no web. It was a very different world and things moved a lot slower. But, wow... were people interested! They still are today, but now it's on social media and I think somehow it doesn't sink in as much as when you have the hard copy and you're there and watching it, rather than waiting for an announcement on Twitter.

△ Voyager's shots of Neptune were turned into lithograph prints for use by the press

NASA/JPL-CALTECH

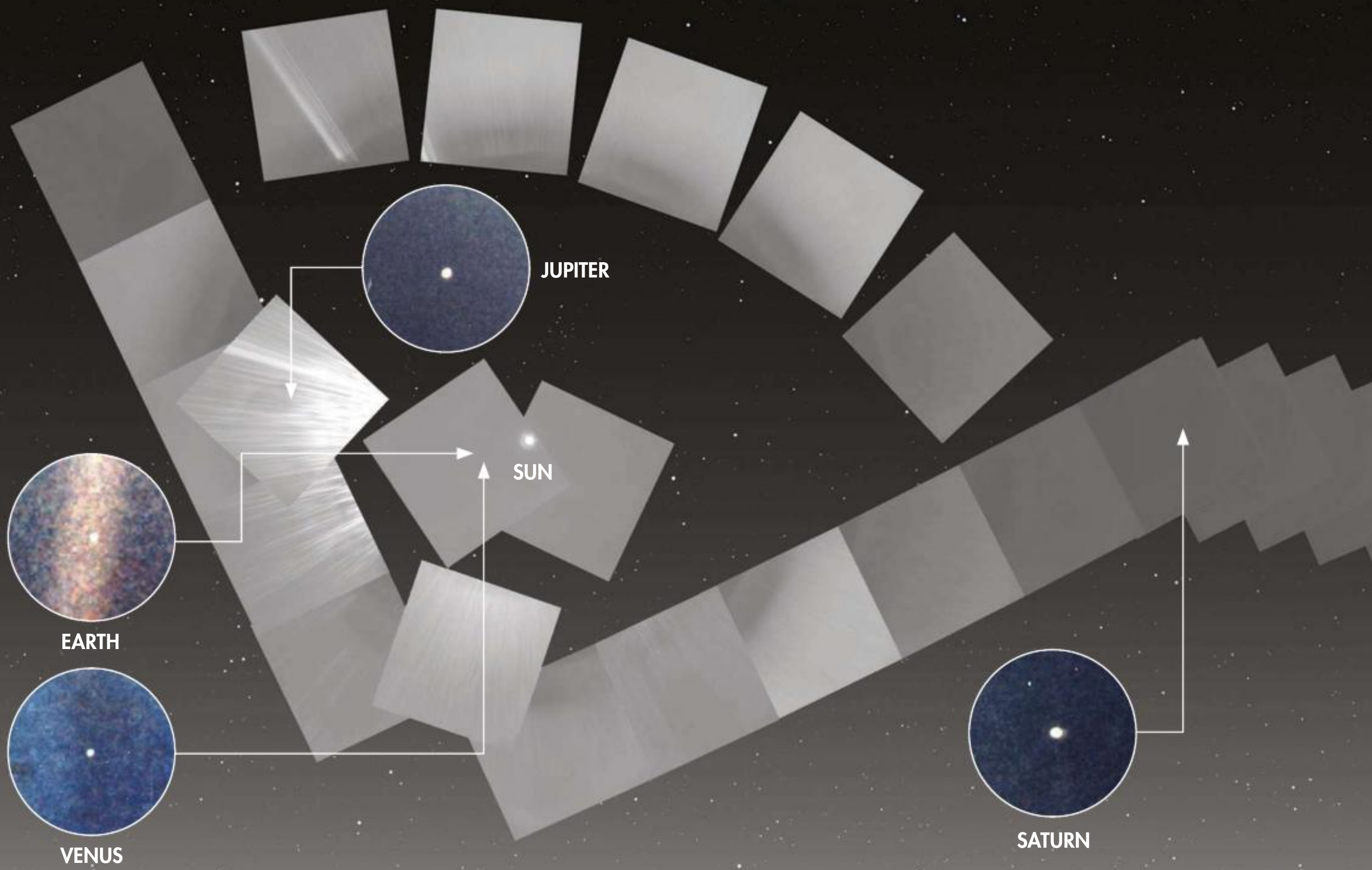
Uranus and Neptune are worthy for follow-up missions.
Our big constraint at NASA is money. If we had infinite amounts of money, we would be sending missions to every planet once a year. There are scientists currently doing a study mission on Uranus to go back and orbit the planet. After you do a reconnaissance mission, the next step in the process is to send an orbiter. We're also looking at putting an orbiter around Pluto and Neptune as well.

"WE WERE THE FIRST TO SEE URANUS AND NEPTUNE, AND THE FIRST TO LOOK AT MOONS OF SATURN AND JUPITER CLOSE UP"

Unlike Cassini, we'll never have to destroy Voyager.
In the case of Cassini, we have to get rid of the spacecraft in the name of planetary protection, since we've found what could be a habitable environment in the saltwater ocean under the icy crust on Saturn's moon Enceladus. If there's liquid water, a source of energy, a source of food – which is usually some kind of organic molecule – we have to prevent that environment from being contaminated by the spacecraft.

With Voyager, we never have to face that prospect so we'll keep listening to the probes for as long as we can. The two constraints are that the Deep Space Network might not be able to hear them or that their generators eventually run out. But we'll listen to them for as long as we can.

I look upon Voyager as the most extraordinary mission that I've been involved with.
It's the nature of humanity to explore; it's in our genes to want to know what's on the other side of the mountain. It was a great voyage of discovery. That's what makes it human. I think Carl Sagan had a lot to do with it. There were a lot of larger-than-life people involved in the mission. My advisor, Joe Veverka, was one of them. He was so charismatic and we had so many people like that on the mission. I think that's what made it so exciting. Ⓥ



The Solar System's family portrait

On Valentine's Day 1990 Voyager 1 looked back at its home system and took an iconic set of images

Words: Paul Sutherland

BY 1990, VOYAGER 1 was heading towards the edge of the Solar System at close to 65,000km/h. It was then, after its successful encounters with Jupiter and Saturn, that it produced a portrait of our home in the Galaxy, including an iconic image of the Earth known as the 'Pale Blue Dot'.

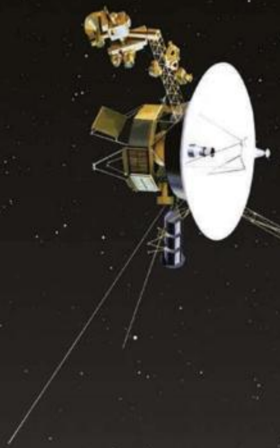
On 14 February, when it was almost six billion km away, beyond the orbits of Neptune and Pluto, the spacecraft turned itself around to gaze back at the family of worlds it was leaving and give us a view that had never been seen before. It collected a sequence of 60 images – the last pictures taken by either of the Voyager probes – that would take three months to beam home. A valentine to our planetary neighbourhood.

They were transmitted back during March, April and May. When combined, they produced a snapshot of six planets. It included the Earth as a tiny speck caught in a ray of light caused by sunlight reflecting within the camera's optics. Mercury was lost in the Sun's glare, while Mars and Pluto, which was then still regarded as a planet, were too small to show up. Uranus and Neptune look smeared because they moved during the exposure.

Great minds...

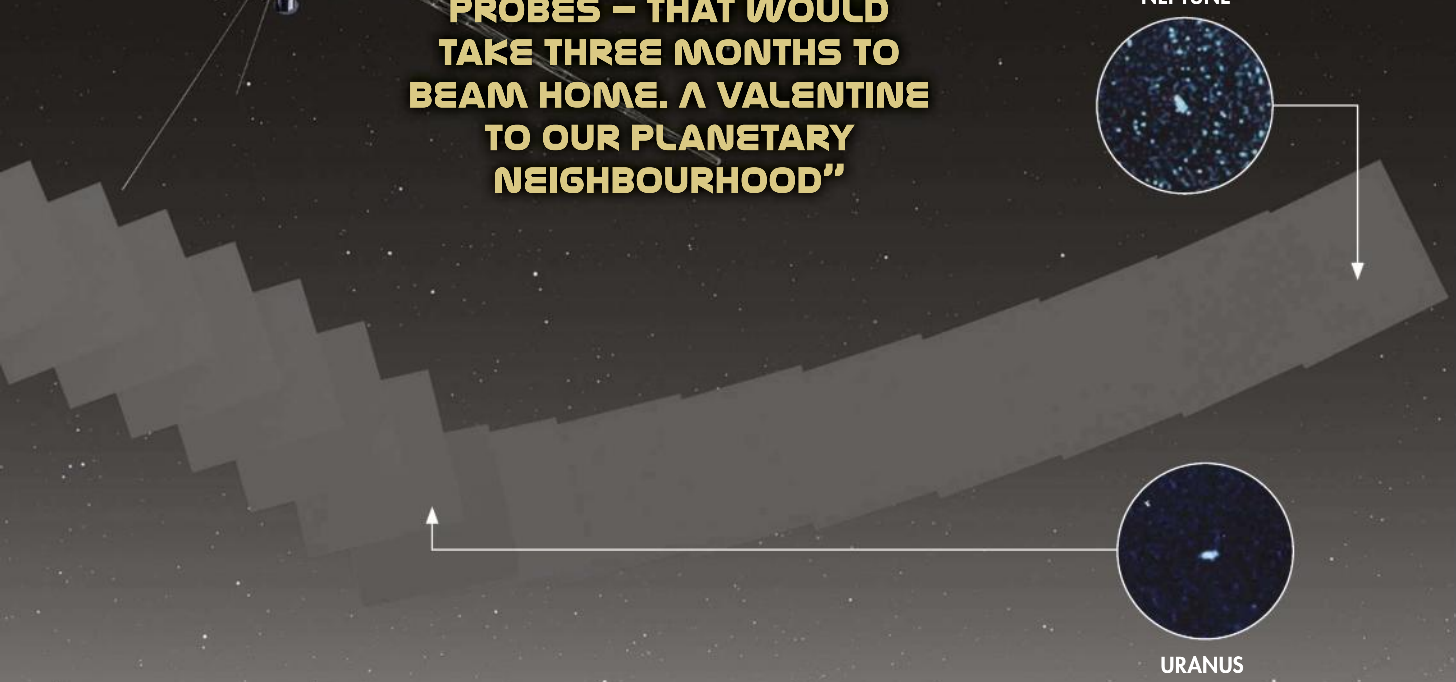
The idea for this family portrait came from two people, the astronomer and science populariser Carl Sagan and Carolyn Porco, then a young member of the Voyager team from the University of Arizona. But they came up against opposition from mission managers at NASA's Jet Propulsion Laboratory (JPL) in Pasadena, who failed to see the point of the exercise and feared it could damage Voyager 1.

"Soon after I joined the Voyager project in October 1983



"VOYAGER 1 COLLECTED A SEQUENCE OF 60 IMAGES – THE LAST PICTURES TAKEN BY EITHER OF THE VOYAGER PROBES – THAT WOULD TAKE THREE MONTHS TO BEAM HOME. A VALENTINE TO OUR PLANETARY NEIGHBOURHOOD"

Voyager 1's famous family portrait captures six of the Solar System's planets; only Mercury and Mars are missing. The individual frames stand out because they were taken at different exposures and through various filters to capture as much detail as possible



I started promoting the idea of having Voyager 1 turn around to take a picture of Earth and all the other planets. I thought it would be a magnificent 'we are here' look at our cosmic place," says Porco. "The mission managers at JPL looked at me like I was crazy because there was no science in doing so – all these objects would be a pixel across or less – and the engineers didn't want to waste resources to make a useless observation. A couple of years later I learned that Carl Sagan had also proposed this 'portrait of the Solar System' for the same reasons and he got the same response. I spoke to him about it and we decided to join forces."

Sagan went to the very top, persuading NASA administrator Richard Truly to agree to the picture, while Porco worked with JPL's Candy Hansen on making it happen. Voyager 1 was chosen because it would be able to capture Jupiter free from the glare of the Sun.

"I worked on designing the observations with Hansen, who was responsible for executing the Voyager imaging team's image sequences. She worked out the commands to turn the spacecraft from one planet to the next," Porco explains.

"My job was to figure out how long the exposures had to be. Believe it or not, the biggest challenge was figuring out how to expose correctly on Earth. No one had taken this kind of observation of Earth before, so we weren't sure how bright it would be."

Looking back

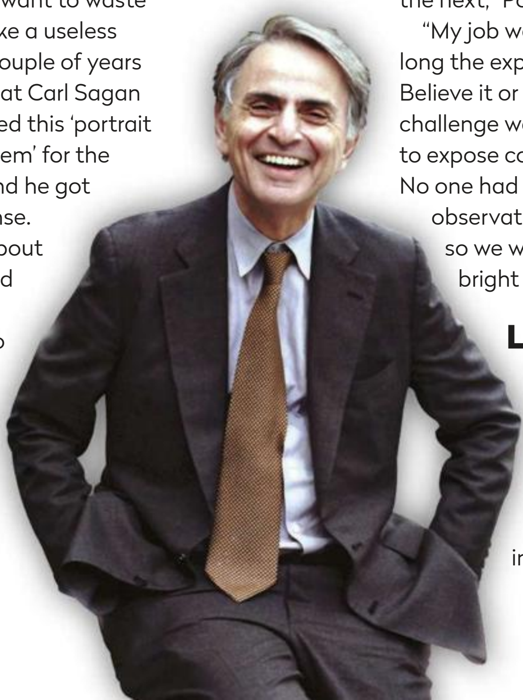
Shown above, the combined picture is an odd one at first glance. Rather than a single panorama, the individual frames are quite distinct, each exposed to bring out the detail within.

In many ways, this project defied common sense, like looking the wrong way through a telescope. Space probes are meant to bring us close-ups of unexplored worlds. Instead, the world we know best – our own – was close to invisible, occupying less than a pixel in the shot. But from a distance of around six billion km, it revealed the fragile nature of Earth, small and vulnerable, suspended in the infinite void of space.

Sagan dubbed the picture the 'Pale Blue Dot'. In a book of the same name, he later wrote: "Look again at that dot. That's here. That's home. That's us. On it everyone you love, everyone you know, everyone you ever heard of, every human being who ever was, lived out their lives."

On the Voyagers' 40th anniversary, the family portrait and the 'Pale Blue Dot' have lost none of their power to bring home the unknowably vast spaces of the Universe. **V**

▽ **Carl Sagan, below, worked with Carolyn Porco to convince NASA of the benefit of using Voyager 1 to create a 'family portrait' of the Solar System**

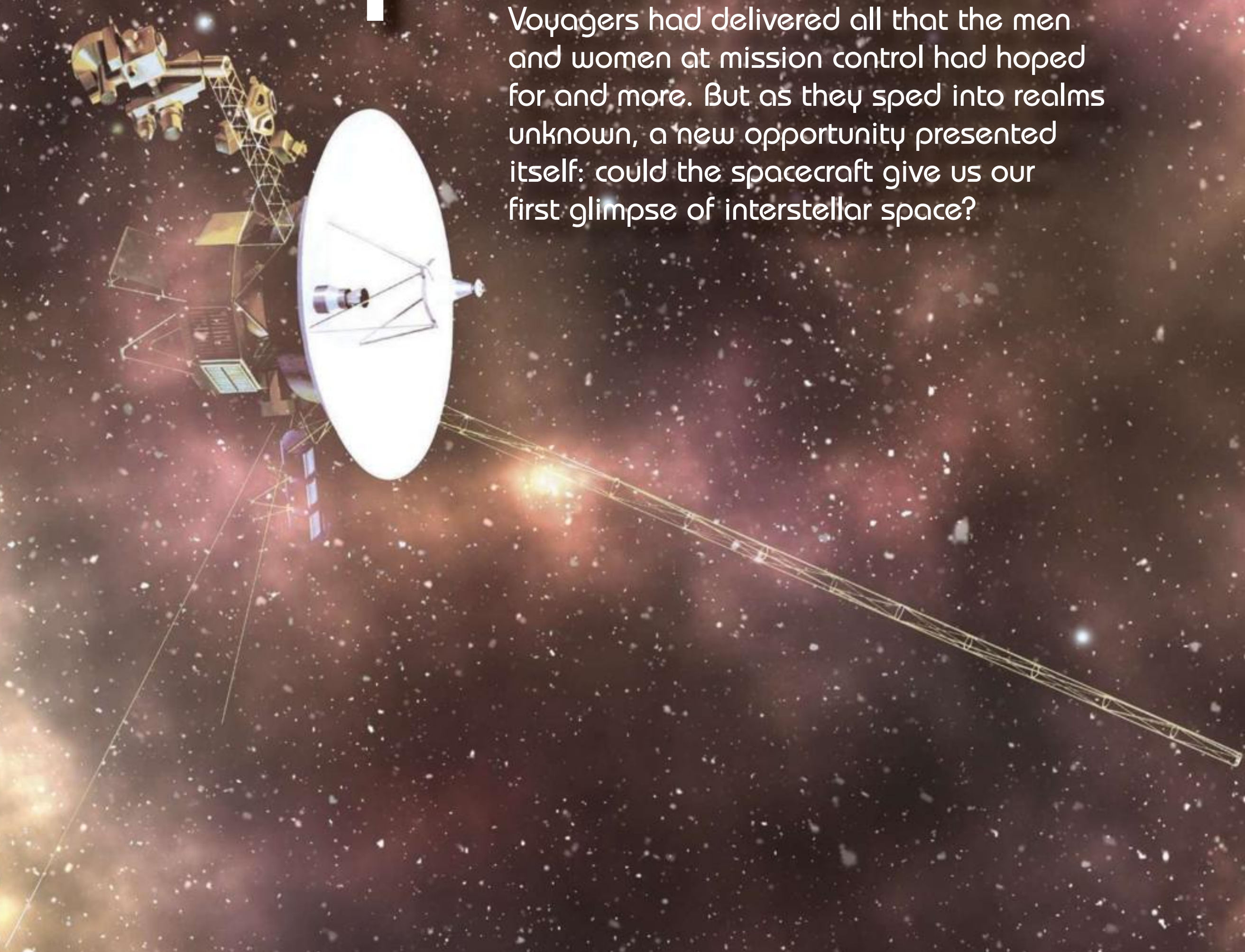


NASA/JPL/SPACE SCIENCE INSTITUTE X 7, NASA PHOTO/ALAMY STOCK PHOTO

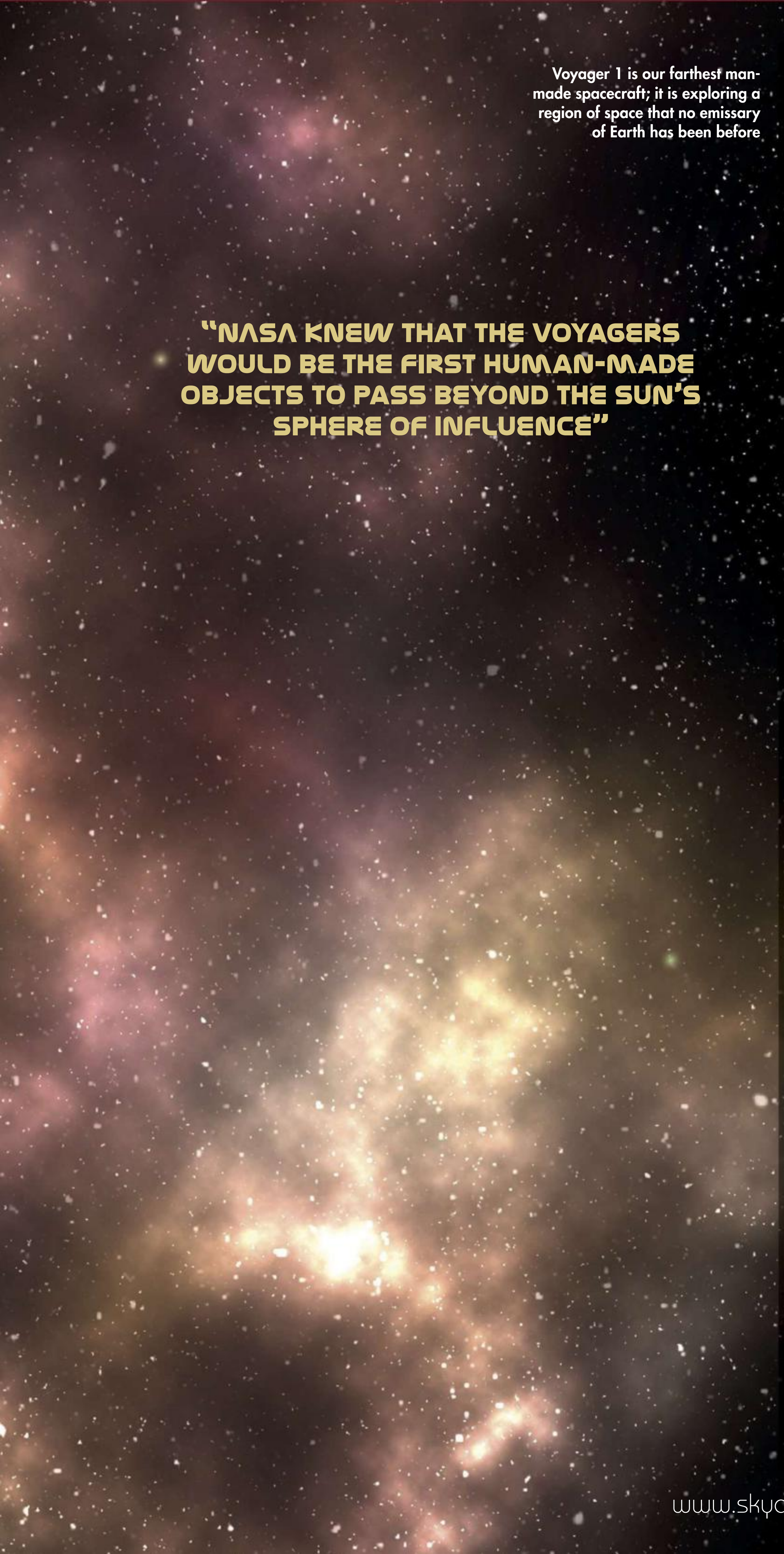
So long, Solar System

Words: Ben Skuse

With the outer planets behind them, the Voyagers had delivered all that the men and women at mission control had hoped for and more. But as they sped into realms unknown, a new opportunity presented itself: could the spacecraft give us our first glimpse of interstellar space?



ISTOCK, NASA/JPL



Voyager 1 is our farthest man-made spacecraft; it is exploring a region of space that no emissary of Earth has been before

"NASA KNEW THAT THE VOYAGERS WOULD BE THE FIRST HUMAN-MADE OBJECTS TO PASS BEYOND THE SUN'S SPHERE OF INFLUENCE"

THE PALE BLUE Dot and Family Portrait images taken by Voyager 1 on Valentine's Day 1990 are among the most iconic from the mission. They highlight the scale of our home in the vastness of space. But they also represent the moment when the Voyager probes ended their exploration of the planets and began a new adventure, one that would take them into interstellar space.

After the Family Portrait, both probes were blinded. Their cameras were turned off permanently to save power and memory for the instruments needed to investigate the environment in the darkness beyond the Sun's grasp.

In the late 1960s when Voyager was being planned, the longest planetary mission had lasted less than three and a half years. As such, a mission capable of sustaining itself long enough to reach interstellar space was seen as little more than a pipe dream for the NASA engineers tasked with building the spacecraft. Yet at the beginning of 1990, Voyager 1 was around six billion km (40 AU) from the Sun, while Voyager 2 was a slightly closer but still substantial 4.6 billion km (31 AU) away.

They were travelling much faster than the then-more-distant Pioneer probes, so NASA knew that the Voyagers would be the first human-made objects to pass beyond the Sun's sphere of influence. In doing so, they would provide us with our first opportunity to study the outer Solar System environment and so the Voyager Interstellar Mission (VIM) was born.

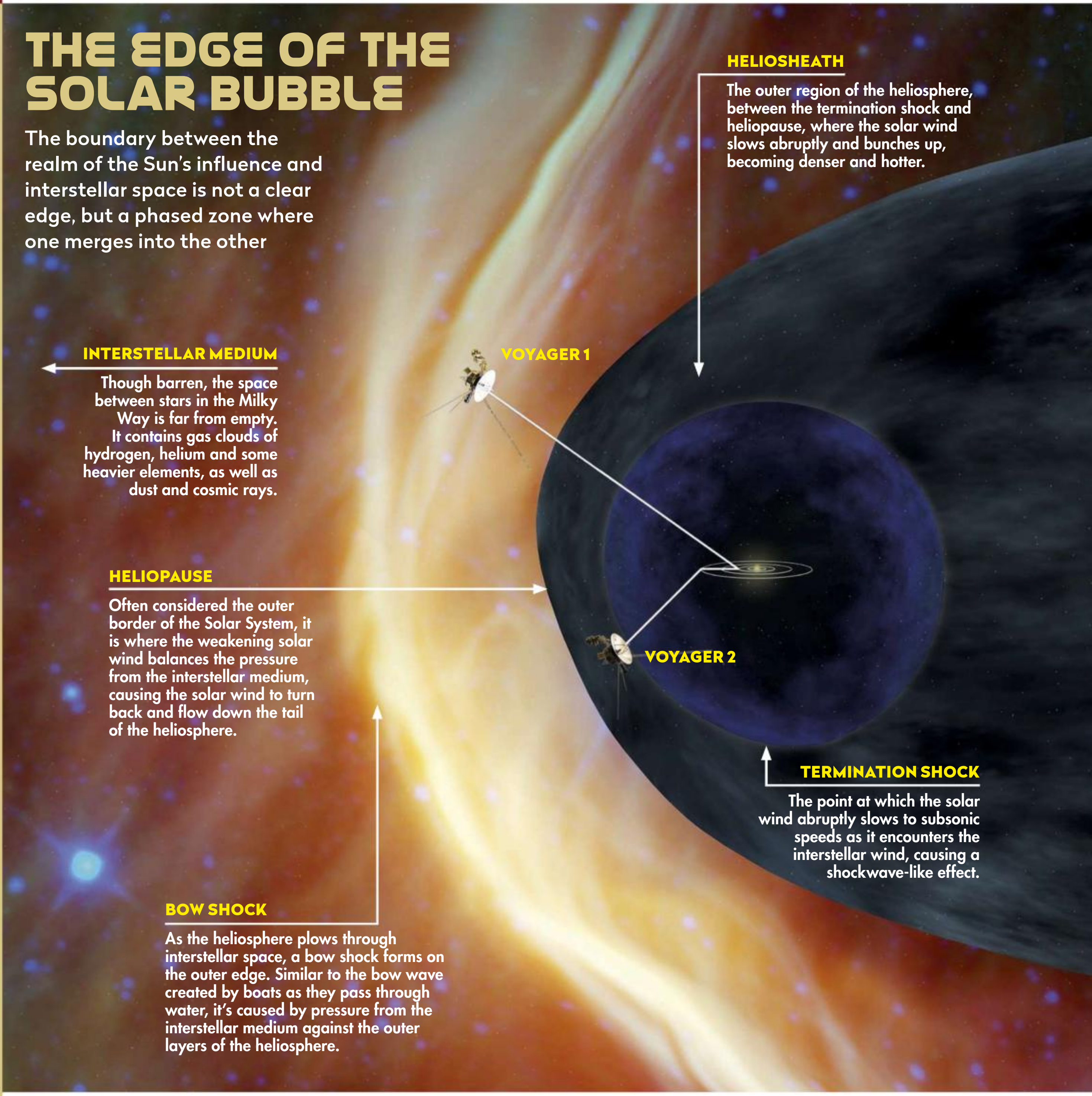
A long reach

The Sun's influence stretches far beyond the planets. When the two Voyager spacecraft began their interstellar mission, they were within reach of the Sun's magnetic field and the solar wind, a 'gust' of subatomic plasma particles released from its atmosphere.

The first phase of the Voyagers' interstellar mission lasted well over a decade, in ▷

THE EDGE OF THE SOLAR BUBBLE

The boundary between the realm of the Sun's influence and interstellar space is not a clear edge, but a phased zone where one merges into the other



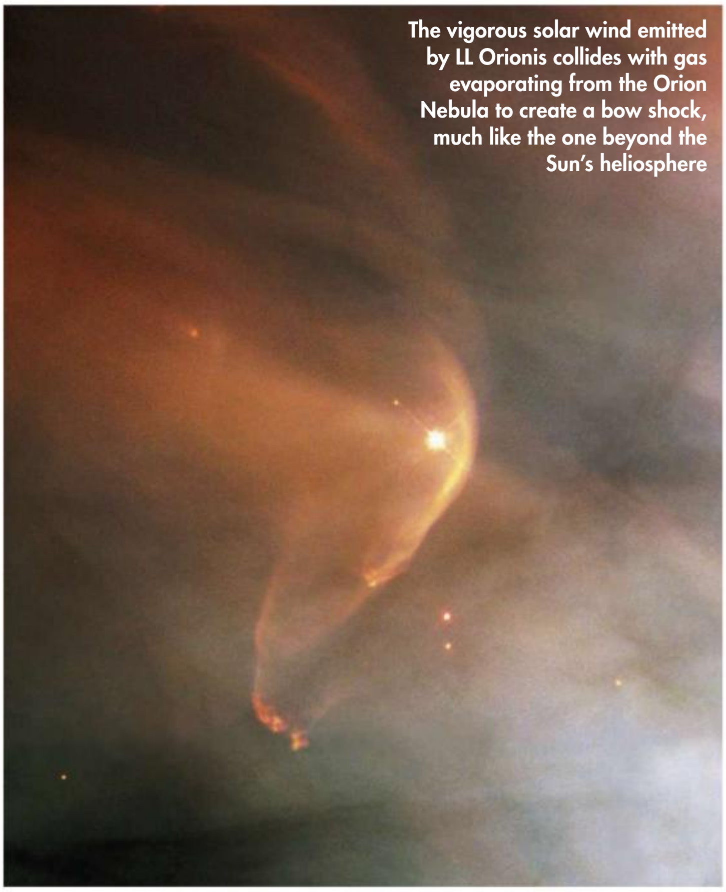
▷ which time the Pioneer 11 mission ended (its final transmission was sent in 1995) and Voyager 1 managed to overtake Pioneer 10 as human-made object furthest from the Sun (in 1998).

Despite covering a distance of roughly 3 AU per year, little changed for the Voyager spacecraft until mid-2002, when Voyager 1 – now 85 AU from the Sun – started to detect energetic ions and electrons. These particles suggested the probe was nearing a region known as the termination shock, where solar wind particles abruptly slow down and bunch up as they hit the interstellar medium.

Unfortunately, this was difficult to confirm because Voyager 1's plasma detector (the instrument best suited to measuring the solar wind) had stopped working in 1980 during its encounter with Saturn. As a result, the VIM team had to infer whether the spacecraft had reached the termination shock by using its other instruments.

Possible confirmation

Over the next two and half years, painstaking work was undertaken by the VIM team to indirectly measure the particles of the solar wind. Their efforts revealed that the wind's intensity steadily rose until December 2004, when there was a large, sustained spike in Voyager 1's


The vigorous solar wind emitted by LL Orionis collides with gas evaporating from the Orion Nebula to create a bow shock, much like the one beyond the Sun's heliosphere

NASA/JPL-CALTEHCH, NASA AND THE HUBBLE HERITAGE TEAM (STSCI/AURA)

readings. The spacecraft was 94 AU from the Sun, but the intensity of the readings was equal to those taken when it was a mere 15 AU from the Sun in 1982. It meant the VIM team could finally announce that the probe had reached the first major boundary of the Solar System.

> "VOYAGER 1 AND 2'S CROSSING POINTS PROVED A LONG-LIVED THEORY THAT THE SOLAR SYSTEM IS NOT PERFECTLY ROUND, BUT ACTUALLY SQUASHED"

Farther behind but with its solar-wind detector intact, and with scientists lucky enough to be listening at the crucial moment, Voyager 2 crossed the termination shock almost three years later on 30 August 2007 – although this time the crossing occurred at a distance of 84 AU from the Sun.

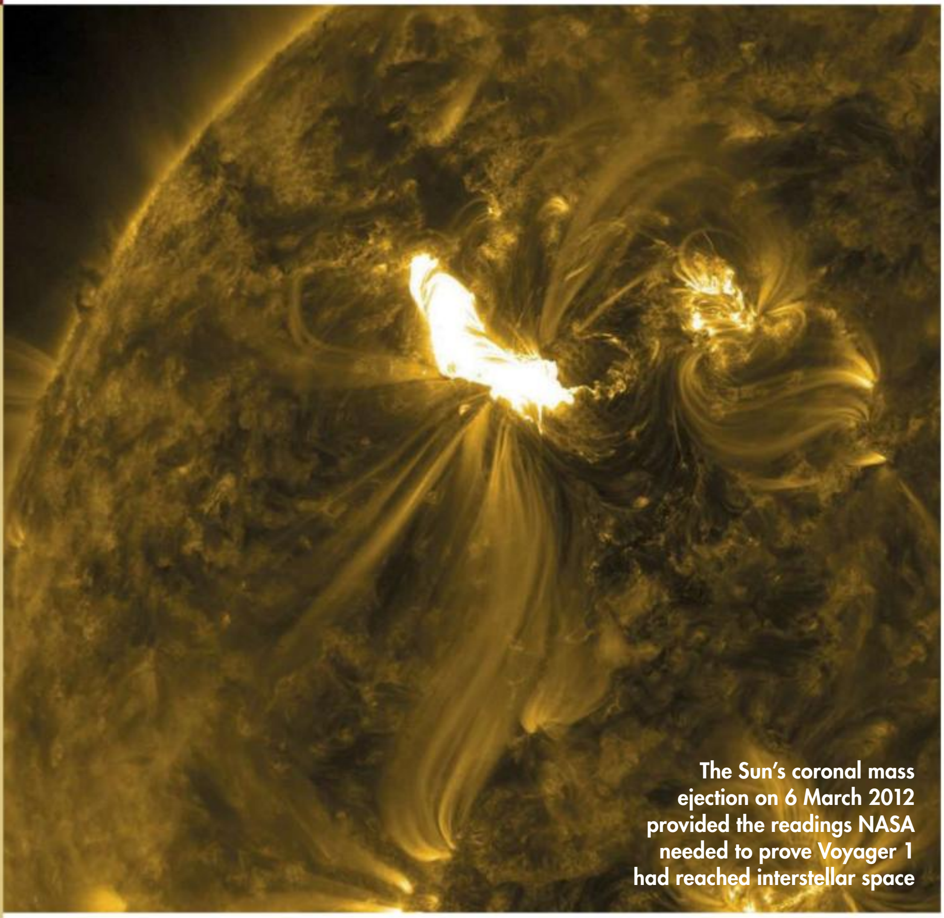
This crucial 10 AU difference between the probes' crossings proved a long-lived theory that the Solar System is not perfectly round but actually squashed. Where Voyager 2 crossed the termination shock, the local interstellar magnetic field pushes it closer in towards the Sun. Voyager 2 also revealed that the termination shock is not a normal shock wave at all. In a normal shockwave, fast-moving material slows down and forms a denser, hotter region as it encounters an obstacle. In contrast, Voyager 2 found itself in one that was much colder than predicted. One possible explanation for this is that energy is transferred to cosmic ray particles that are accelerated to high speeds at the shock.

Slowing the decline

After passing through the termination shock and entering the heliosheath, where the solar wind slows down dramatically and becomes turbulent, the VIM team faced a new challenge.

By August 2007, the Voyagers were 30 years old. During their lifetimes, they had each relied on three plutonium-fuelled radioisotope thermoelectric generators (RTGs) as a power source. At launch, the RTGs provided 470 Watts of 30 Volt DC power, but as the plutonium's radioactivity decayed, power had been steadily declining at 4 Watts per year.

In an effort to prolong their working lives, the planetary radio astronomy investigation instrument was disabled on both probes, as was the infrared spectrometer on Voyager 2. The power was also cut on various non-essential systems. ▹



The Sun's coronal mass ejection on 6 March 2012 provided the readings NASA needed to prove Voyager 1 had reached interstellar space

▹ Yet the mission continued and in July 2012, at a distance of 122 AU, Voyager 1 hit its second Solar System boundary: the heliopause. It's the point at which the wind and magnetic field no longer come from the Sun, but from nearby supernovae and the Milky Way Galaxy, respectively. At least, that's what the VIM team thought, because the same difficulty that blighted the termination shock announcement faced them once again at the heliopause: the plasma detector wasn't working.

The crossing

To try and confirm when they hit the boundary, the VIM team relied on Voyager 1's cosmic ray and low-energy charged particle instruments. Their reasoning was that cosmic rays from the Sun (solar wind particles that leak out of the termination shock, become ionised and are sped up to as much as five per cent of the speed of light) fill the heliosheath uniformly. Hence, they would appear at a constant intensity that could be measured. When Voyager 1 hit the boundary, it was expected that these ions would escape into interstellar space and the intensity would plummet.

This did indeed happen, but a few days later the intensity rose again. Three weeks later the intensity dipped even further and again came back.

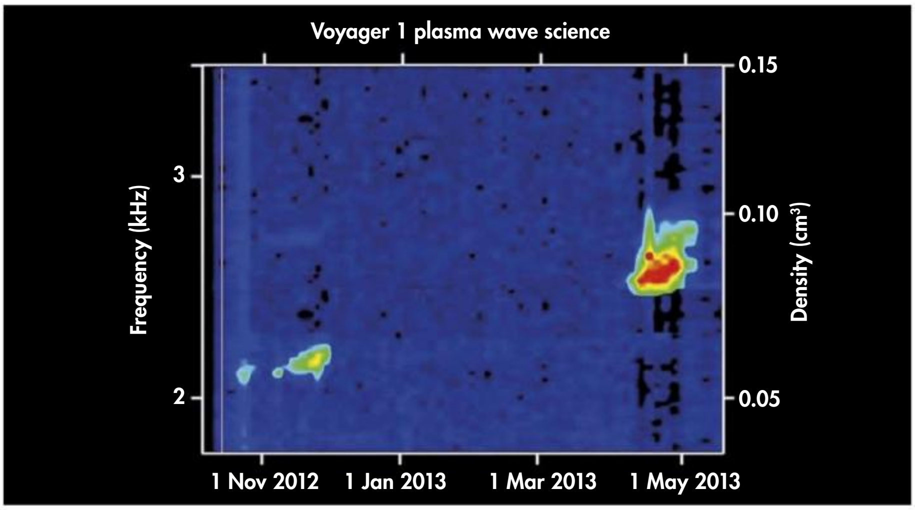
"THE PLASMA AROUND THE SPACECRAFT WAS VIBRATING LIKE A GUITAR STRING"

Finally, on 25 August 2012 their intensity dipped by 90 per cent and has not risen again since. On the same day, the intensity of a different set of cosmic rays from the Milky Way, which are far more energetic than those from the Sun, dramatically increased, adding further evidence that Voyager 1 had entered interstellar space.

Making sure

To be certain though, the VIM team needed a way of measuring the spacecraft's plasma environment. A coronal mass ejection (a massive burst of solar wind and magnetic field from the Sun) that erupted in March 2012 provided just what they needed. On 9 April 2013, after an anxious 13-month wait for the burst to reach the spacecraft, Voyager 1's instruments picked up the signal. It showed that the plasma around the spacecraft was vibrating like a guitar string.

These vibrations could be turned into sounds and their pitch allowed scientists to determine the plasma's density. To the VIM team's delight, the probe's environment was revealed to be 40 times denser than had been observed inside the heliosphere. It was exactly the density they had expected to see in interstellar space and finally ▹

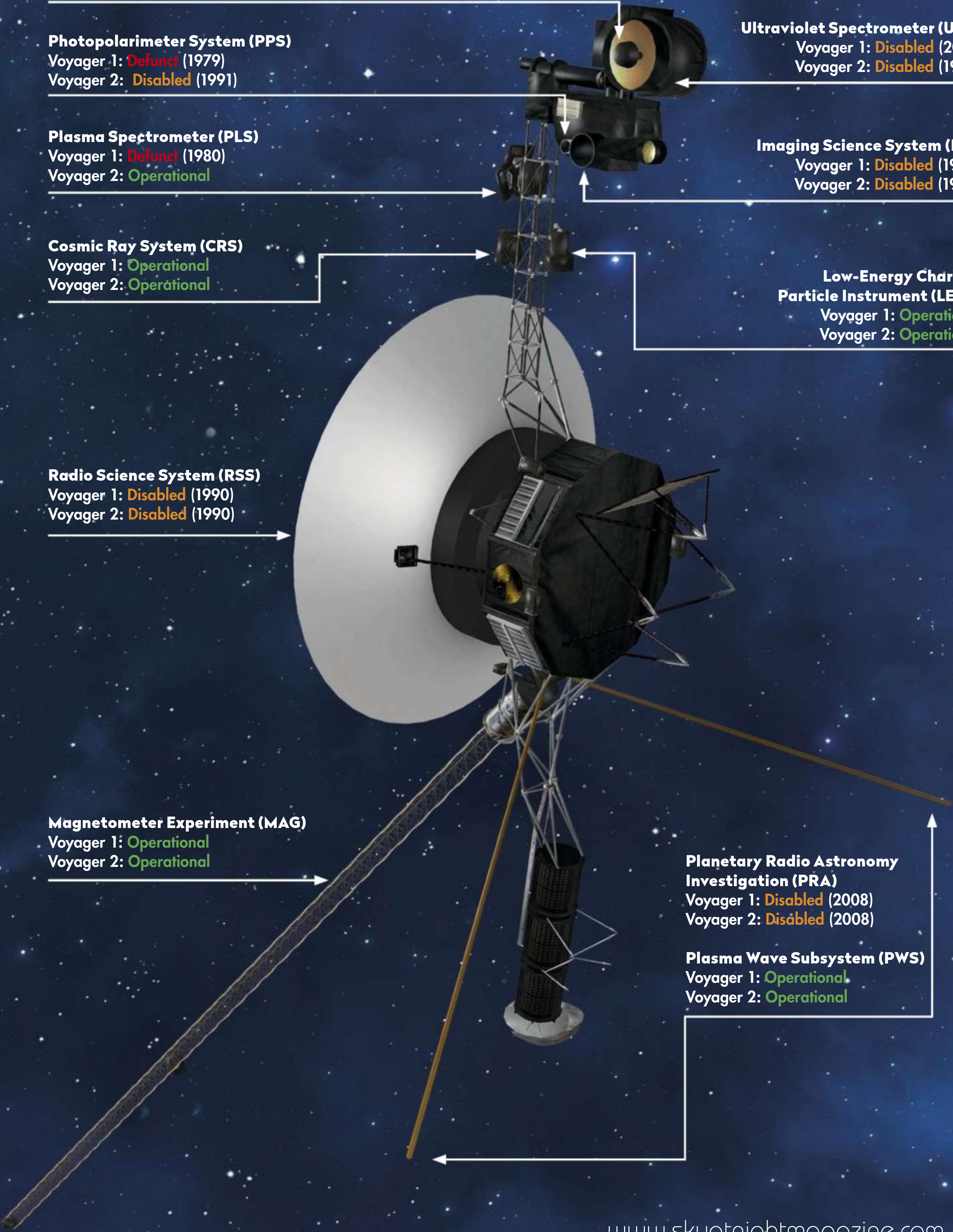


△ Voyager 1's increasing plasma readings indicated the probe was beyond the heliosphere

NASA/SDO/AIA, NASA/JPL-CALTECH/UNIVERSITY OF IOWA, ILLUSTRATION BY MARK GARLICK

THE VOYAGERS' SLOW SHUTDOWN

After 40 years in space, the Voyagers are showing some wear and tear. Some of their instruments have failed, others have been intentionally disabled and those that remain will be shut down in phases as the power of the probes' batteries continues to fade



Infrared Radiometer/Interferometer/Spectrometer (IRIS)
Voyager 1: Disabled (1998)
Voyager 2: Disabled (2007)

Photopolarimeter System (PPS)
Voyager 1: Defunct (1979)
Voyager 2: Disabled (1991)

Plasma Spectrometer (PLS)
Voyager 1: Defunct (1980)
Voyager 2: Operational

Cosmic Ray System (CRS)
Voyager 1: Operational
Voyager 2: Operational

Radio Science System (RSS)
Voyager 1: Disabled (1990)
Voyager 2: Disabled (1990)

Magnetometer Experiment (MAG)
Voyager 1: Operational
Voyager 2: Operational

Ultraviolet Spectrometer (UVS)
Voyager 1: Disabled (2016)
Voyager 2: Disabled (1998)

Imaging Science System (ISS)
Voyager 1: Disabled (1990)
Voyager 2: Disabled (1990)

Low-Energy Charged Particle Instrument (LECP)
Voyager 1: Operational
Voyager 2: Operational

Planetary Radio Astronomy Investigation (PRA)
Voyager 1: Disabled (2008)
Voyager 2: Disabled (2008)

Plasma Wave Subsystem (PWS)
Voyager 1: Operational
Voyager 2: Operational

▷ allowed the team to claim that Voyager 1 was humanity's first interstellar traveller.

Not only was this a moment to mark in the history of space exploration, it also provided an insight into our tenuous existence. Voyager 1 had revealed how important the heliosphere is in protecting the Solar System, shielding us from more than 75 per cent of DNA- and ozone-destroying galactic cosmic rays.

A clearer crossing

Behind Voyager 1 and travelling roughly 10 per cent slower, Voyager 2 remains in the heliosheath. It is expected to hit the heliopause – the boundary between the solar wind and the interstellar medium – in one or two years' time. With its working plasma instrument it should be far easier to conclusively say when Voyager 2 reaches the heliopause and also reveal details of how the solar wind turns in terms of its speed, density and temperature.

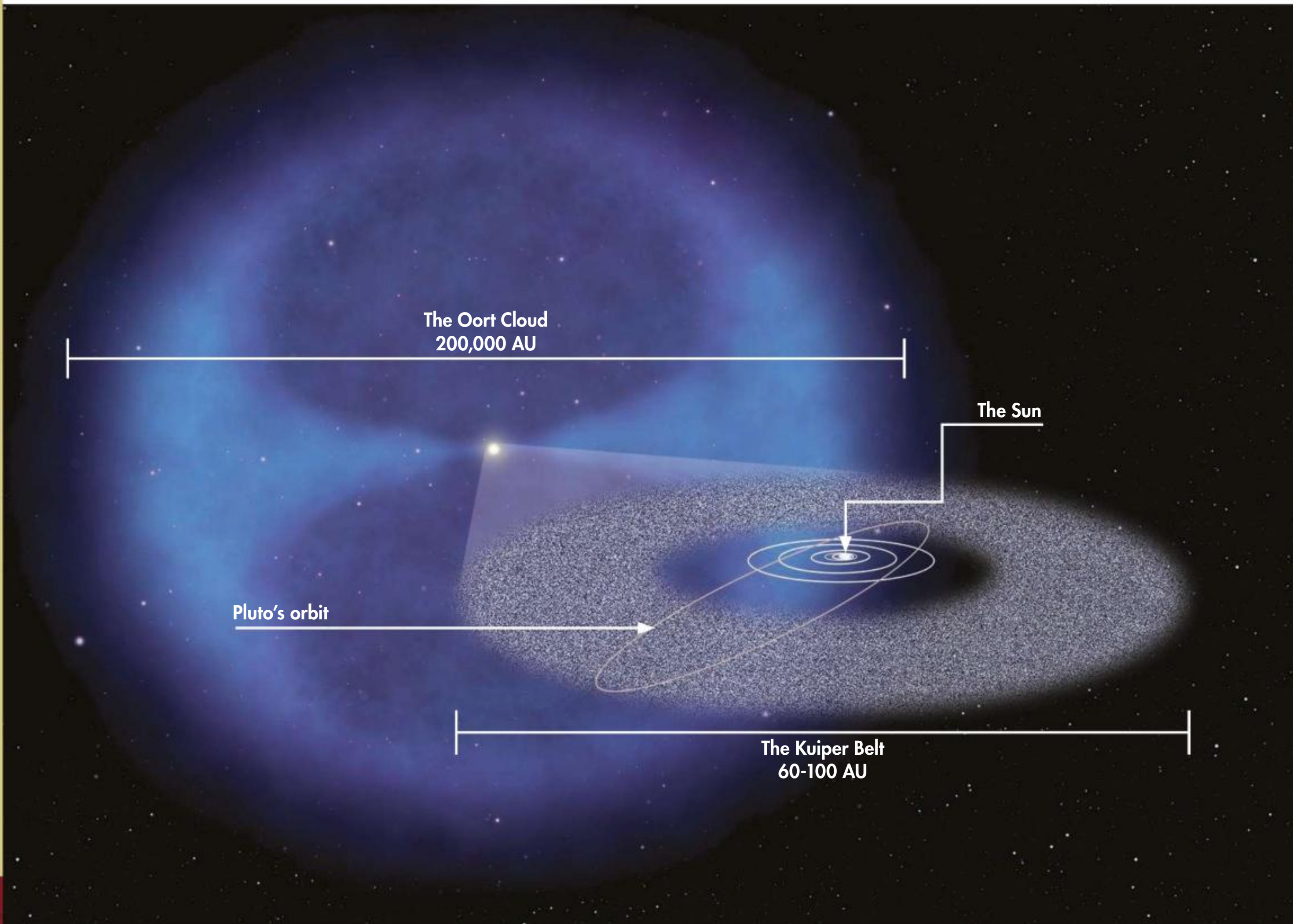
Today, Voyager 1's faint signals take around 17 hours to reach Earth because the probe is over 20 billion km away. At this unimaginable distance, and with the spacecraft having passed through the heliopause years ago, it would be easy to assume that there is consensus in the scientific community that it is indeed in interstellar space. But this is not the case.

Pluto, 3.5 times closer to the Sun than Voyager, was once thought to be where our Solar System ends and interstellar space begins, but the Sun's gravity stretches far beyond the former ninth planet or even the 30 AU-distant Kuiper Belt. As a result, some believe that the Oort Cloud – the birthplace of comets theoretically predicted to envelop the Solar System some 5,000–100,000 AU away – is the boundary. At the earliest, Voyager 1 might reach the Oort Cloud in 300 years.

"IN 2020, THE REMAINING SCIENCE INSTRUMENTS WILL NEED TO START BEING SHUTDOWN"

The final steps

Others suggest the point at which the Sun no longer has a magnetic influence is where the Solar System ends. This invisible, magnetic line in the sand is subtly different from the heliopause, because although the solar wind is halted at the heliopause boundary, it surprisingly still influences the nearby magnetic field. As a result, the probe continues to



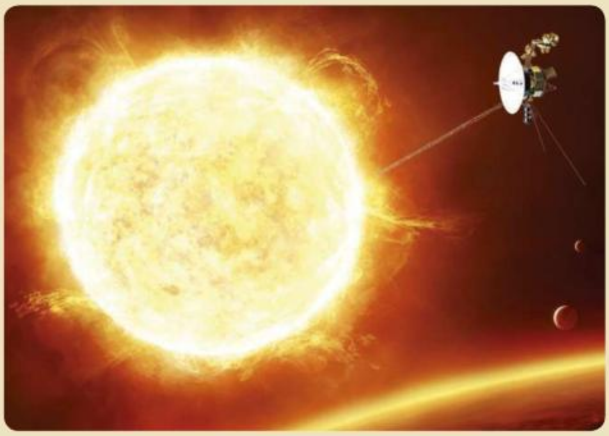
▽ **Exactly where interstellar space begins is debated. Pluto's orbit, the Kuiper Belt and the Oort Cloud have all been suggested as candidates for the boundary**

WHERE NEXT FOR THE VOYAGERS?

◁ THE OORT CLOUD

Voyager 1 & Voyager 2; 300 years' time

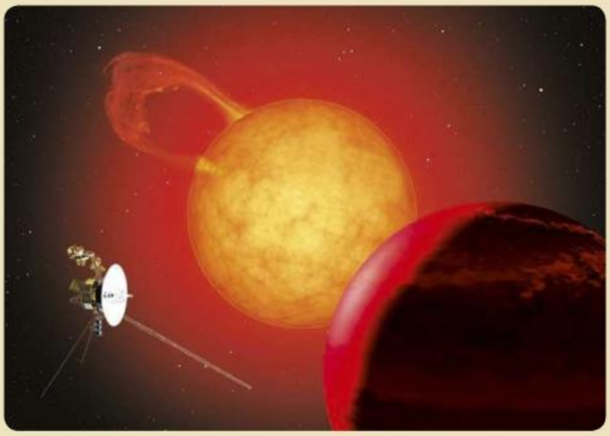
Though never directly observed, a shell of billions of icy objects known as the Oort Cloud is thought to surround the Solar System. It's so vast, that it's thought that the Voyagers could take 40,000 years to pass through it.



GLIESE 445 ▷

Voyager 1; 40,000 years' time

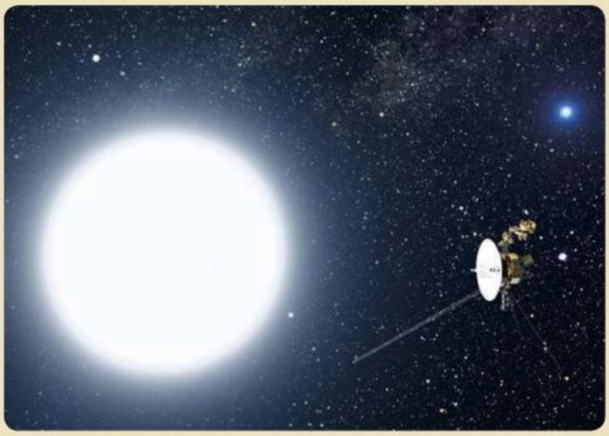
Currently 17.6 lightyears from the Sun, Gliese 445 is a main sequence star in Camelopardalis. It's moving towards Earth and, at the point Voyager 1 passes by, it should be just about visible to the naked eye.



◁ ROSS 248

Voyager 2; 40,000 years' time

Ross 248, 10.3 lightyears away, is a dim red dwarf star that spits out relatively frequent, large flares. There's some (inconclusive) evidence that this star has a large Jupiter or brown-dwarf-sized companion.



SIRIUS (ALPHA CANIS MAJORIS) ▷

Voyager 2; 296,000 years' time

Voyager 2 will eventually pass the brightest star in the night sky, which is in fact a two-star system, consisting of a main sequence star (Sirius A) and a companion white dwarf (Sirius B). It's 8.6 lightyears from Earth.

transmit peculiar magnetic field readings. To show that Voyager 1 is truly in the 'pristine' interstellar medium, occasional disturbances from waves of magnetism from the Sun need to cease and the solar-wind-influenced magnetic field needs to turn roughly 40°. But detailed investigations have revealed that this influence is waning and the field is slowly turning.

In eight years' time, it should be pointing in the right direction, meaning that, for those who sign up to the magnetic boundary interpretation, Voyager 1 will have finally and undeniably reached interstellar space.

Unfortunately, this is likely to occur at about the same time that Voyager 1 and 2 will stop communicating with Earth. In 2020, the remaining science instruments will need to start being shutdown to save power in order to last until 2025, when the final science instrument will be turned off. At that point both probes will fall silent, except for periodically emitting faint electronic blips to indicate each of their positions for a few more years to come.

In these eight remaining years of useful science, the VIM team will be rushing to learn as much as possible about the outer reaches of the Solar System. Key aims include: understanding how the Sun's magnetic field is wrapped around the heliosphere, by watching it peel open as the probes travel farther away; shedding light on the interstellar wind, by listening to plasma oscillations caused by coronal mass ejections; and elucidating the interaction of the Sun's atmosphere with winds in interstellar space. Ⓥ

OORT CLOUD: MARK GARLICK, ESA_AOES MEDIALAB, ISTOCK, NASA, NASA/ESA AND G. BACON (STSCI)

THE VOICES OF VOYAGER

Suzanne Dodd

Suzanne Dodd joined the Voyager mission straight from college, working as an engineer on the Uranus and Neptune encounters. She left in 1990 to work on other projects, returning some 20 years later to oversee the Voyager Interstellar Mission

Interviewed by: Elizabeth Pearson

Voyager was my first job after college. It'll probably be close to my last job, if it lasts for 10 more years.
I was hired before the Uranus flyby and stayed on for the Neptune flyby. Then, in 1990, I went off and did various missions – including Cassini, the Mars Observer and Spitzer. I never thought that when I left the mission in 1990 it would still be going 20 years later and that I'd be able to come back as a project manager.

There were times when we thought they'd cancel us.
In the early 2000s, they thought nothing was going to come of this and that we'd never reach interstellar space because we didn't know where the heliopause was. I wasn't on the project at that time, but it went all the way up to making charts for a termination review. They never had the review, but they were preparing for it. We still have to ask for funding every two to three years.

It wasn't until the mid 2000s that we began to think the probes might be getting close to interstellar space.
The start of something interesting happening – in terms of the interstellar mission – was when Voyager crossed the termination shock; when particles went from ultrasonic to subsonic. That happened in the mid 2000s for both probes. Voyager 1 crossed in December 2004, after 14 years of travelling between Neptune and the termination shock. For Voyager 2 it happened in August 2007. That started to get interesting. In 2012 Voyager 1 saw a really rapid drop of particles coming from the Sun. Along with that, we saw a rather large increase in particles from interstellar space and we were able to get some measurements on the plasma that we couldn't take until about eight months later. When we put those two pieces together we could backtrack and say 25 August 2012 was when Voyager 1 crossed the heliopause and started travelling in interstellar space.

> **"WE LOSE 4 WATTS A YEAR FROM OUR NUCLEAR POWER SOURCE, SO WE HAVE TO MAKE PLANS FOR TURNING THINGS OFF"**

The first indication that Voyager 1 was in interstellar space came from the cosmic ray spectrometer.
The particles coming from the Sun dropped way off at the same time that we got an increase in particles coming from interstellar space. That was the first hint, but because Voyager 1 doesn't have a working plasma instrument on board (it broke during the planetary encounter phase) we couldn't see that the density of the plasma was increasing, which was what was predicted to happen.

Voyager 2 has that instrument, so when it reaches interstellar space we'll have a direct measurement of the plasma.
For Voyager 1, the way we discovered it had reached interstellar space was through a solar flare that was emitted 13 months earlier and just happened to be travelling in the direction of Voyager 1. The solar flare vibrated the plasma and our radio instrument could detect that. Putting that piece of data together with when solar flares

NASA/JPL-CALTECH

△ **Suzanne with a memento from her first stint with Voyager – a sheet that shows the timeline of commands for Voyager 2 during its close approach to Neptune on 25 August 1989**

were happening, along with the particle drop in the plasma, told us that the spacecraft was in a more dense plasma, which would be a marker for being in interstellar space.

We also expected to see a shape change in magnetic field direction – but we didn't. That's based on the fact the magnetic field of interstellar space would be coming from a steeper incline. We still haven't seen that. There are a lot of theories about why we didn't see that. We saw a subtle change in direction but not a big one.

Our best guess is that Voyager 2 will be in interstellar space within five years, but I say that every year! Voyager 2 is in the heliosheath, between the termination shock and the heliopause. It's already been thicker for Voyager 2 than it was for Voyager 1. If you look at solar cycles, the Sun's activity is decreasing, so the distance the heliosphere stretches out to should be decreasing a little bit because the pressure from the Sun has reduced. That gives Voyager 2 a chance to cross a little bit sooner.

There was a lot of discussion to consider whether we had actually crossed into interstellar space or not. It almost came down to a vote. You could see the drop in charged particles, so that was very exciting. This was humanity's first crossing into interstellar space. We didn't have any of the other information to go with it then. Once we got the data back on the plasma, the Voyager science team along with some non-Voyager scientists who were considered experts in the field had several discussions about it.

There are some people who had various models suggesting that we weren't in interstellar space – we were just seeing the ripple on the shoreline, rather than being out in the ocean. But those models have since been debunked as the plasma has been pretty steady. So after five years I think we can say we really are in interstellar space. But it wasn't like seeing a picture.

The probes remain very healthy for senior citizens. We mostly monitor the power now. We lose 4 Watts a year from our nuclear power source, so we have to make plans for turning things off. We might turn off a heater and eventually, in a couple more years, we'll be turning off instruments because we don't have enough power to keep them all on. ▷

▷ We have to be careful about what we turn off though, because the probes are in a place that's very cold.
We need to keep our propellant lines warm so that the hydrazine doesn't freeze, because we need the thrusters to keep the Voyagers antennas pointed towards Earth. If we don't, the probes will eventually drift and we'll lose the antenna pointings. So we're very careful about conserving both power and the thermal condition on each of the spacecraft.

My goal is to have a 50th anniversary party for the Voyager probes.
We hope to get at least 10 more years out of them. It takes work though. As engineers, we have to manage trades between all of the functioning systems as the power gradually runs out. We'll operate them until we no longer get a signal from the probes. If we don't hear anything it would likely mean that we don't have enough power to operate the transmitter anymore. We'll try a lot of things to recover the spacecraft, but at some point there'll be nothing left to try.

I think they're great ambassadors for Earth, in particular, because they carry the Golden Record.
It gets a lot of romancing and it lends gravity to the mission that we have this record that will tell whoever finds it about the planet Earth and the people on it – what music we like as well as certain images and sounds. It's interesting to think about what will happen to that record in say 500 million years. Where will it be? Who will have found it? What other beings might have found it? What will they think of us? People are interested in that.

Voyager has always been lucky because it's always been popular with the general public.
People are always interested in it and want to see how far it will go. When you talk about missions that last decades there's a lot of opportunity to cancel them or stop funding them for whatever reasons. It takes a lot of political willpower to keep these missions going.

Suzanne presented the 5am edition of JPL's *Voyager Update* programme on 25 August 1989 to share the Neptune encounter with the public

That said, there are always concerns because each of the spacecraft has a different set of ailments.
There are concerns now that we're playing with low power margins. The mission is so old it's hard to go back. A fair number of the early engineers have passed on, so you can't ask them how something was designed, or how much margin they put in their design numbers. Does it really take 12 Watts or does it take 10 Watts and there's 2 Watts of margin on it? Now those margins are very, very important. Every day we make decisions and we cross our fingers and hope that they don't result in a nasty surprise, but do what we think they're going to do.

"WE'LL TRY A LOT OF THINGS TO RECOVER THE SPACECRAFT, BUT AT SOME POINT THERE'LL BE NOTHING LEFT TO TRY."

When I first came back on in 2011, we had a redundant side of heaters in one of the propellant lines and we decided we needed to turn that off to save power. It was a risky decision.
The question was: do we turn off the side we haven't used for 35 years or do we turn off the side that we're on because it's getting beyond its lifetime, even though we've never used the other side. We ended up deciding to switch to the side that had never been used because that would give us the longest lifetime going forward, but there's always that question of if you switch and it doesn't work... what have you done? We designed it so that we could switch there and if it wasn't working we could switch back to the other side. There was a certain philosophy of 'don't tamper with what's working on a spacecraft'. But it all worked and it all worked well. Ⓥ

△ During the *Voyager Update* Suzanne was able to show viewers images of Triton that had been taken just a few hours before broadcast

NASA/JPL X 2

PHASE IV A GRAND LEGACY

Voyager 1 is now over 20.7 billion km from Earth, roughly 138 times farther away from our planet than the Sun, forging ahead into interstellar space. Voyager 2, approximately 17.1 billion km away from our parent star, is still within the heliosphere; it's expected to go interstellar in the next few years. The probes will continue on, analysing this unexplored territory so far from home, until their plutonium batteries finally run out, but the Voyager legacy will go on. This mission has changed the way we think about the Solar System, paved the way for later spacecraft and, in the Golden Records, will forever carry a glimpse of Earth as it was in 1977 in the cosmos. And who knows? Maybe another species will find that sliver of our civilisation and come looking for the descendants of the people who sent it out into the stars all those years ago.

MARK GARLICK

Alone in the dark: Voyager 1 has passed beyond the boundary of our Solar System but its journey continues into interstellar space

The success of Voyager helped shape subsequent spacecraft and mission design

Lessons from the Voyage

Words: Dr James Green

We asked Dr James Green, director of planetary science at NASA, about the lasting influence of the Voyager programme. Here he explains how the probes went on to inspire the missions that followed – and how part of the Voyager legacy remains unfulfilled

VOYAGER WILL BE remembered as one of the greatest achievements in exploration. As you read this, the two Voyager probes are still operating and travelling where no spacecraft – or anything else touched by human hands – has ever gone before.

In August 2012, Voyager 1 left our planetary system and entered the mysterious region between the stars: interstellar space. Voyager 2 is expected to join its pioneering twin in the outer limits of the Sun's sphere of influence within a few years.

The Voyager mission not only transformed our knowledge of Jupiter, Saturn and their dozens of moons, it also gave us our first close-up look at the strange and wondrous planets Uranus and Neptune. In the 40 years since the two craft were launched into space, Voyager 1 has travelled more than 20 billion km, while Voyager 2 has hit the 17 billion km mark. As we approach the 40th anniversary of the mission beginning, it's worth pausing to reflect on the vision that inspired Voyager, its greatest achievements and its enduring legacy – how the two probes and their findings inspired those that followed and how they continue to influence NASA missions today.

Ambassadorial duties

In my quieter moments, I think about a time, billions of years from now, when our Sun has become a red giant. By then, Earth will no longer be habitable and, in order to survive, humans will have 'left the nest' for another home, following a path forged by the Voyager missions.

It's humbling and inspiring to think that, even then, the Voyagers will still be Earth's ambassadors – each one a time capsule from an era when audacious explorers on our Pale Blue Dot reached out to the stars beyond our Solar System.

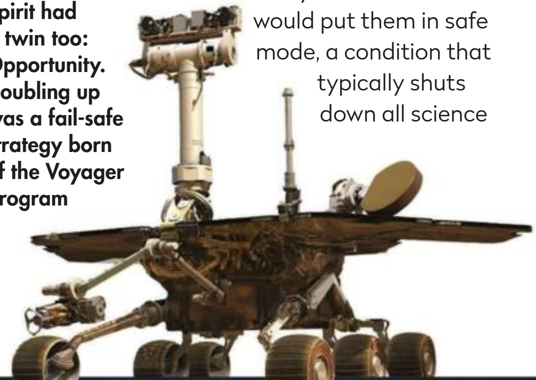
Not only has the science produced by the Voyager mission been captivating, the probes themselves captured the world's imagination by each carrying a greeting for extraterrestrial civilisations, in the form of the Golden Records.

While Pioneers 10 and 11 each carried small metal plaques detailing their origin and date of launch, the Voyagers' Golden Records were considerably more ambitious. The twin phonograph records brim with images and sounds that provide a snapshot of the diversity of life and culture on Earth to anyone that might discover them. As Carl Sagan noted, "The launching of this 'bottle' in the cosmic ocean says something very hopeful about life on this planet."

"BY HAVING TWO SPACECRAFT WE COULD INCREASE THE ODDS OF THE MISSION'S SUCCESS"

The Voyager mission was as ambitious as it gets. Collectively, the Voyagers visited more planets, discovered more moons and imaged more places than any other spacecraft in NASA history.

One of the questions I'm often asked is: why were there two Voyagers? Voyager was an early NASA mission, at a time when flight systems were known to suffer many anomalies that would put them in safe mode, a condition that typically shuts down all science instruments and looks for commands from Earth. Since the Voyager missions were flybys, anomalies that would require a lot of time to diagnose and correct could result in us missing an encounter and all the science that might derive from it. By having two spacecraft we could increase the odds of the mission's success. The same strategy was employed with the Mars exploration rovers, Spirit and Opportunity; having two rovers not only provides a redundancy and gives us a bigger margin for error.

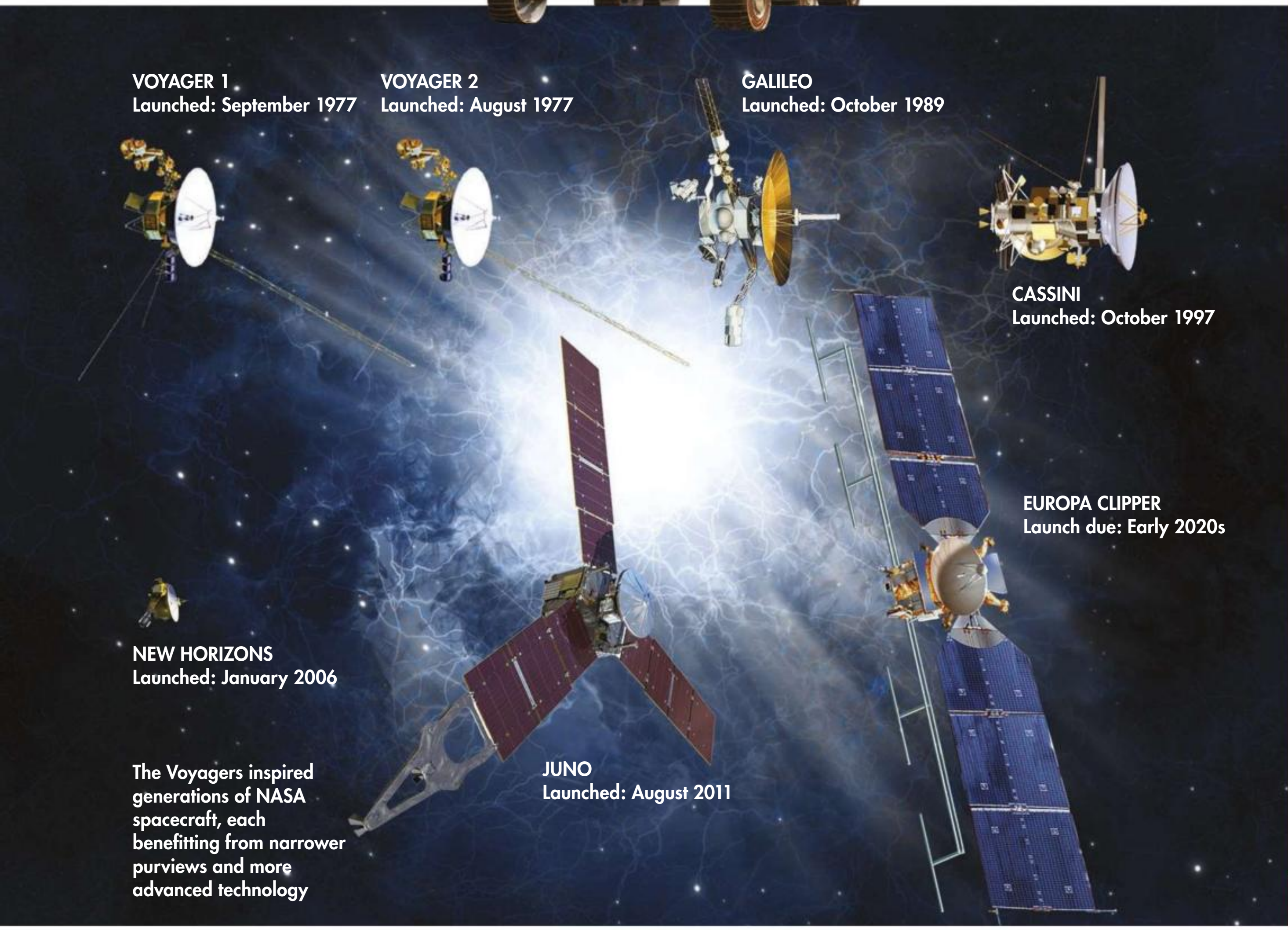


▷ Mars rover Spirit had a twin too: Opportunity. Doubling up was a fail-safe strategy born of the Voyager program

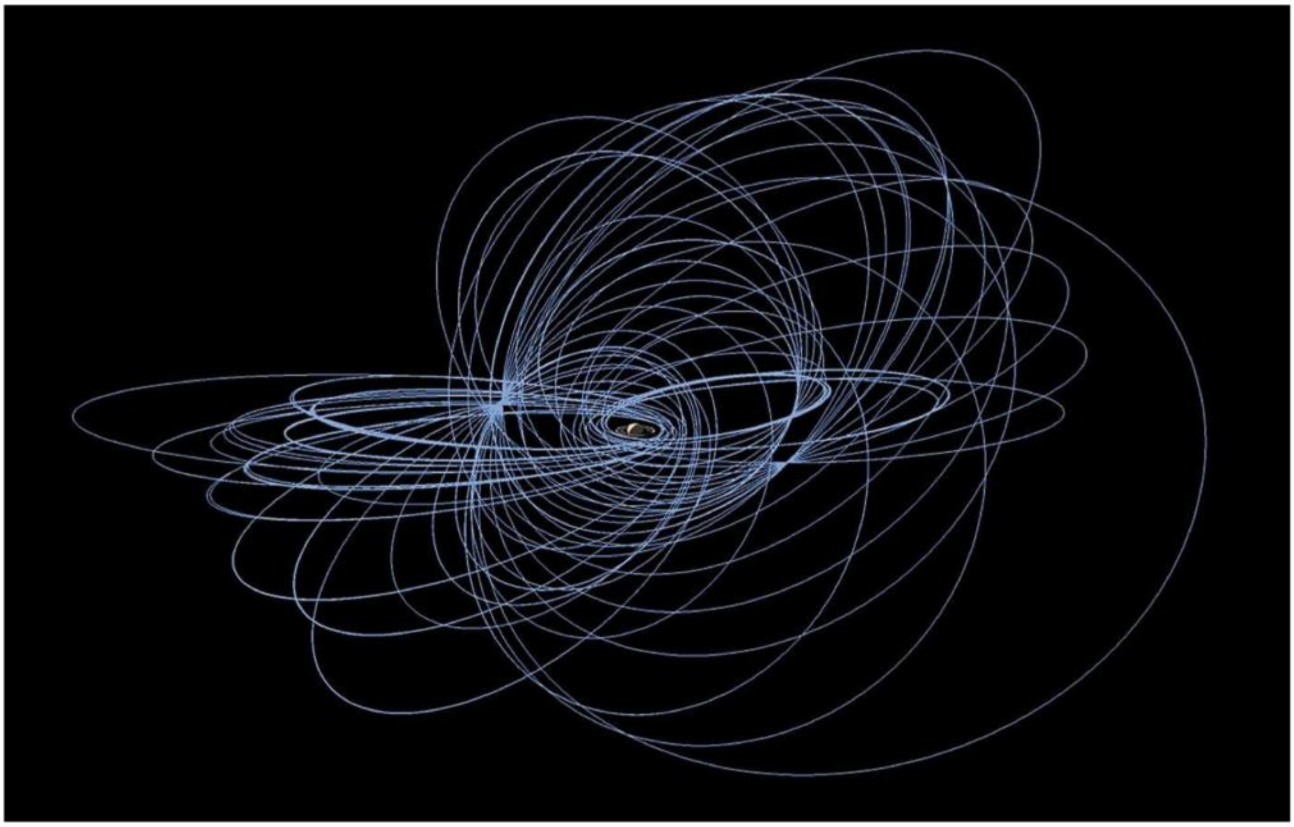
Always have a plan B

It quickly became clear that this 'one-two punch' strategy was the best one to adopt. Voyager 1's scan platform, the swivel that moves its cameras and instruments from side to side, became stuck for several weeks in 1978. The same platform ▹

NASA/JPL-CALTECH X 8, ISTOCK



The Voyagers inspired generations of NASA spacecraft, each benefitting from narrower purviews and more advanced technology



△ **The gravity-assist concept vital to Voyager also became an integral part of the Cassini mission; here you can see how the Saturn probe used them to repeatedly alter its orbit**

▷ became stuck on Voyager 2's as the spacecraft was pulling away from its closest approach with Saturn. Fortunately Voyager 2 produced fantastic results at Saturn despite the technical problems, but the anomalies reinforced the value of redundancy and having a second craft as a back-up.

As the first mission to take in the four giant planets in the outer Solar System, Voyager produced a bonanza of new science. Among the mission's accomplishments was the discovery of previously unknown moons and rings, the finding of active volcanoes on Io, Neptune's Great Dark Spot and powerful winds and erupting geysers on Triton.

The discoveries didn't stop with the probes' last planetary flybys though. In 2012 Voyager 1 became the first spacecraft to leave the heliosphere, delivering the first measurements of the full intensity of cosmic rays and the galactic magnetic field from interstellar space. Voyager 2, which, at the time of writing, has yet to cross the boundary into interstellar space, provided the first measurements of the solar wind termination shock.

When will Voyager 2 join its companion and begin tasting the solar winds from other stars? We hope it will join Voyager 1 in interstellar space within the next few years.

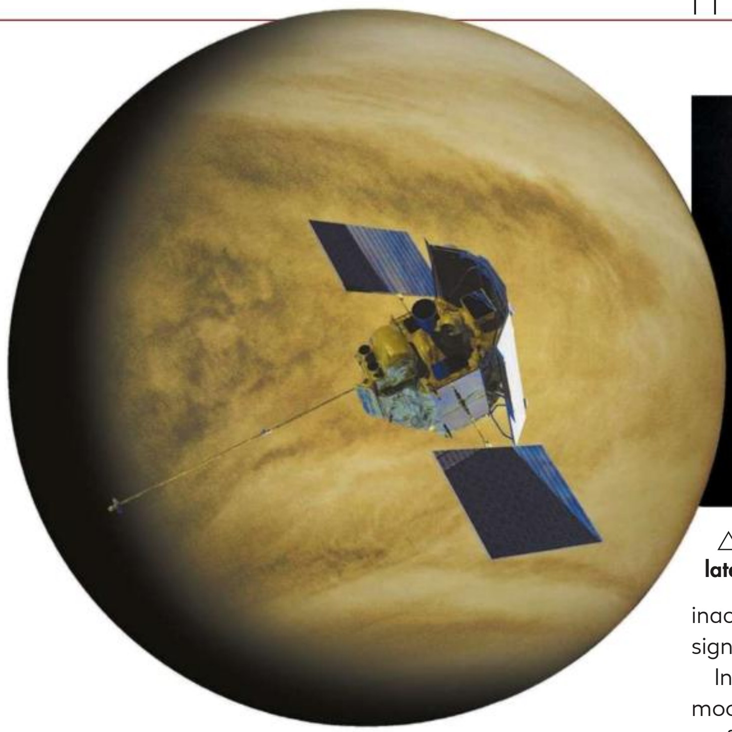
Scouting party

NASA's Planetary Science Division follows a paradigm for its exploration of the Solar System: flyby, orbit, land, rove and return samples. The Voyagers were – and in some ways continue to be – the scouting party and the instigators of this paradigm. They forged the way with flybys that have enabled us to take the next steps. Indeed, the Voyager spacecraft allowed us to survey what's out there and decide on our priorities for further study. As flyby missions, the Voyagers reinforced the planetary science paradigm, which has been, and continues to be, tremendously successful.

> "NASA's Planetary Science Division follows a paradigm: flyby, orbit, land, rove and return samples"

Critical to the success of the Voyagers' tours of the outer planets was the principle of gravity assist – using the mass of a planet or another object in space to alter the speed and trajectory of a spacecraft. Voyager 2 nailed the gravity assist to tour Jupiter, Saturn, Uranus and Neptune.

Since then, a number of missions have employed gravity assists to save fuel and dramatically reduce the amount of time it takes to reach destinations in the outer Solar System. New Horizons flew by Pluto two years ago with a boost from Jupiter's gravity. OSIRIS-REX, bound for asteroid 101955 Bennu, will get a gravity assist from Earth on 22 September to slingshot it more rapidly to its destination. On the other hand, mission planners for Messenger used gravity assist not to speed the spacecraft up, but to slow it down, so it could successfully enter Mercury's orbit. Messenger received assists at Earth and Venus, and three separate assists from Mercury itself before being placed into Mercury's orbit.



△ The Voyagers used gravity assists to speed up, but they can also be used to slow down; the Messenger probe to Mercury did just that as it passed Venus

△ Voyager 2's closest flyby was within 5,000km of Neptune; NASA was later able to program Cassini to fly at 15km above Enceladus (above)

NASA/JPL-CALTECH X 16

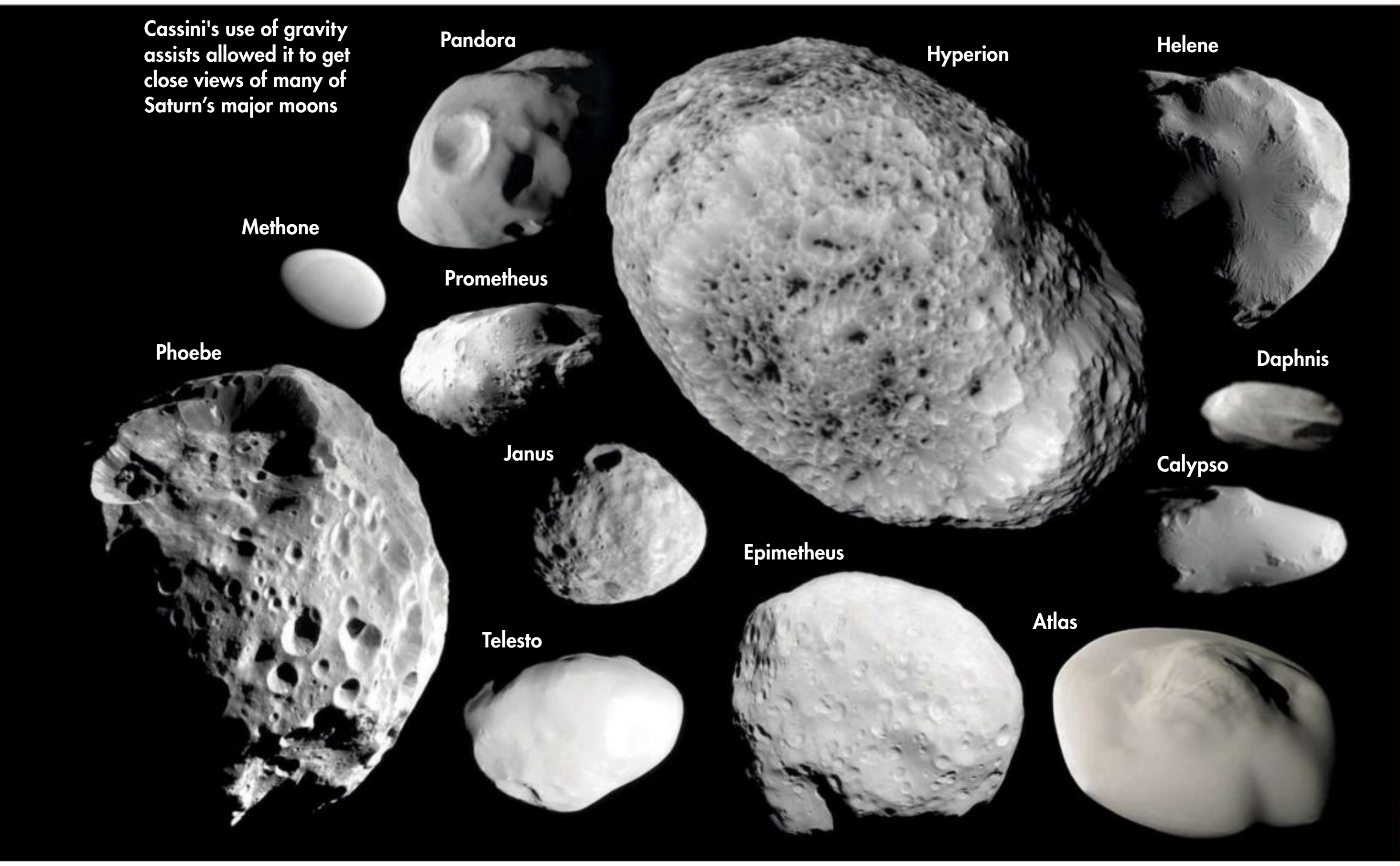
Cassini received two gravity assists at Venus and one each at Earth and Jupiter en route to Saturn. Cassini has mastered the art of gravity assists and uses close flybys of Saturn's largest moon Titan to continually reshape its orbit. This has allowed Cassini to obtain new views of many of the Saturnian moons that would be otherwise inaccessible, and produced significant scientific results.

In order to observe Neptune's moon Triton, Voyager 2 performed a very close flyby of Neptune that saw it pass about 5,000km above the planet's north polar cloud tops. This was the closest trajectory that any spacecraft had followed around one of the outer planets and initiated the development of precision trajectories for future flybys that would be even closer. One such flyby took Cassini through the plumes bursting up from Enceladus, bringing the probe within 15km of the moon's icy surface.

Raising the bar

While the Voyagers had limited programmable memory, it proved to be a critical resource that was used extensively and reprogrammed on a number of occasions. Consequently, all subsequent planetary missions were given large programmable memories.

The Voyagers set the agenda for future planetary exploration. ▷



Cassini's use of gravity assists allowed it to get close views of many of Saturn's major moons

The Juno spacecraft over Jupiter's south pole; the mission's main camera is a citizen science instrument, meaning anyone can download the data and process it into images

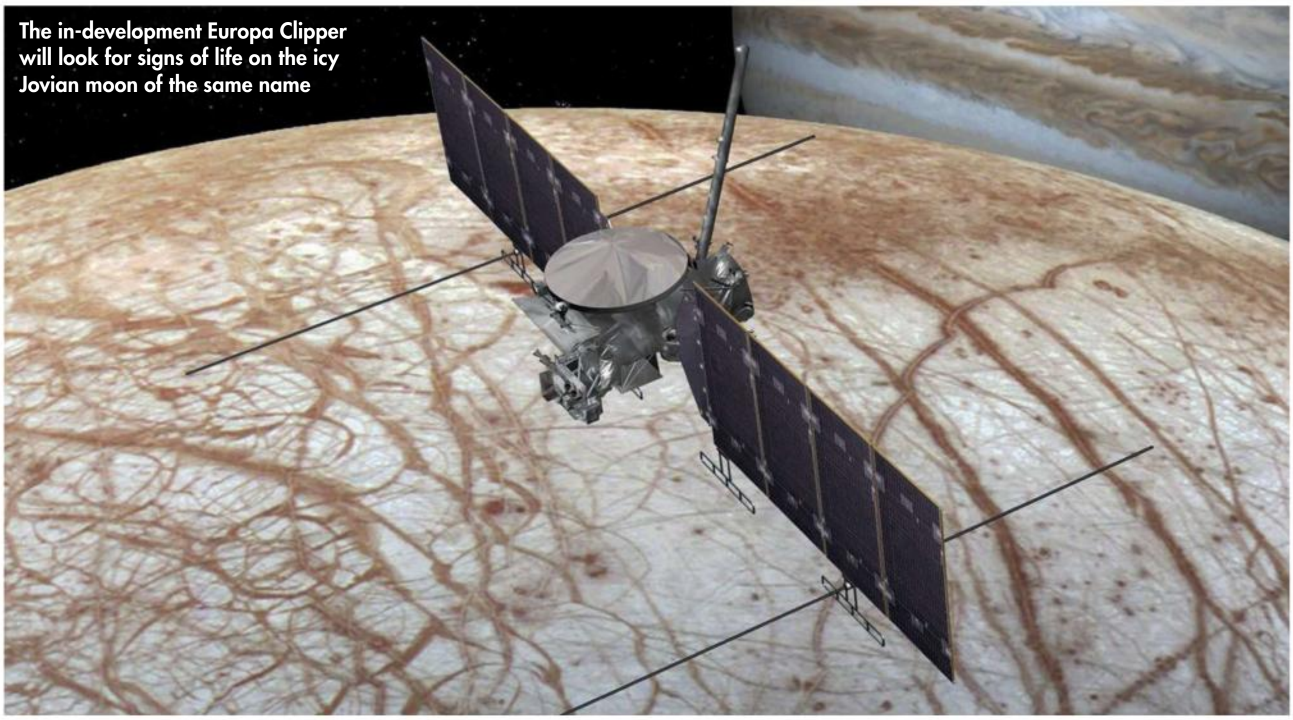
▹ Though they taught us much about the ice giants and their moons, the relatively primitive instruments of those missions, and the relatively low volume of data returned raised more questions than answers.

The Voyager mission was a case of the more we know, the more we appreciate what we need to learn. As such, Voyager paved the way for a number of NASA missions: both the Galileo and Juno missions to Jupiter, and the Cassini mission to Saturn with, appropriately, a gravity assist from Jupiter. The Europa Clipper mission, currently under development, is an orbiter that also builds on the experience gained from Voyager. Clipper is scheduled to launch in the early 2020s and a subsequent lander mission would be a logical successor that could explore the surface but also seek evidence of life beyond Earth.

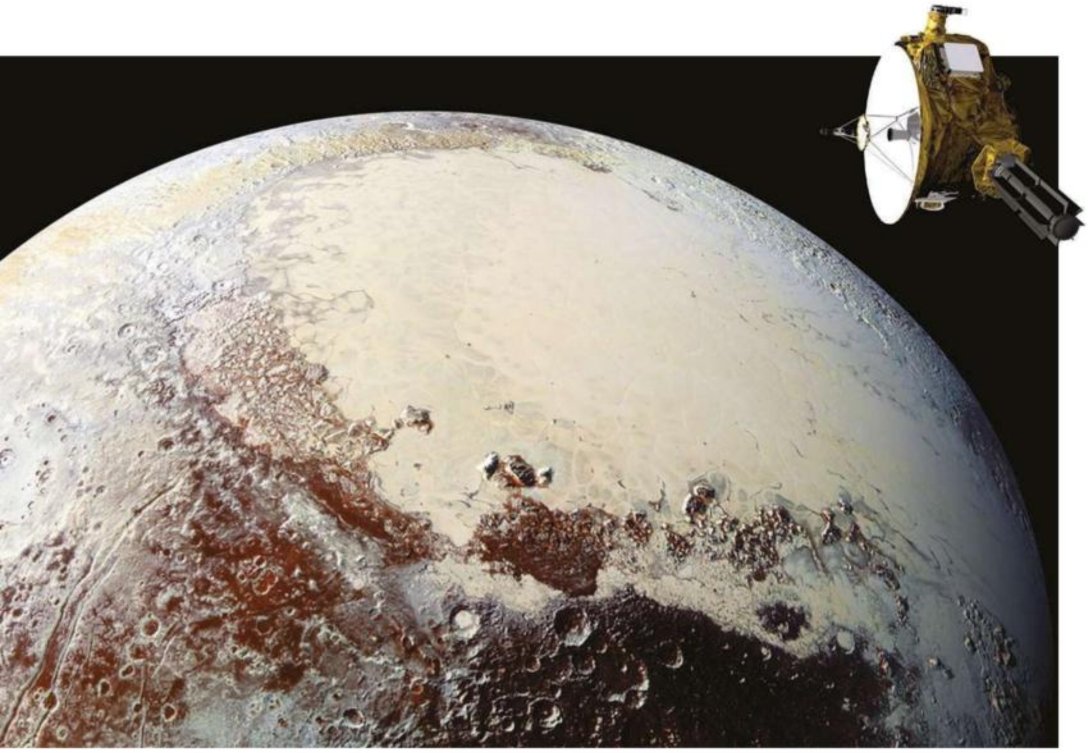
While the Voyagers' 'grand tours' didn't include Pluto, the New Horizons mission 'completed the set' with a flyby of Pluto in July of 2015 – aided once again by a gravity assist from Jupiter.

Return journeys

The ice giants Uranus and Neptune have remained unexplored since Voyager 2, but that could change in the years to come. The current Planetary Science Decadal Survey, which covers 2013–2022, lists a return to Uranus or Neptune as a top priority. A recent NASA-led pre-decadal survey explored a variety of potential mission concepts including orbiters,



The in-development Europa Clipper will look for signs of life on the icy Jovian moon of the same name



△ **The New Horizons probe fulfilled one of the Grand Tour's discarded objectives in 2015 – a brief visit to Pluto**

flybys and probes that would dive into Uranus's atmosphere to study its composition, possibly in the late 2020s.

Voyagers' discoveries also inspired a future mission to Jupiter's fascinating volcanic moon Io, with an Io Observer listed as one of the priorities in NASA's New Frontiers line of missions in 2003.

The Voyagers piqued our curiosity about the internal structures and compositions of the giant planets. We have much to learn about their polar regions and the origin of their magnetic fields. Very little is known about the magnetic fields and magnetospheres of Uranus and Neptune, aside from what was learned through the Voyager encounters more than two decades ago. But questions remain about their magnetosphere-ionosphere coupling processes and their link to the aurorae and moons.

Also puzzling are Neptune's heat flow, which is around 10 times larger than expected, and Uranus's, which is about three times greater than anticipated. But the causes are unknown. At Neptune, Voyager found nitrogen geysers erupting into the stratosphere from Triton's ultra-cold surface.

We also still have much to learn about the final frontier of the Solar System, so visiting the heliopause with a more capable mission is on my bucket list.

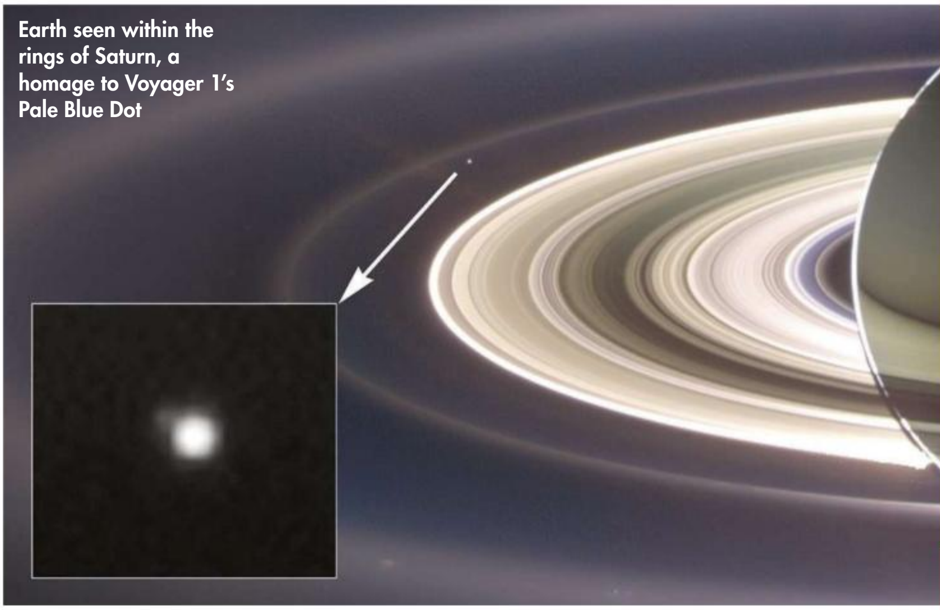
Enquiring minds

Voyager's 40th anniversary is the ideal time to reflect on what drives us to understand our origins and what our future may hold. Curiosity is in our DNA. As humans, we're compelled to explore, to find out what lies beyond the next hill. The Voyager probes not only transformed our view of science and the Universe, they also changed us as people. Who isn't awestruck and humbled by the iconic image of our home planet, that Pale Blue Dot, seen by Voyager 1 from a distance of six billion km? We were compelled to repeat that experiment with Cassini as we viewed Earth through Saturn's rings.

Voyager also taught us the art of patience. The time it took for the probes to complete their investigations required that the NASA scientists involved with the mission make a long-term investment in the project. Any gratification that came from it would be severely delayed, but, as history show has shown, it would be worth the wait.

As a graduate student, I was transfixed by the Voyager flybys. Now, as NASA's director of planetary science, I yearn to return to the outer Solar System, to go back to Uranus and Neptune and discover even more about the ice giants. There are still legacies of the Voyager mission out there waiting to be fulfilled. V

"CURIOSITY IS IN OUR DNA. AS HUMANS, WE'RE COMPELLED TO EXPLORE, TO FIND OUT WHAT'S BEYOND THE NEXT HILL"



Earth seen within the rings of Saturn, a homage to Voyager 1's Pale Blue Dot

NASA/JPL-CALTECH X 3, NASA/JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY/SOUTHWEST RESEARCH INSTITUTE

Messages to the stars

Ambassador, message, mixtape, invitation. No matter how Voyager's Golden Records are interpreted by any extraterrestrials that may find them in the future, they are, in every sense of the word a 'record' of humanity and our intrepid nature

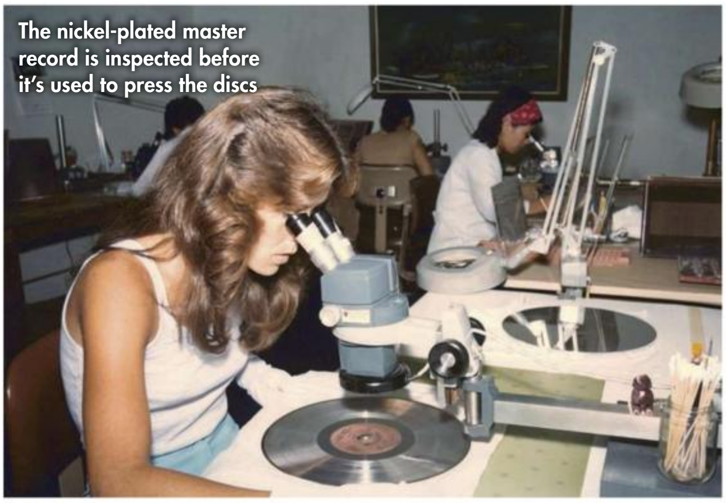
Words: Ben Skuse

IN AROUND 10 years' time, the Voyager spacecraft will no longer have enough power to communicate with Earth. As far as NASA is concerned, this will officially mark the end of a mission that, by then, will have lasted almost half a century. But even though regular signals to and from Earth will cease, the hope remains that one final message will be received.

The message in question is not intended for anyone at NASA or on Earth, but for an advanced extraterrestrial civilisation.

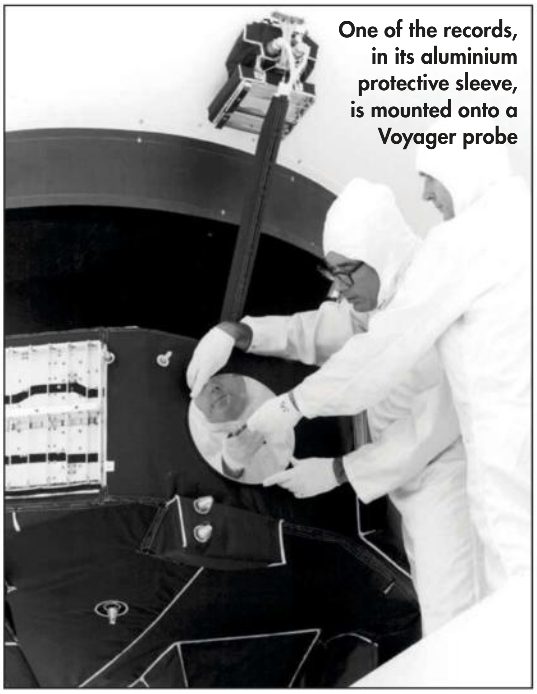
Perched on each of the Voyager spacecraft is a time capsule from 1977 in the form of a 12-inch gold-plated copper disc,


Production begins on the Golden Records for the Voyager probes in June 1977


The nickel-plated master record is inspected before it's used to press the discs


Instructions are etched into the protective sleeves


The gold-plating is applied to the copper records


One of the records, in its aluminium protective sleeve, is mounted onto a Voyager probe

NASA/JPL-CALTECH X 7

a phonograph record containing a glimpse of our planet as it was then. The technology behind these 'Golden Records' might be antiquated by modern standards, but it is a simple one, and NASA believed that an advanced civilisation would be able to comprehend it easily enough.

Each Golden Record carries a wealth of information, including 116 analogue-encoded images, greetings in 55 languages, a 12-minute montage of natural sounds from Earth and 90 minutes of music. The records are mounted in protective sleeves made from aluminium, into which are etched diagrams and binary code containing all the information needed to play them. Also inscribed on them is the location of the Sun in relation to 14 known pulsars so that the origin of the records can be deduced should anyone find either one of them.

"NASA BELIEVED THAT AN ADVANCED CIVILISATION WOULD BE ABLE TO COMPREHEND THE TECHNOLOGY EASILY"

The packages are completed by ultra-pure samples of the isotope uranium-238, allowing the age of the Voyagers to be determined through radioactive dating, and a stylus to play back their message.

Portraying the diversity of life and culture on Earth on a record was no mean feat, but luckily NASA had two astronomers experienced in sending physical messages into space: famed astrophysicist and science populariser Carl Sagan and SETI founder Frank Drake. Sagan and Drake had designed the plaques used for the earlier Pioneer mission – a pair of gold-anodised aluminium panels that pictured a nude man and woman, along with symbols providing information about the origin of the two spacecraft.

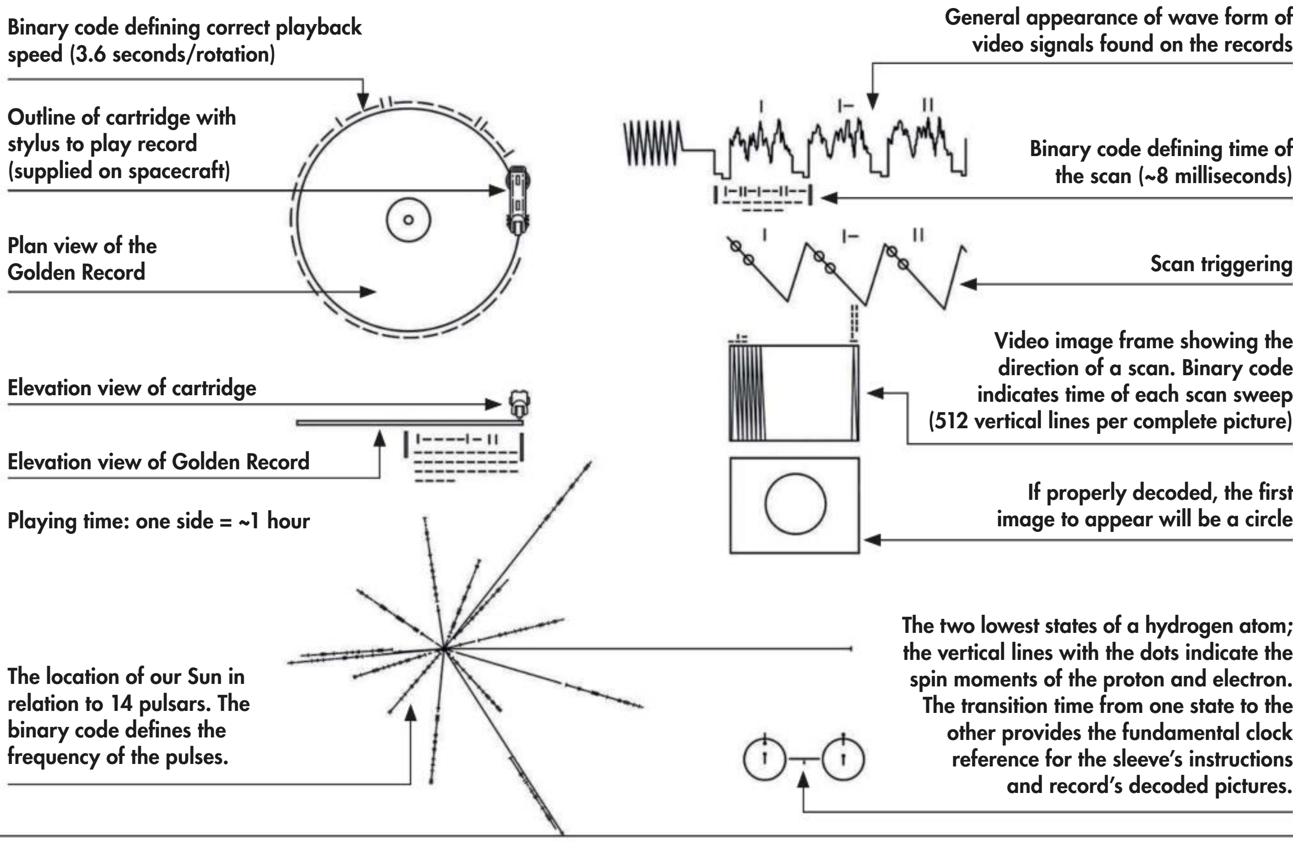
Earth in a groove

It was Sagan and Drake who first suggested a more ambitious message for the Voyager probes during a meeting of the American Astronomical Society in January 1977. Soon after, NASA approved the idea and tasked Sagan, Drake and a committee that included artists and authors to depict as much of our existence as possible on the record in a matter of months.

The team set to work, talking to historians, folklorists, artists and ethnomusicologists, as well as consulting with political groups and documentarians. Artist Jon Lomberg selected the pictures of Earth, which were highly diverse: from an image of the Taj Mahal to a picture of fallen leaves. The images came from various sources, including NASA, *National Geographic* and *Sports Illustrated*, but if Lomberg couldn't find an appropriate image or diagram, he or Drake simply drew it themselves. ▷

HOW TO PLAY A GOLDEN RECORD

The etchings on the records' protective sleeves serve as playback instructions – here's what they mean



▷ Meanwhile, Sagan's then-wife, artist and writer Linda Salzman, was in charge of acquiring greetings in various languages. Due to the time constraint, many of the speakers were from Sagan's university Cornell and the surrounding communities. Given little instruction on what to say, results were eclectic – ranging from Sagan's six-year-old son Nick saying in English "Greetings from the children of planet Earth" to the one-word, minimalism

MESSAGES FROM EARTH

A snapshot of the contents of the Golden Records, the time capsules carried on the Voyager probes

SCENES

Shots of Earth's deserts, mountains, seas and cities appear, but what's not included is just as interesting. Images of war were left out due to concerns they could be interpreted as a sign of aggression. Politics and religion were also omitted for reasons of inclusivity.

GREETINGS

If this selection of greetings were truly intended to be understood by anyone, Sagan's team would have sent one language with a key to decipher it. But it was more an exercise in keeping people on Earth happy and so it included a Swedish message from a computer programmer in New York.

MUSIC

The Golden Record holds all sorts of music: from Beethoven and Bach to Sengalese percussion and traditional Georgian music. Translating the lyrics of this latter piece, 'Tchakrulo', to ensure there were no offensive associations, the team found that the song is about a peasant revolt.

A THOUGHT EXPERIMENT

An unexpected inclusion was the sound of Ann Druyan's brainwaves. Druyan had wondered if a civilisation with the technology to decode thoughts could exist; Sagan and the other team members liked the idea, and so Druyan volunteered to undergo an EEG scan.

of "peace" in Aramaic or the bizarre Amoy greeting that translates as "Friends of space, how are you all? Have you eaten yet? Come visit us if you have time."

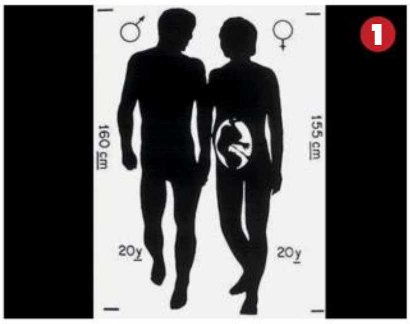
"SAGAN REQUESTED THE BEATLES' 'HERE COMES THE SUN', BUT EMI REFUSED TO GRANT NASA PERMISSION TO USE IT"

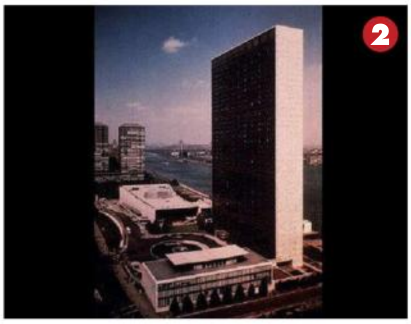
Sounds and music

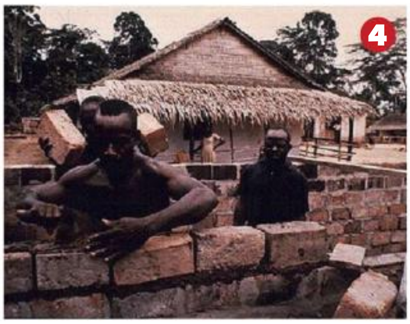
Of course, greetings were not the only audio sent into the heavens. Ann Druyan, the project's creative director and later Sagan's third wife, oversaw the 'Sounds of Earth' recordings, which include thunderstorms, erupting volcanoes and crashing ocean waves, as well as human and animal noises such as a baby's cry, a chimpanzee's call and a dog's bark. Responsibility for the music fell to science writer and *Rolling Stone* editor Timothy Ferris. Classical music features prominently, with excerpts from Mozart, Bach and Beethoven among others, but to give a sense of the range of music humanity has to offer, traditional songs from various cultures and even Chuck Berry's 'Johnny B Goode' were also included. Sagan also requested The Beatles' 'Here Comes the Sun', but EMI, the band's record company, refused to grant NASA permission to use it, despite the Beatles themselves being in favour of its inclusion.

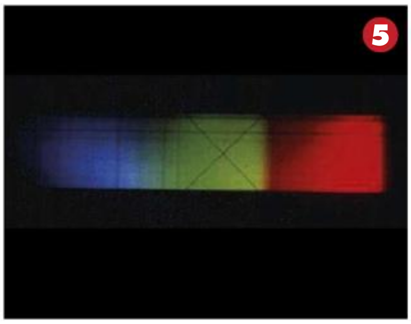
Once the content was assembled, the team thought the hard part was over. But, Ferris threw a spanner in the works just after they had finished cutting the master by adding the inscription 'To the makers of music – all worlds, all times' in the space between the grooves and the label. NASA quality control rejected the record as with the inscription it no longer matched the design specifications. If Sagan hadn't hastily produced a waiver for the NASA administrator to sign, the records would have to have been replaced with blank discs.

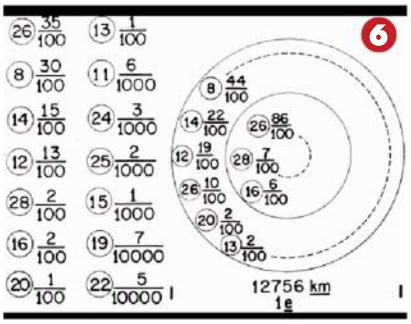
Including the records transformed the Voyagers from robotic explorers into interstellar ambassadors. The probes will likely never reach alien hands, but the fact that the Golden Records were sent anyway speaks volumes for the hope humanity harbours of one day discovering that we are not alone. V











△ **This is a small selection of the images encoded on the Golden Records, chosen to describe our planet, our region of space and the human race: [1] Male and female forms; [2] The UN building; [3] Children with globe; [4] House construction in Africa; [5] The solar spectrum; [6] The structure of Earth; [7] Earth from space [8] Sprinters at the Olympic Games [9] A demonstration of licking, eating and drinking**

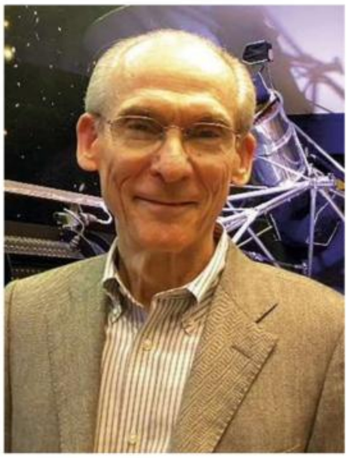
NASA/JPL-CALTECH X 12, ISTOCK X 2

THE VOICES OF VOYAGER

Ed Stone

Ed Stone – the 'face' of Voyager – has been the mission's project scientist since 1972. He looks back at the challenges of the early days of the mission and how the twin space probes continue to explore the edge of the heliosphere and beyond

Interviewed by: Elizabeth Pearson

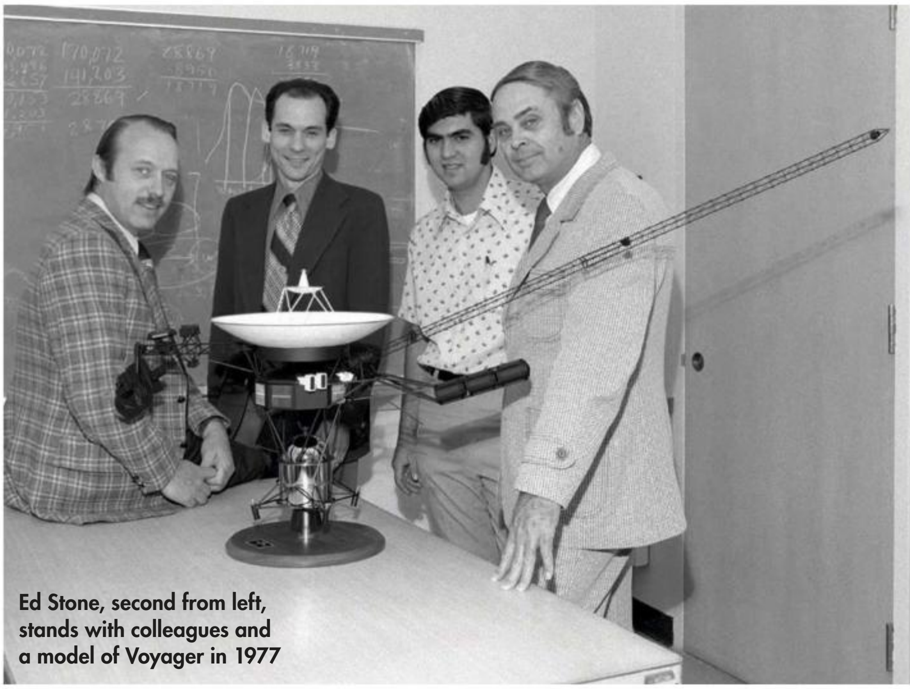


The Voyager project began in July 1972 and shortly thereafter I became the project scientist. For the planetary part of the mission there were 11 scientific teams, each of which had a particular instrument on the spacecraft. The teams formed what was called the science steering group. My role was to coordinate the scientific efforts and then to take a lead in reporting the encounters to the public, leading them through the two probes' journeys and the things we were discovering.

Generally, everyone worked well together but there were times when we had to make a decision to do A or B because we only had a limited amount of time during a flyby and we could only look at one thing at once. So we had to make decisions of what to do, but we organised our efforts in such a way that things worked quite well.

We learned a lot while we were building the probes, because the Voyagers were the first fully automated spacecraft that could fly themselves. Previous spacecraft were more or less flown by commands from Earth that told them what to do next. For Voyager we wrote computer programs, which the spacecraft then executed. The array of instruments that had to be integrated and tested – even the programming for the computers – was something really new as these spacecraft were built to be autonomous. They fly using small onboard computers. By today's standards, the computers are quite primitive, but at the time they were the most advanced machines in space.

> "EVERYTHING IS SYSTEMATICALLY ORGANISED AS THERE ARE MANY STEPS IN THE PROCESS OF DECIDING THAT YOU'RE READY FOR LAUNCH"



Ed Stone, second from left, stands with colleagues and a model of Voyager in 1977

△ The science steering group for the Voyager mission (then called MJS-77) at JPL in 1972, after their first meeting. Ed Stone stands fourth from left

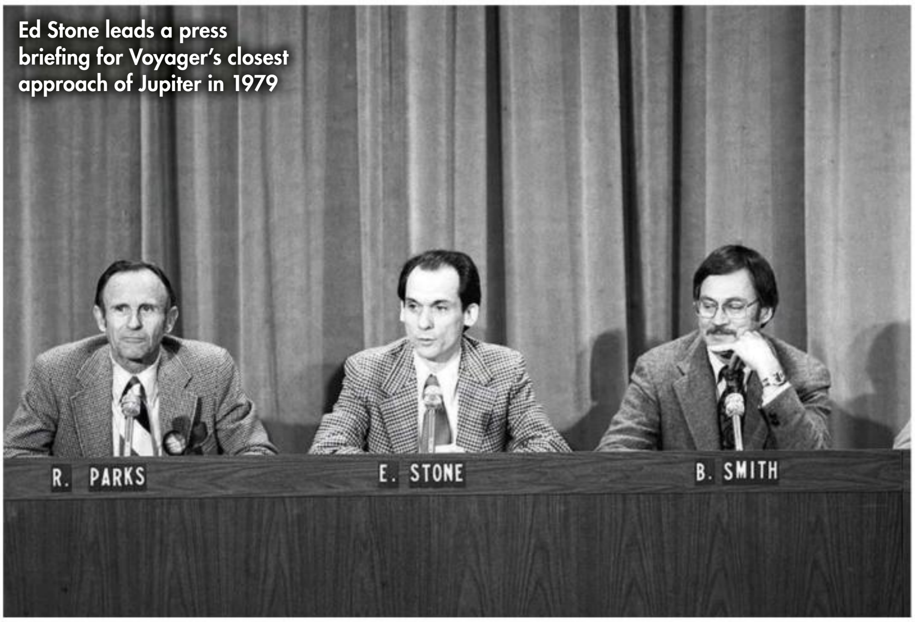
We had a rather good payload of instruments.
Of course, today you could do much better with the instruments than we could with Voyager. For instance, your smartphone has 240,000 times more memory than Voyager has, which gives you an idea of the challenge of making it all fit.

Launch day was like any other.
Everything is systematically organised as there are many steps in the process of deciding that you're ready for launch. The countdown is a very exciting time, but one that has a lot of attention because the launch is one of the most critical parts of any mission.

We were constantly learning how to fly these very complicated, automated spacecraft for the first time.
Voyager 2 – which was launched first because it was on a slower trajectory and would reach Jupiter second – had onboard computer programs that detected faults. If something was outside of expected limits, the programs would make a change and keep on changing things to find the right combination [to bring the thing back within those limits]. During its launch Voyager 2's fault-protection system reported things weren't as expected. But it turned out that was because it was being launched! That caused some confusion as the spacecraft was in fault-protection mode when, in fact, everything was fine. It took care of itself and everything came back online and orientated itself.

There were some other peculiar things that happened with Voyager 2. For example, some bright dust specks would fly past the star tracker and the spacecraft would begin to act as if it had been bumped by something, but it hadn't; it was just passing by some dust.

We hoped that the spacecraft would last long enough to get to interstellar space, but we didn't know if it could.
We had no experience with anything that old in space. But we had two Voyagers and each ▷



Ed Stone leads a press briefing for Voyager's closest approach of Jupiter in 1979

NASA/JPL-CALTECH

▹ one had redundancy on many of its subsystems, so if anything failed on one system we had another that could substitute for it. And, of course, we had the other spacecraft.

I think if you're doing research in space you have to be optimistic that somehow things will work.
When Voyager was launched, the space age was only 20 years old. We had no experience with anything that could last 40 years in space. We didn't know how long the Voyager spacecraft would last or how far they would have to travel to reach interstellar space. Now we know how far, because Voyager 1 has reached interstellar space. We're pretty sure that it has enough power to allow it to keep sending data for about another 10 years.

Every day of a flyby was a day of discovery.
During the encounters, we would convene every afternoon to try and understand what we'd just got back and to get ready for the next day. It's hard to pick out one favourite moment. The discovery of volcanoes on Io does stand out though. It was symbolic of what Voyager was doing: revealing things that were not within our usual realm. Up until that point the only active volcanoes in the Solar System were here on Earth. And yet here was a moon – just a moon of Jupiter – that had 10 times more volcanic activity than Earth. That's when we really realised we were on a journey to discover just how diverse the bodies in the Solar System are.

We kept getting surprised.
The last object we visited was Triton, which is about the size of Pluto. It probably was a sibling of Pluto before it was captured by Neptune and became a moon. It had a different history as it was captured and its orbit was circularised. Triton was a body unlike anything we had seen before. You could see the icy surface and the polar cap on Triton was nitrogen. It was cold, about 40°C above absolute zero [–273°C], so even the nitrogen was frozen. But even at that temperature, there were geysers. We saw two of them erupting on that polar cap so despite the severe cold, there was still geologic activity occurring.

△ Ed (left) meets President Jimmy Carter, who provided a message of greeting for the Golden Records

Eventually we realised Voyager 1 had entered interstellar space.
The Sun creates this huge bubble called the heliosphere, a giant pocket of ionised plasma. It's mainly hydrogen, protons and electrons, pushing out at supersonic speeds, but it gets weaker as it gets further from the Sun. So it fills more and more space until, eventually, it can't push out any further. We know that the plasma density inside the heliosphere is 100 times less dense than it is outside, where the plasma is coming from other stars. We saw a jump [in the plasma density] by a factor of about 40 when Voyager 1 finally left the bubble and entered interstellar space.

The other clue was that inside the heliosphere some of the solar wind is accelerated to about five per cent the speed of light. It's called an energetic ion at that point. There's lots of those inside the heliosphere but none of them outside. We saw them disappear.

> "VOYAGER WAS RIGHT AT THE CUTTING EDGE FOR ITS TIME AND IT TAUGHT US HOW TO MOUNT ALL THE SUBSEQUENT PLANETARY MISSIONS"

Another thing Voyager 1 saw when it reached interstellar space was cosmic rays.
These are heavy ions that have been stripped of their electrons. They come from supernovae that occurred 5-10 million years ago. They have difficulty getting into the Solar System because the wind keeps sweeping them back out, but we saw them jump to an intensity that we'd never seen before. We'd predicted that the inside particles would disappear

△ Journalists question Ed regarding Voyager's encounter with Uranus in 1986

when we went outside and the outside particles would be at a maximum, and that's what we saw. We also predicted that the plasma density would be higher and we saw that too. So we saw the signatures that we expected.

The only signature we didn't see was a change in the magnetic field direction, which we expected to differ. It did jump in intensity, but it didn't change direction. We figured it would change direction, but instead it just became stronger.

Voyager 2 won't enter interstellar space for a while.
It's still inside the heliospheric bubble that the Sun has created around itself, so it still has a few years to go. But because it's following a different trajectory we're already seeing things that are different. For example, the part of the heliosphere Voyager 2 is passing through is a different size to section that Voyager 1 passed through.

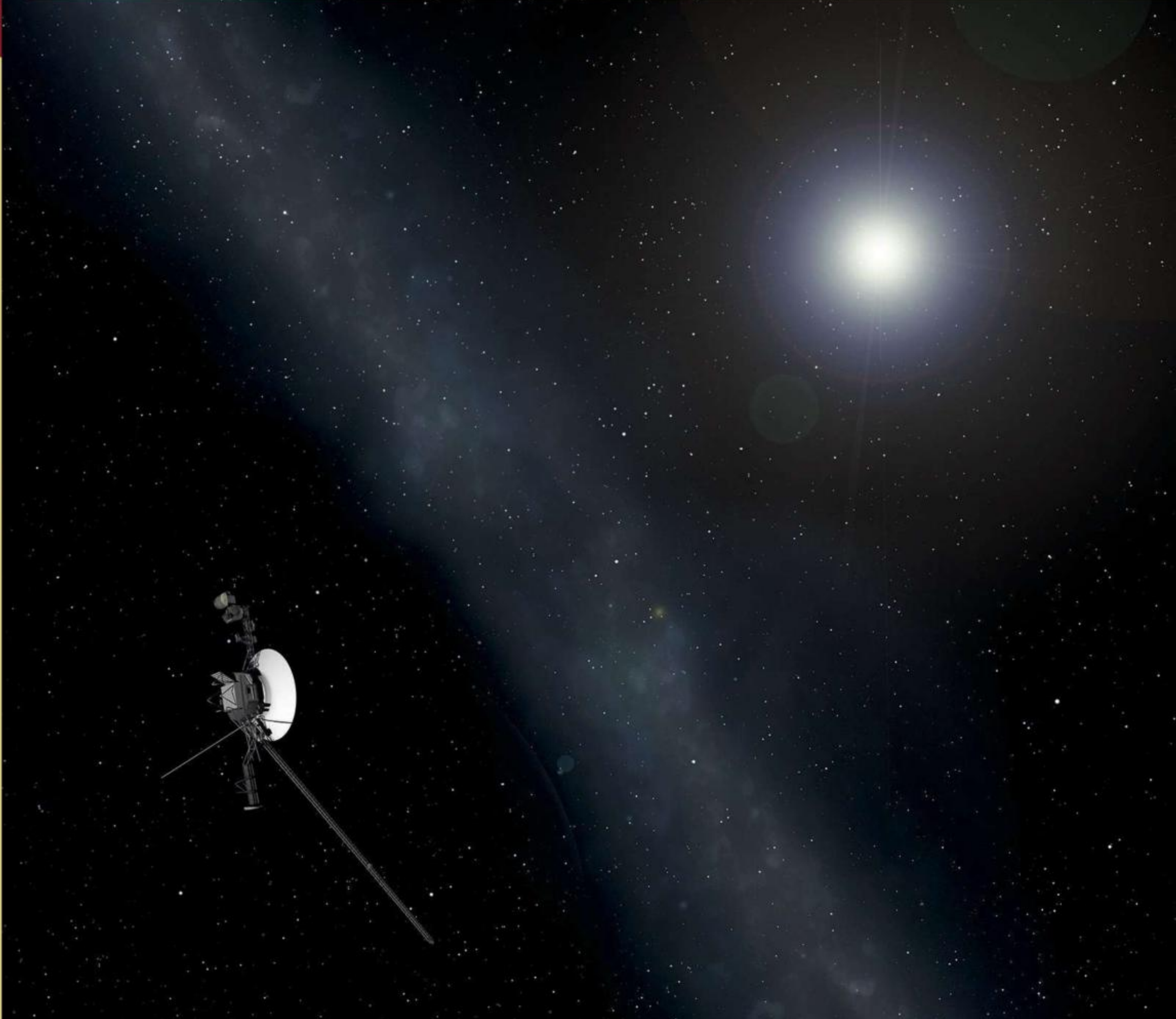
Voyager's greatest legacy is revealing just how diverse the bodies of the Solar System are and how each of them has had a unique geological history.
They're quite different from each other. Even though they started out in similar ways, they've evolved differently. Some of them are still active. Io, we know, is active with its volcanoes, but there are geysers erupting from Enceladus that were discovered by Cassini. Voyager completely changed our view of planets and our view of the Solar System.

Looking forwards, I think the general consensus is to not do more flybys.
In terms of planetary science, now is the time to go into orbit so that we can explore these objects in much more detail. You still discover interesting and unexpected phenomena. That was what Galileo did. That's what Cassini will be doing until September this year.

With Voyager, we did pretty much everything you could do at the time.
Now technology is much more advanced – computational power is greater, sensors are better. You can do things better with the technology that's emerged in the last 40 years. Voyager was right at the cutting edge for its time and it taught us how to mount all the subsequent planetary missions.

There are some things we can't measure with the Voyager probes, though, such as the natural atoms that float in interstellar space.
We can only measure charged particles. We can't measure the flow of the wind outside the heliosphere, at least not very accurately – especially the faster winds. So we are limited. There are some things that we couldn't measure then, but we can today.

The Voyager mission won't really end.
The probes will remain in orbit around the centre of the Milky Way for billions of years, making an orbit about once every 225 million years. They'll be out there, carrying their messages from Earth, telling whoever might find them about the planet they came from. V



Words: Ben Skuse

How will the Voyagers meet their end?

MUCH LIKE AGING athletes, the closer the two Voyager spacecraft get to their 40th birthdays, the more they need to conserve their energy. The Voyager team estimate the probes' radioisotope thermoelectric generators should be able provide power for another 10 years, but NASA will have to shut down their instruments, one by one, to keep them both going for as long as possible – long enough, the space agency hopes, for Voyager 2 to punch through the heliosheath and join Voyager 1 in interstellar space.

If the last science data is transmitted to Earth in 2025 as expected, Voyager 1 will be 169 astronomical units (AU) away from us while Voyager 2 will be at a distance of 142 AU. Those figures might not sound like much until you realise that one AU is equivalent to the distance between Earth and the Sun, approximately 150 million km. They'll be far enough away that nothing from the Solar System can slow them down as they hurtle into the abyss carrying their Golden Records.

No longer able to measure and record the environments they pass by, the Voyager probes will become expensive messages in bottles. Despite the inconceivable odds, it's possible our interstellar envoys might just encounter spacefaring alien civilisations, and let them know that there is life in the Milky Way and it wants to meet them. **V**

WHERE ARE THE VOYAGERS RIGHT NOW?

VOYAGER 1
Location: Interstellar space
Distance: 20.7 billion km (139 AU)

VOYAGER 2
Location: The heliosheath
Distance: 17.1 billion km (114 AU)

BACKGROUND: MARK GARLICK, VOYAGER: YAY MEDIA AS/ALAMY STOCK PHOTO

CELESTRON®

TECHNOLOGICALLYSUPERIOR

THE NEXSTAR EVOLUTION KEEPS **EVOLVING**


NexStar® EVOLUTION

8" EdgeHD with StarSense

Now paired together, enjoy the EdgeHD 8" optics and StarSense AutoAlign on the Evolution Mount. All controlled from your favourite iOS or Android phone or tablet with the new SkyPortal App.

Upgrade your NexStar Evolution for longer exposure astrophotography with the new Evolution equatorial wedge.

NexStar Evolution 8" EdgeHD with StarSense AutoAlign

iPAD and iPHONE SHOWN NOT INCLUDED.

NexStar Evolution 6" SCT

NexStar Evolution 9" SCT

Equatorial Wedge

Sky at Night MAGAZINE REVIEWED IN ISSUE 112 SEPTEMBER 2014 ★★★★★

Available from specialist astronomy retailers and selected other dealers nationwide.

Celestron is distributed in the UK & Ireland by David Hinds Limited. Trade enquiries welcomed.

www.celestron.uk.com