New Scientist

ESSENTIAL GUIDE №22

RETURN TO THE MOON
THE NEW SPACE RACE
REVELATIONS FROM THE JAMES WEBB SPACE TELESCOPE
EXPLORING THE SOLAR SYSTEM
AMATEUR ASTRONOMY
AND MORE

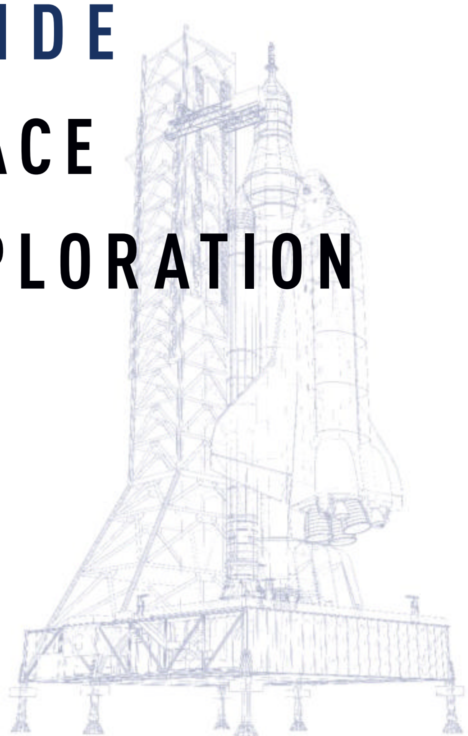
SPACE EXPLORATION

THE PROBES, TELESCOPES AND CREWED MISSIONS TRANSFORMING OUR VIEW OF THE COSMOS

EDITED BY
ABIGAIL BEALL

NEW SCIENTIST ESSENTIAL GUIDE

SPACE EXPLORATION



WE HAVE always had an itch to know what is around the next corner or over the next ridge. This same curiosity led us towards space when we began observing how orbs moved across the night sky.

Then came Galileo Galilei, who used telescopes to observe mountains on the moon and spots on the sun and realised that the heavens weren't perfect celestial spheres. In doing so, he brought the night sky down to Earth. These were just other places that must abide by the same laws of nature. In other words, he made us realise that we can go into space.

Uncovering these laws let us build the tools needed to explore further – eventually sending space probes and people to the moon and beyond. This twenty-second *New Scientist Essential Guide* looks at this modern era of space exploration, from the high-stakes space race to the first space telescopes. We will delve into the discoveries that space missions are making in all corners of the solar system, find out how the James Webb Space Telescope is searching for extraterrestrial life, and hear what it will take to create a colony on the moon or Mars – our latest space venture.

Where we choose to go and for what purpose is still up for grabs, but we can be sure that the itch to find out what is over yonder will continue to blow our minds. All titles in the *Essential Guide* series can be bought by visiting shop.newscientist.com; feedback is welcome at essentialguides@newscientist.com. *Abigail Beall*

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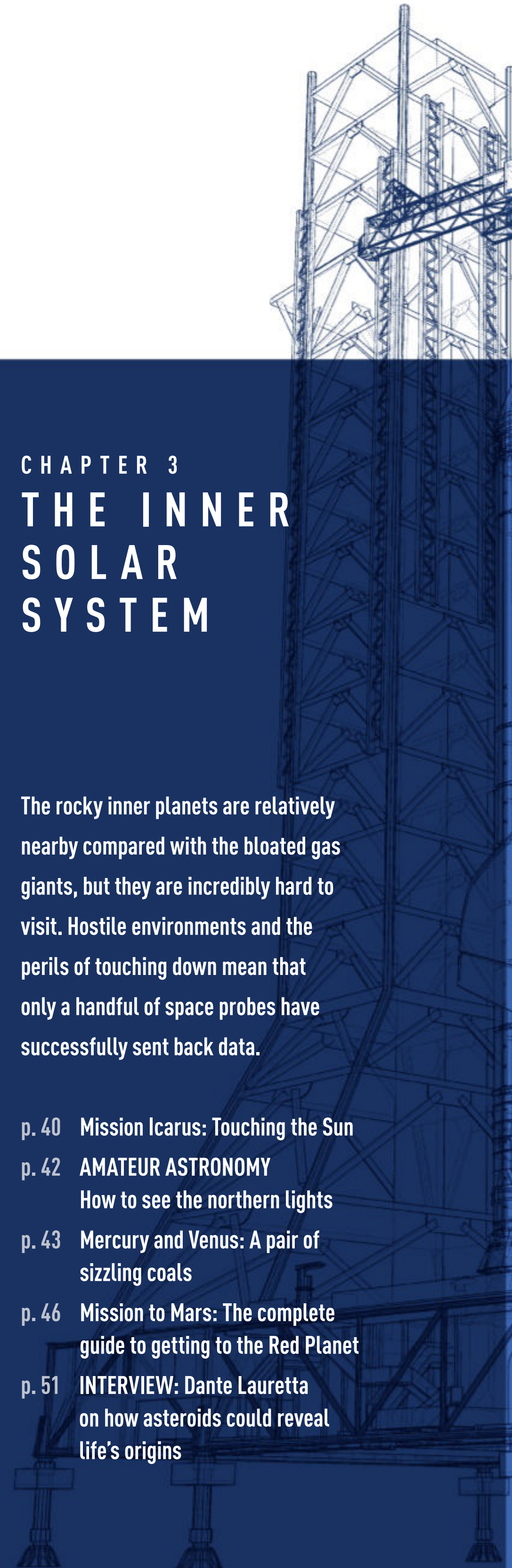


CHAPTER 1

INTO SPACE

A small piece of metal launched into orbit set off a chain of events that saw 12 humans walk on the moon, nine space probes reach the outer solar system and some 10,000 satellites put into orbit around Earth.

CHAPTER 2

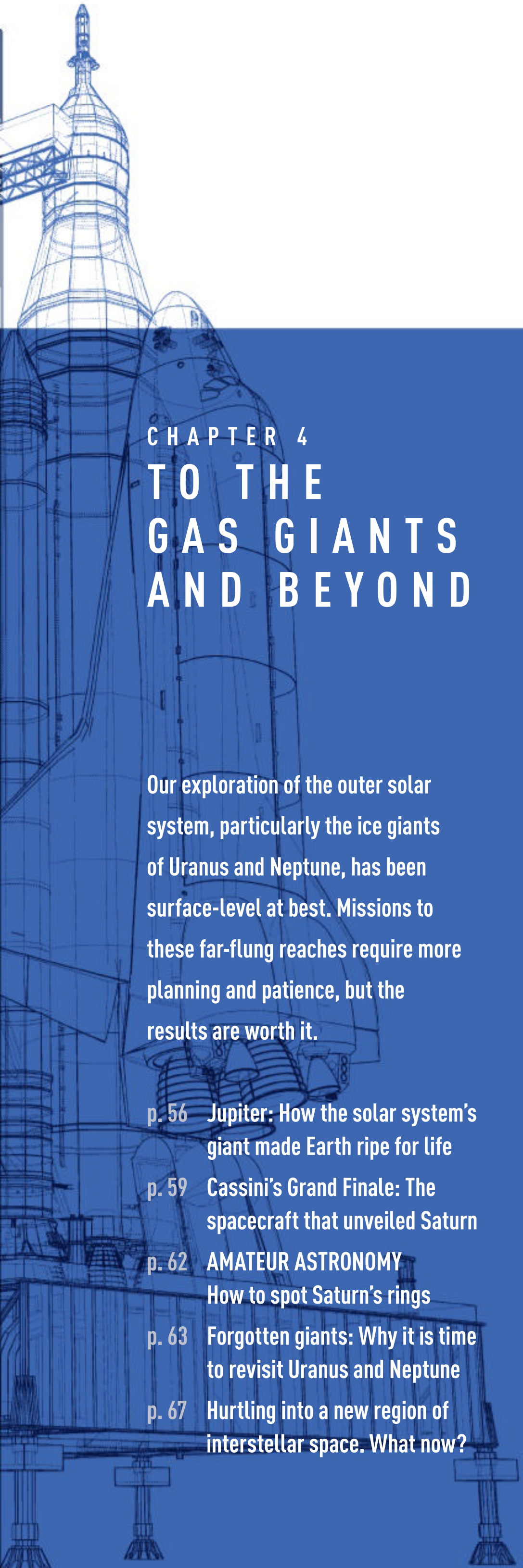
RETURN TO THE MOON

There is renewed interest in sending people back to the moon as a stepping stone for further pastures: Mars. But, in the age of private space travel, getting to the moon is going to look very different this time around.

CHAPTER 3

THE INNER SOLAR SYSTEM

The rocky inner planets are relatively nearby compared with the bloated gas giants, but they are incredibly hard to visit. Hostile environments and the perils of touching down mean that only a handful of space probes have successfully sent back data.



CHAPTER 4

TO THE GAS GIANTS AND BEYOND

Our exploration of the outer solar system, particularly the ice giants of Uranus and Neptune, has been surface-level at best. Missions to these far-flung reaches require more planning and patience, but the results are worth it.

CHAPTER 5

SPACE TELESCOPES

Some of our most sophisticated and ambitious space missions have been telescopes. From the iconic images of NASA's Hubble Space Telescope to the state-of-the-art James Webb Space Telescope, these intricate instruments have redefined the cosmos and our place within it.

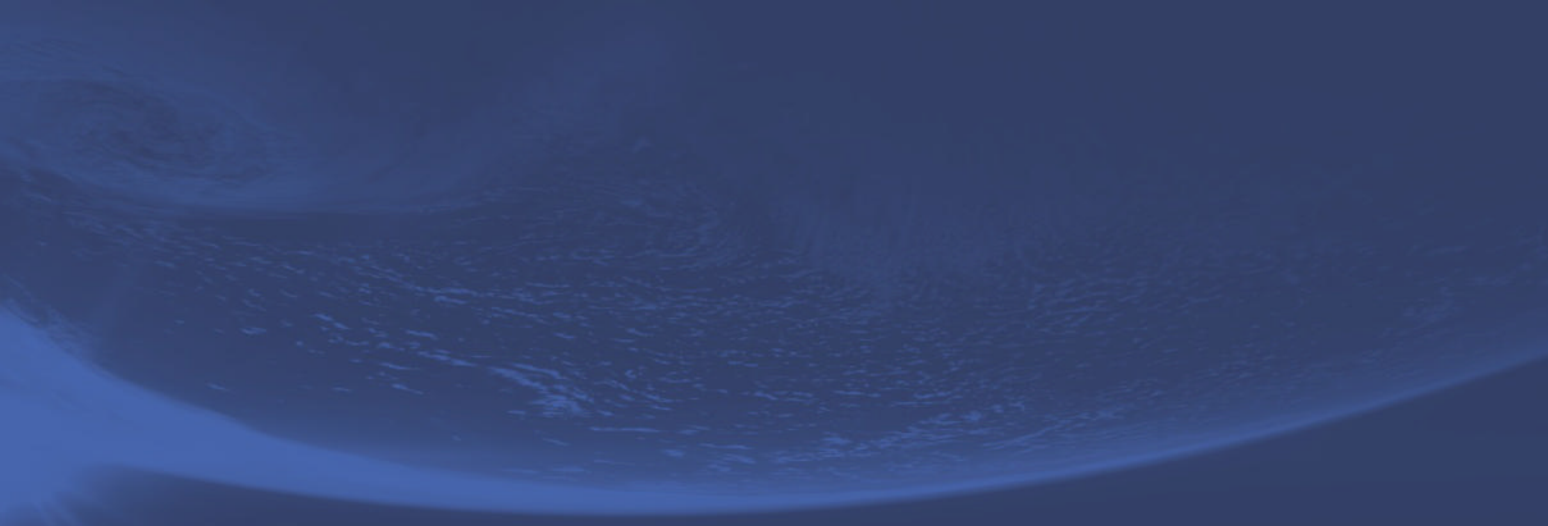
CHAPTER 6

SEARCHING FOR LIFE

For all of our landers, orbiters, spacewalks, sample return missions and space telescopes, there is one question we have yet to answer: is there any other life out there? There no shortage of ideas about how we might find extraterrestrial life, but a slam-dunk sign seems trickier than ever to come by.

CHAPTER 1

INTO SPACE



Today, there are almost 10,000 active satellites in orbit around Earth. We use them for everything from communications to weather forecasting, and one of them has even been home to a handful of adventurous humans.

But how did we get here? A small piece of metal launched into orbit set off a chain of events that saw 12 humans walk on the moon and nine space probes reach the outer solar system. At least two of them are still hurtling into interstellar space, sending signals back home.

Animals and humans have been launched out of Earth's gravity, with some tragedies along the way. And it all began with a political rivalry.

THE SPACE RACE

The space race in the 1950s and 60s was driven by cold war politics. Without the Soviet Union and the US battling to outmanoeuvre each other, we wouldn't have had Sputnik, Vostok or Apollo. Here are some key events that marked our first ventures into the realm beyond Earth.

1957:
THE FIRST SATELLITE

It was the beginning of the space age: the launch by the Soviet Union on 4 October 1957 of Sputnik 1, the world's first artificial satellite. With the Soviet Union and the US locked in an ideological war, the West watched with trepidation as a small, polished metal orb circled above Earth, sending a simple, bleeping signal back home.

Just a month later, on 3 November, the Soviet Union chalked up another iconic first when Laika, the most famous of the Soviet space dogs, was shot into orbit on the considerably larger Sputnik 2. She didn't make it back to Earth. For decades, the official line was that she died painlessly after about a week in orbit. New evidence unearthed in 2002, however, suggests she only survived a few hours before succumbing to heat and stress. Whatever the ethics of sending animals into space, Laika's craft, Sputnik 2, showed how the Soviet Union was leading the space race.

Four months later, the US had its own satellite in orbit, Explorer 1, and in July 1958, it belatedly formed the organisation that, to most, symbolises the space race: the National Aeronautics and Space Administration, NASA. ›

ASSOCIATED PRESS / ALAMY STOCK PHOTO PREVIOUS PAGE: ILEXX/

1961:
THE FIRST HUMAN IN SPACE

Cosmonaut Yuri Gagarin went down in history as the first human ever to enter space. From humble beginnings, he would attain the rank of senior lieutenant as a fighter pilot in the Soviet Air Forces before being accepted into the Soviet space programme in March of 1960. It was little over one year later, on 12 April 1961, that he was launched into orbit from Baikonur Cosmodrome in present-day Kazakhstan, where he spent 108 minutes aloft, orbiting the globe once in his craft, Vostok 1.

Officially, he came back to Earth in his capsule. However, it subsequently emerged that he actually parachuted to safety when it was still 7 kilometres from the ground. Despite that glitch, this was another technological and PR victory for the Soviet Union.

Weeks later, on 5 May, the US managed to send a human – Alan Shepard, who later went on to walk on the moon – although only on a short sub-orbital flight. But the gauntlet was picked up: on 25 May, President John F. Kennedy announced to a special session of the US Congress the intention that an American would walk on the moon before the decade was out. This was the beginning of what became the Apollo programme. The following February, John Glenn became the first American in orbit.

HERITAGE IMAGE PARTNERSHIP LTD / ALAMY STOCK PHOTO

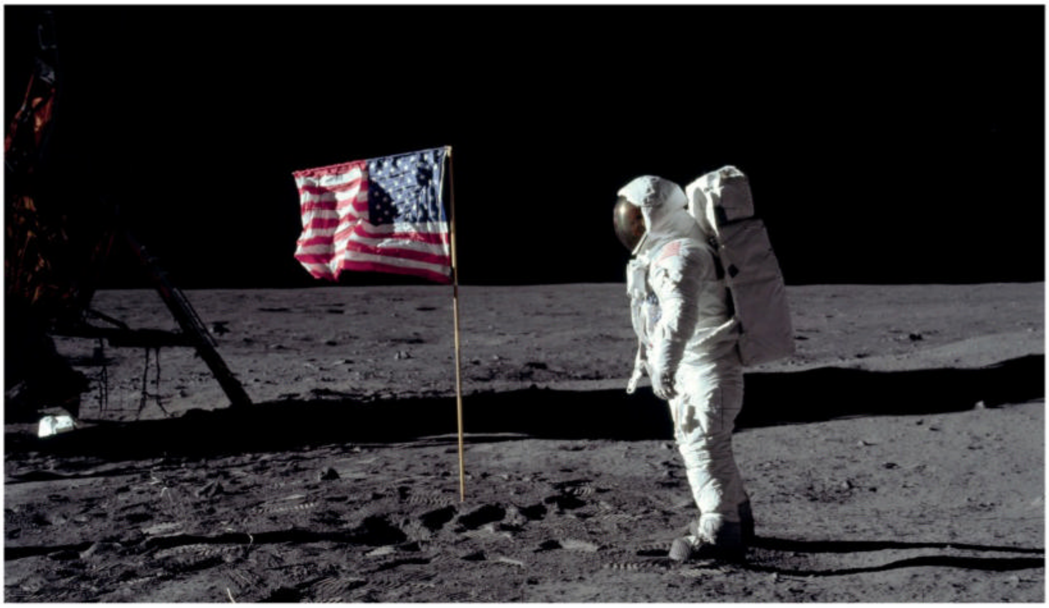
ASSOCIATED PRESS / ALAMY STOCK PHOTO

1965:
THE FIRST SPACEWALK

On 18 March 1965, Soviet cosmonaut Alexei Leonov became the first person to leave a space capsule and, tethered to it, float freely in orbit – to spacewalk. He was pilot of the Voskhod 2 mission, part of the Soviet Union's attempt in competition with the US to reach the moon.

Leonov's walk was not without its difficulties. Although outside his craft for only a little over 12 minutes, his suit ballooned when no longer constrained by his spacecraft's internal atmosphere and he could not re-enter the airlock. Bleeding the suit beyond its safety limits to make it more flexible, Leonov suffered the bends from decompression. He later noted that he had perspired so much that the sweat sloshed around inside his suit. Not all seems to have gone well on the re-entry flight, either.

Still, it was a massive first, and one that left the US, as often in the early days of the space race, playing catch-up. But fewer than three months later, the US astronaut Ed White also took a wander in space. White later became one of the first casualties of the space race, dying in 1967 in a tragic launch pad fire that consumed the Apollo 1 mission, the first crewed mission of the US moon programme. Apollo 8 flew around the moon in December 1968, humanity's first venture beyond Earth orbit. After two more test flights, Neil Armstrong took his famous "giant leap for mankind". ▮


NASA

APOLLO 11: THE FIRST FOOTSTEPS ON THE MOON

On 21 July 1969, Apollo 11 mission commander Neil Armstrong uttered the famous words "that's one small step for a man, one giant leap for mankind" as he took his momentous "small step" onto the lunar surface.

FOR a long time, it looked as if the Soviet Union would beat the US towards the ultimate victory in the space race. But when the Soviet Union's N1-L3 test vehicle toppled backwards in flames onto its launch pad, it become clear that the US would make it to the moon first.

On 21 July 1969, just five days after taking off from Cape Canaveral in Florida, the Apollo 11 crew touched down on the moon. Following Neil Armstrong onto the lunar plain of the "Sea of Tranquility" was Buzz Aldrin, the second man to walk on the moon. Completing the mission's crew of three was Michael Collins, who remained alone circling the moon in the orbiter that had dispatched the landing module, codenamed Eagle.

But how did the crew know how to land on the moon? Practice. In the early days of the space race, NASA engineers spent countless hours simulating space flight before the first astronaut ever left Earth. That is why most Fridays in 1960, Harold Miller and ›

"The simulation supervisors got reputations for being diabolical with the problems they concocted"

Dick Koos took the "fruit flight" from Cape Canaveral in Florida to NASA's Langley Research Center in Virginia.

Miller and Koos had been part of a small team working on space simulations at Langley for about a year. But eventually they needed to move their operations far from their homes, to Florida, where the mission control would be based. The passenger planes that flew them home at the end of the week were always loaded with the Sunshine State's citrus bounty. When travellers grabbed their bags at the end of the journey, they could also get a large sack of oranges for $3.

Cheap fruit was one of the few perks of working at the Mercury Control Center and launch facilities on the isolated and jungle-like Cape Canaveral all week. If a test rocket blew up (which happened about half the time in those days) and a brush fire started, you had to watch out for the alligators or wild hogs trying to escape the flames.

Project Mercury, NASA's first human space-flight programme, had the goal of putting humans in Earth orbit and getting them safely down again – preferably before the Soviet Union did so. But in those days, no one knew for certain if a person could stay alive, let alone work, in the weightless environment of space. Even if they could, no one knew how humans should operate a spacecraft.

Miller, Koos and the small simulation task group were charged with figuring out not only how to teach the Mercury astronauts to fly in space, but also with training the fledgling flight control team on the ground. Like everything else under NASA's purview at that time, it meant figuring out how to do things that had never been done before.

"My first trip to Florida in 1960," Koos recalls, "Harold gave me a tour around the cape, and I said, 'it sure is sink

HOW MANY PEOPLE HAVE WALKED ON THE MOON?

Just 12 people have walked on the moon, all between 1969 and 1972. Here's the full list:

Neil Armstrong Apollo 11 (1969)
Edwin "Buzz" Aldrin Apollo 11 (1969)
Charles "Pete" Conrad Apollo 12 (1969)
Alan L. Bean Apollo 12 (1969)
Alan Shepard Apollo 14 (1971)
Edgar D. Mitchell Apollo 14 (1971)
David Scott Apollo 15 (1971)
James B. Irwin Apollo 15 (1971)
John Young Apollo 16 (1971)
Charles M. Duke Jr. Apollo 16 (1971)
Eugene A. Cernan Apollo 17 (1972)
Harrison "Jack" Schmitt Apollo 17 (1972)

In the 1960s, astronauts trained in mock cockpits and rigs that simulated the effects of spacecraft thrusters on the capsule

or swim around here.' And he said, 'That's right. And we don't have time to teach you how to swim either.' And that's really what it was. Everything was happening so fast; it was like drinking out of a fire hose."

Chris Kraft, NASA's first flight director, had the idea to combine the instruction for flight controllers with the astronaut crew training, because astronauts would work closely with mission control during the flights. Members of the simulation group needed to organise these "integrated simulations".

In a back room at the first Mission Control Center at Cape Canaveral, they used the Mercury cockpit trainer, a rudimentary spacecraft simulator that contained replica switches, gauges, dials and controls – just like the real Mercury spacecraft that would soon carry the first Americans into space. All the instrumentation was connected to a computer console that could manipulate the readouts. In turn, the readouts were wired to the basic consoles developed for the flight control team so it could monitor the spacecraft's "dashboard" during a mission.

The simulations used a room-sized computer to recreate the gauge readings of many events that would take place in a spacecraft during a real mission. Ways were also developed to inject problems during the simulations. Staff could fake a huge drop in cabin pressure, for instance, or loss of the manoeuvring thrusters. They could also make the various gauges in the cockpit show readings that called for a simulated abort or flight modifications.

Unrealistic problems were deemed off limits, but the simulation team's goal was to think about all the things that could go wrong so that flight controllers could develop solutions to have at their fingertips.

Using simulations, mission controllers went through every system, working out what could be done if the spacecraft malfunctioned. This helped them produce guidance for what to do in the event of almost every potential glitch.

During the run-up to Apollo, the team usually worked seven days a week, and 10 to 12 hours a day. The simulation supervisors began to develop reputations for being diabolical, with the crazy, complicated problems they concocted. "In the *Star Wars* era, we would have been considered to be on the dark side," jokes Koos. But they had an uncanny knack for coming up with problems that ultimately happened during real missions. For example, they inserted engine failures in several early Apollo simulations. Then during the uncrewed Apollo 6 flight, two engines shut down prematurely. Because of the training, the flight control team knew to burn the remaining three engines longer to compensate.

The most celebrated instance might be the "1202" computer alarms that occurred during the Apollo 11 lunar landing. This obscure error code signalled that the lunar module's navigation computer was overloaded and needed to reboot. The flight control team knew how essential the navigation computer was for the lunar landing and might have called it off.

However, just a few days before Apollo 11 launched, Koos introduced the same computer alarms in the final training run, and one of the flight controllers knew the computer could handle a reboot. Without that simulation, Neil Armstrong and Buzz Aldrin's Apollo 11 moon landing may have very well been aborted, changing forever the mission's distinguished place in space history. ∎

Katherine Johnson's calculations were critical to NASA's first crewed space flights

NASA/BOB NYE

PROFILE

HIDDEN FIGURE

Katherine Johnson was a NASA mathematician whose calculations helped the US get an astronaut into orbit and were crucial for the first moon landing.

BORN in White Sulphur Springs, West Virginia, in 1918, Katherine Johnson excelled academically from an early age. She finished high school at the age of 14 and graduated summa cum laude from West Virginia State College with a double major in mathematics and French aged 18.

Following a brief stint working as a public school teacher, Johnson became the first African American woman admitted to graduate school at West Virginia University, enrolling in the mathematics programme.

In 1953, she started working at the all-Black West Area Computing section of the Langley Aeronautical Laboratory at the National Advisory Committee for Aeronautics (NACA), which would later become the space agency NASA. In addition to the computing pool, the toilets and cafeteria at Langley were also racially segregated at the time. Johnson refused to use the "colored" toilets and ate lunch at her desk.

Within two weeks of working at Langley, she landed a position in the Flight Research Division, where over the next four years, she worked alongside aeronautical engineers analysing data from flight tests. At the same time, the space race was heating up.

In 1957, the Soviet Union launched Sputnik 1 – the first artificial Earth satellite – and in April 1961, cosmonaut Yuri Gagarin became the first person to journey into space and orbit Earth. Meanwhile, at NACA (which had since become NASA), Johnson had been working on the trajectory analysis for the US's first human space flight. In May 1961, astronaut Alan Shepard became the first person from the US and second person in the world to go to space.

Less than a year later, NASA was preparing for the mission that would see John Glenn become the first US astronaut to orbit Earth in February 1962. The agency was relying on a network of computers, programmed with orbital equations that would control the trajectory of Glenn's capsule. As part of the pre-flight checklist, Glenn asked engineers to "get the girl" – referring to Johnson – insisting that she run the numbers through the same equations by hand to check the computer's calculations. "If she says they're good, then I'm ready to go," Johnson recalled the astronaut saying.

Johnson went on to join the Space Mechanics Division, where she calculated the trajectory for the 1969 Apollo 11 flight to the moon and worked on key calculations that helped synchronise the mission's lunar lander with the moon-orbiting command and service module. Her work helped the US become the first country to land a person on the moon on 20 July 1969. Johnson died in Newport News, Virginia, on 24 February 2020 at the age of 101.

Following the news of her death, the then NASA administrator James Bridenstine described Johnson as "an American hero", adding that "her pioneering legacy will never be forgotten". ∎

THE SPACE SHUTTLE

NASA's Space Shuttle programme heralded a new era of space flight and exploration, whose fruits we still enjoy today. Over 30 years, 135 flights were made by five shuttles: Columbia, Challenger, Discovery, Atlantis, and Endeavour.

STS-1, the first orbital space flight of NASA's Space Shuttle programme, launched from Kennedy Space Center in 1981


NASA

TWENTY years to the day since Yuri Gagarin's space flight, the US launched the world's first reusable spacecraft into orbit. STS-1, better known as Columbia, left NASA's Kennedy Space Center in Florida on 12 April 1981 and landed just over two days later in California.

The iconic shuttles remain the only winged spacecraft to have made multiple flights into orbit, but the programme has also been marked by very public tragedy.

On 28 January 1986, Challenger was set to carry the first American civilian into space. Christa McAuliffe was killed along with another six NASA crew members when the shuttle broke up 73 seconds into its flight. In 2003, damage to Columbia's protective heat panels during launch meant it was destroyed as it re-entered Earth's atmosphere on its return journey, killing seven crew members. The shuttles would continue flying until 2011, but the continuing dangers of crewed space flight had been laid bare.

In many ways, the shuttle ushered in a new era of space flight and exploration – one whose fruits we all enjoy. Besides carrying out missions to the International Space Station and placing the Hubble Space Telescope into orbit (as well as fixing its idiosyncrasies), the shuttle launched private satellites and carried out missions and experiments on behalf of corporations. Space could now be exploited for profit, tempting private finance and commercial spacecraft builders to look skywards – as Elon Musk and others are showing us today. Space flight was no longer the preserve of nations looking for an ideological advantage, but open to all. ∎

SPACE STATIONS: FROM SALYUT TO THE ISS

These orbiting homes-from-home have helped us master the basics of survival in space and revealed the challenges we face if we want to travel to other planets.

SALYUT 1

The world's first space station, Salyut 1 was launched on 19 April 1971. It spent only 175 days in orbit before it burned up in the atmosphere. It was visited twice, but the first crew couldn't enter because of a docking problem. Equipment failure forced the second crew to leave after just 23 days. The three cosmonauts died during re-entry because of a malfunction in their Soyuz capsule.

SKYLAB

This was the first US space station, launched on 14 May 1973. During its six years in orbit, astronauts spent some 2000 hours on scientific and medical research projects. NASA planned to use the space shuttle to boost the station to a safer orbit, but delays in the shuttle programme left Skylab to break up in the atmosphere and scatter debris over Western Australia.

Skylab

NASA

DRAGAN ILIC / ALAMY STOCK PHOTO

Salyut 6

SALYUT 6

Launched in 1977, this was the eighth Salyut station and it spent 1764 days in orbit. It was visited by 16 crews and offered new levels of comfort: a shower and a gym. Visiting cosmonauts took part in astronomy and Earth-observation studies, as well as experiments on the effects of space flight on the human body.

SALYUT 7

The next Salyut was launched on 19 April 1982. Cosmonaut Svetlana Savitskaya visited the station twice and became the first woman to walk in space. In 1986, the station was parked in a high orbit with plans to recover it using the Buran shuttle. However, in an echo of Skylab's fate, Salyut 7 eventually re-entered the atmosphere and broke up over Argentina after the Buran programme was cancelled.

MIR

Despite system failures, fire, fungal infections and a near-catastrophic collision with a supply craft, Mir set a number of records during its 15 years in orbit. Launched by the Soviet Union in 1986, it was the first modular spacecraft and the largest artificial satellite in orbit. One of its crew, Valeri Polyakov, still holds the record for the longest uninterrupted human space flight: 437 days.

GENESIS

On 12 July 2006, US firm Bigelow Aerospace launched Genesis 1 into orbit. This inflatable unit was a scale model of the module that Bigelow hoped to use to create its Next-Generation Commercial Space Station. A second space station, Genesis II, was launched in 2007. Its cargo included a population of Madagascar hissing cockroaches. Both Genesis space stations are still in orbit, and are expected to eventually burn up in Earth's atmosphere.

TIANGONG

Launched on 29 September 2011, Tiangong-1 was China's first space station. Its inaugural crew, including the country's first female taikonaut, Liu Yang, arrived on 18 June 2012. Tiangong-1 was retired in 2018, crashing down to Earth after the ground operators lost control during the de-orbit operation. Most of the station burned up as it entered the atmosphere, and the remaining pieces fell in the southern Pacific Ocean.

Another test space station laboratory, Tiangong-2, blasted off in September 2016, before it was de-orbited in a controlled destruction and in July 2019 it disintegrated over the Pacific Ocean.

In 2021, the China National Space Administration launched the first module of its permament space station. The station, called Tiangong, consists of three main modules. The first was Tianhe, which means "Harmony of the Heavens", and it contains living quarters for up to three astronauts, along with the station's control centre and its power, propulsion and life-support systems. The second module, Wentian, which means "Quest for the Heavens", has the ability to perform more advanced scientific experiments in microgravity than Tianhe. Mengtian, which means "Dreaming of the Heavens", was the final section of the observatory and it joined up with the rest of the station in October 2022.

Tiangong

ASSOCIATED PRESS / ALAMY STOCK PHOTO

The International Space Station

NASA

THE INTERNATIONAL SPACE STATION

Over 20 years ago, five space agencies representing 15 countries came together to build one of the most ambitious engineering projects the world had ever seen. It took more than 30 missions, with parts manufactured thousands of kilometres apart and assembled by spacewalkers orbiting at 28,000 kilometres per hour, before the International Space Station (ISS) was completed in November 2000.

In the long term, NASA hopes that spacecraft in low Earth orbit, including the ISS, will be primarily operated by private companies, with NASA buying services where necessary. This may be the start of a new space economy. ▮

"WHEN YOU LOOK DOWN ON THE EARTH, YOU CAN'T SEE THE POLITICAL BOUNDARIES"

Some three decades after her historic space flight, Helen Sharman sat down with us to talk about the experience and her concerns for the future of our planet

PROFILE
HELEN SHARMAN

In 1991, aged 27, Helen Sharman became a household name, after she spent eight days in space performing scientific experiments, as the first British astronaut. She retreated from public life in the 2000s, before joining the National Physical Laboratory in 2011 and then moving to Imperial College London to become operations manager at the chemistry department in 2015.

What was your first view of Earth from space like?

As soon as you're out of the atmosphere, the fairings jettison and light can come through the window. Luckily for me, I was on the part of the spacecraft that was pointing towards the Earth so I could see the Pacific Ocean, with the curvature of the Earth and black space above. It was really, really bright.

How would you describe the overview effect?

When you look down on the Earth, you can't see the political boundaries. Politics means absolutely nothing because you're seeing the natural world. When you're zipping around in low Earth orbit, in 92 minutes you've gone completely around the Earth. So instead of it being this huge place that you can apparently do anything to that's really robust, it's actually a very tiny place where everything is affecting everything else.

We're all part of the Earth and the Earth is as much part of us as we are of it. I am angered by the fact that we are apparently destroying the very thing that's given us life, as opposed to what we could be doing, which is living symbiotically.

What did being in space make you realise?

Physical possessions, material stuff is absolutely meaningless. I had everything around me that I

GARY DOAK / ALAMY STOCK PHOTO

needed. I had the basic clothes that I needed. I had food, warmth and shelter. We use our possessions as an extension of ourselves. We should just think about what's really important, and generally consume less.

You almost sound like an environmentalist. Would you describe yourself as one?

I describe myself as a scientist and as somebody who cares for the world we live in. But I've never been an environmentalist in the sense of somebody who's devoted their life to protecting the environment. Being a scientist and trying to encourage people to take an interest in science or logical thought protects the environment as much as anything else.

What are your biggest environmental concerns today?

Climate change over and above pretty much everything else, because that will affect every single one of us. It's affecting us now, but it could easily make the world uninhabitable.

How do you square the carbon footprint of space flight with climate concerns, especially when you have entrepreneurs like SpaceX's Elon Musk sending a Tesla car into space?

We didn't need to send an electric sports car, did we? But I think space gives us a huge amount of information on the environment. What concerns me most is the debris we are creating around the Earth, particularly in low Earth orbit and geostationary orbit. I think that's probably one of the biggest challenges for space flight in the future. ∎

AMATEUR ASTRONOMY: HOW TO SPOT THE ISS FLYING OVERHEAD

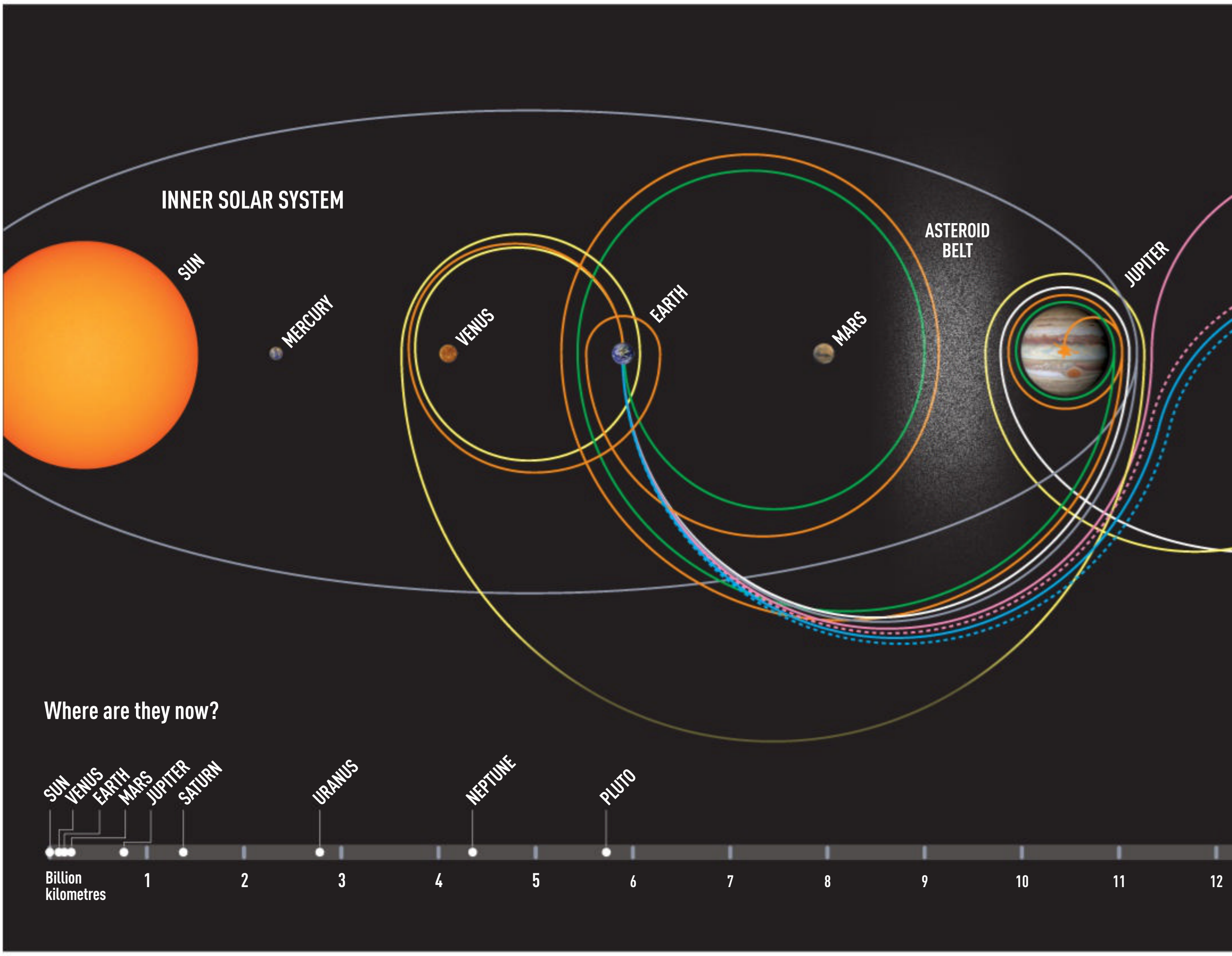
The space station travels at 28,000 kilometres per hour, circling Earth every 90 minutes or so, always from west to east. That means the astronauts on board typically see 16 sunrises and sunsets each day. For the rest of us, it means we can observe the satellite moving steadily across the sky, much faster than planets and stars, but more slowly than an aircraft.

If you live below 51.6 degrees of latitude, you can see the station passing directly overhead, as this is the angle of its inclination. If you live north or south of this, such as in northern Europe and much of Canada, it will always be lower in the sky.

Because of Earth's rotation, each ISS orbit is 22.5 degrees to the east of the previous one. That takes it over most countries at some point, although your chances of seeing it will vary from once a month to a few times in one week.

To spot the station, it has to be dark. The ISS can sometimes be as bright as Jupiter or Venus, but this depends on its altitude and the amount of sunlight reflecting off it. Satellites tend only to be visible just after sunset or just before sunrise. This is because they have no light source of their own, so it is only through the sunlight they reflect that we can see them.

To check when the space station will be visible from your location, go to spotthestation.nasa.gov.



WHERE ARE THEY NOW?

Nine space missions have reached the icy depths of the outer solar system. Some are still broadcasting from interstellar space.

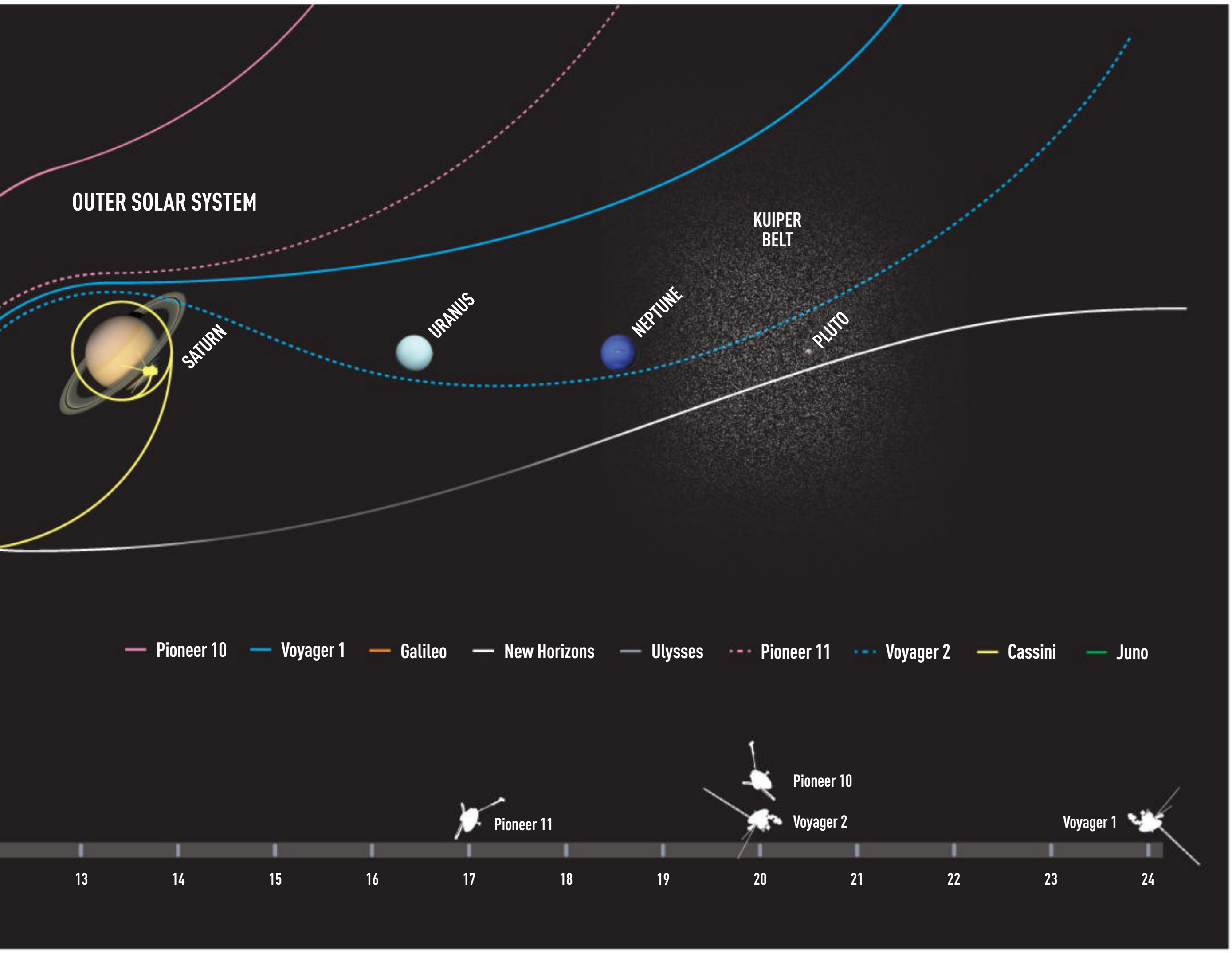
PIONEER 10

LAUNCHED: 3 MARCH 1972

Pioneer 10 was the first probe to cross the asteroid belt, traversing it between July 1972 and February 1973. Arriving at Jupiter in December 1973, it passed some 132,000 kilometres from its cloud tops, and obtained fuzzy images of the four large "Galilean" moons, Ganymede, Europa, Callisto and Io. Now out of contact, this true space pioneer was last spotted coasting towards the constellation Taurus and the red star Aldebaran, which it should reach some 2 million years from now.

CURRENT STATUS:

Last contact 23 January 2003, now estimated to be 20 billion kilometres from Earth



PIONEER 11

LAUNCHED: 6 APRIL 1973

Visiting Jupiter a year after Pioneer 10, Pioneer 11 continued to Saturn, testing the dangers of navigating the planet's rings and flying within 21,000 kilometres of its surface on 1 September 1979. It almost collided with a small Saturnian moon and it photographed Titan, the largest moon. An anomalous slowing of both the Pioneer probes brought long-lasting speculation that the established laws of gravity didn't work in space. The "Pioneer anomaly" is now thought to be down to heat loss from the probes' thermoelectric generators.

CURRENT STATUS:

Last contact 30 September 1995, now estimated to be 17 billion kilometres from Earth, heading towards the constellation Scutum

VOYAGER 2

LAUNCHED: 20 AUGUST 1977

In the 1960s, space scientists realised that a happy configuration of the outer solar system would allow one probe to visit four planets. Voyager 2 remains the only probe to have visited the two furthermost ice giants: Uranus in January 1986 and Neptune in August 1989. Its primary radio receiver failed in 1978, but 40 years on it is still sending back data as it crosses the edge of the solar system, called the heliosheath, and enters interstellar space.

CURRENT STATUS:

20 billion kilometres from Earth, heading towards the constellation Telescopium

›

VOYAGER 1

LAUNCHED: 5 SEPTEMBER 1977

Voyager 1 launched after Voyager 2, but took a faster trajectory to Jupiter and Saturn, arriving at both first. Its route was optimised to bring it within 6500 kilometres of Titan, confirming Pioneer 11's observation that the moon possessed a thick atmosphere. On 14 February 1990, Voyager 1 turned its camera to take the first family portrait of Earth and other solar system planets. Still transmitting from interstellar space, Voyager 1 is now the furthest human-made object from Earth. Both Voyager probes carry "golden records" of sounds and images of Earth for any alien intercepter.

CURRENT STATUS:

24 billion kilometres from Earth, heading towards the constellation Ophiuchus

GALILEO

LAUNCHED: 18 OCTOBER 1989

Galileo was the first mission to spend years orbiting a planetary system, rather than simply passing through on its way elsewhere. On its six-year journey to Jupiter, it turned its instruments on Earth, picking up signs of life such as the absorption of red light by chlorophyll. Inserted into Jupiter orbit on 7 December 1995, Galileo's activities included sending a probe into the giant planet's atmosphere. It also collected data supporting the theory that Jupiter's moon Europa has a subsurface liquid ocean.

CURRENT STATUS:

Mission terminated with a plunge into Jupiter's atmosphere on 21 September 2003

ULYSSES

LAUNCHED: 6 OCTOBER 1990

The prime objective of the Ulysses probe was to survey the sun, but it took a long gravitational slingshot around Jupiter, thus entering an orbit over the top of the solar system that enabled it to monitor the sun's north and south poles.

CURRENT STATUS:

Decommissioned 30 June 2009

CASSINI-HUYGENS

LAUNCHED: 15 OCTOBER 1997

Spending 13 years cruising Saturn's moons, Cassini fulfilled the goal of sending a probe to the moon Titan. During its mission, Cassini captured stunning images of the planet's moons. Titan's methane lakes. Icy Enceladus spouting geysers of hot water. Sponge-like Hyperion. Ravioli-shaped Pan and Atlas. Iapetus with its equatorial ridge battered by ancient craters. Close-ups of those iconic rings engirdling the gas-giant planet itself, and gigantic hurricanes around its poles. What the probe revealed challenged our understanding of planets and their satellites everywhere.

CURRENT STATUS:

Mission terminated in Saturn's atmosphere on 15 September 2017

NEW HORIZONS

LAUNCHED: 19 JANUARY 2006

It is the fastest spacecraft ever launched, but by the time New Horizons reached Pluto on 14 July 2015, its destination had changed: Pluto had been controversially downgraded by the International Astronomical Union from "planet" to "dwarf planet" in August 2006. New Horizons took intriguing photos of this rocky world's hazy atmosphere and surprisingly varied, craggy surface, as well as its moons. It is now cruising through the outer edges of the Kuiper belt finding that this rocky disc extends far further than researchers expected.

CURRENT STATUS:

In the Kuiper belt, 5.7 billion kilometres from Earth

JUNO

LAUNCHED: 5 AUGUST 2011

Unlike previous probes to the outer solar system, Juno doesn't have a nuclear reactor at its heart: it is powered entirely by solar panels. Juno entered into a polar orbit around Jupiter on 5 July 2016, with the intention of measuring the composition and gravitational and magnetic fields of the solar system's largest planet, as well as testing theories of how it formed. Its first results indicated some surprises: huge magnetic and atmospheric storms, and the revelation that Jupiter isn't as uniform as had been assumed. ∎

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CHAPTER 2

THE MOON

The moon was untouched by human footprints for billions of years, until 1969 when two of the Apollo 11 crew members walked on its dusty surface. There was a flurry of activity, with 10 more people following in their large footsteps. Then we stopped visiting our satellite for over 50 years.

Now, there is renewed interest in sending people back to the moon. This time, the motivation is not cold war politics but instead to use it as a stepping stone for further pastures: Mars.

But, in the age of private space travel, getting to the moon is going to look very different this time around.

RETURN TO THE MOON: WHY ARE WE RESTARTING HUMAN LUNAR EXPLORATION NOW?

NASA and SpaceX are among the key players leading a surge of missions to the moon, including crewed ones. Here's what is special about this moment – and why it is happening

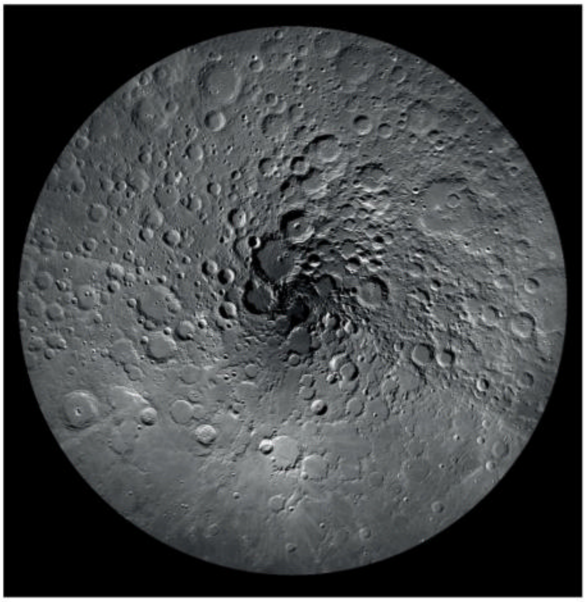
"AS I take man's last step from the surface, back home for some time to come – but we believe not too long into the future – I'd like to just say what I believe history will record: that America's challenge of today has forged man's destiny of tomorrow." These were some of the last words spoken on the moon as NASA astronaut Eugene (Gene) Cernan climbed the ladder back into his lunar module in 1972.

Contrary to Cernan's hopes, no one has since set foot on the lonely, cratered world that orbits our own. But that is about to change, because the US is planning to send people back to the moon by 2025 and set up a permanent base there. Add to that the plans of China and other nations, not to mention the deluge of robotic missions, and it is clear that we are entering a new era of lunar exploration. The question is, after so many years, why now?

The decision to end the Apollo programme was made well before Cernan left his footprints on the moon. "Apollo didn't end because it was too expensive or because it was unsustainable – the sunk costs were already sunk," says Mary Lynne Dittmar, an

NASA PREVIOUS PAGE:SPAWNS/ISTOCK

NASA/CORY HUSTON



NASA/GSFC/ARIZONA STATE UNIVERSITY

NASA's Artemis I, comprising the Space Launch System rocket and the Orion spacecraft, orbited the moon in 2022

influential figure in space policy at the firm Axiom Space. The adventures ended because Apollo was set up to win a politically motivated race, in which the US wanted to beat the Soviet Union to the moon. With that goal achieved, the moon was no longer a priority.

The forces shaping our return to the moon today are dramatically different. In the 1970s, every mission was an epic, do-or-die affair led by the US or the Soviet Union at incredible expense. Each project was defined in advance and then the machinery of the state would strain every sinew to make it happen. Today, the cost of going to space is lower, so many other nations and private companies can afford to get involved. Reduced costs also mean they can try missions out and see what works.

In the past few years, China has ramped up activity, sending a probe to the far side of the moon, among other impressive feats. It has committed to a joint China-Russia robotic research station, and it says crewed missions are possible by 2030, though it hasn't released firm plans for now.

One thing that hasn't changed is that the US is still at the forefront of space exploration. NASA's Artemis programme is taking centre stage. Its first mission, Artemis I, was an uncrewed journey far beyond the moon using the purpose-built Space Launch System (SLS), the most powerful rocket ever built. It launched in November 2022.

The project is set to reach a momentous milestone in 2025 when another two people will follow in Cernan's footsteps, including the first woman on the moon. "One of my deepest hopes, and obviously his, was that Gene Cernan would live to see us back there," says Dittmar. Cernan passed away in 2017. "He almost made it."

It would be easy to be sceptical about NASA's ability to pull off these plans so quickly. After all, the agency has been here before. In 2005, it began a programme called Constellation, with goals that included sending humans to the moon by no later than 2020 and eventually on to Mars. It was binned in 2010. But there is a consensus in the space science community that Artemis is different.

Artemis is one giant collaboration. Various components of the missions are being contributed by the European Space Agency, the Canadian Space Agency, the Japan Aerospace Exploration Agency and others. The design and build of critical pieces of technology, such as moon landers and the planned moon-orbiting space station, will be contracted out to private companies. While the first flights will be powered by the government-owned SLS rocket, NASA's plan is that some subsequent trips carrying cargo to the moon will be aboard Starship, a similarly huge rocket designed and built by Elon Musk's company SpaceX. (It is vastly cheaper to run than SLS and some observers think it could and should end up replacing SLS entirely.)

You might ask why it has taken so long to get to this point. One reason is that humanity's great space project for the past 20 years has been the International Space Station, a collaboration between the space agencies of the US, Russia, Japan, Canada and Europe. This taught us how to have people in space for extended periods. But equally, the time spent ignoring the moon has meant that many of the engineers who worked on the Apollo missions have retired or died, and some of that expertise has to be rebuilt through extensive testing of the new hardware and processes.

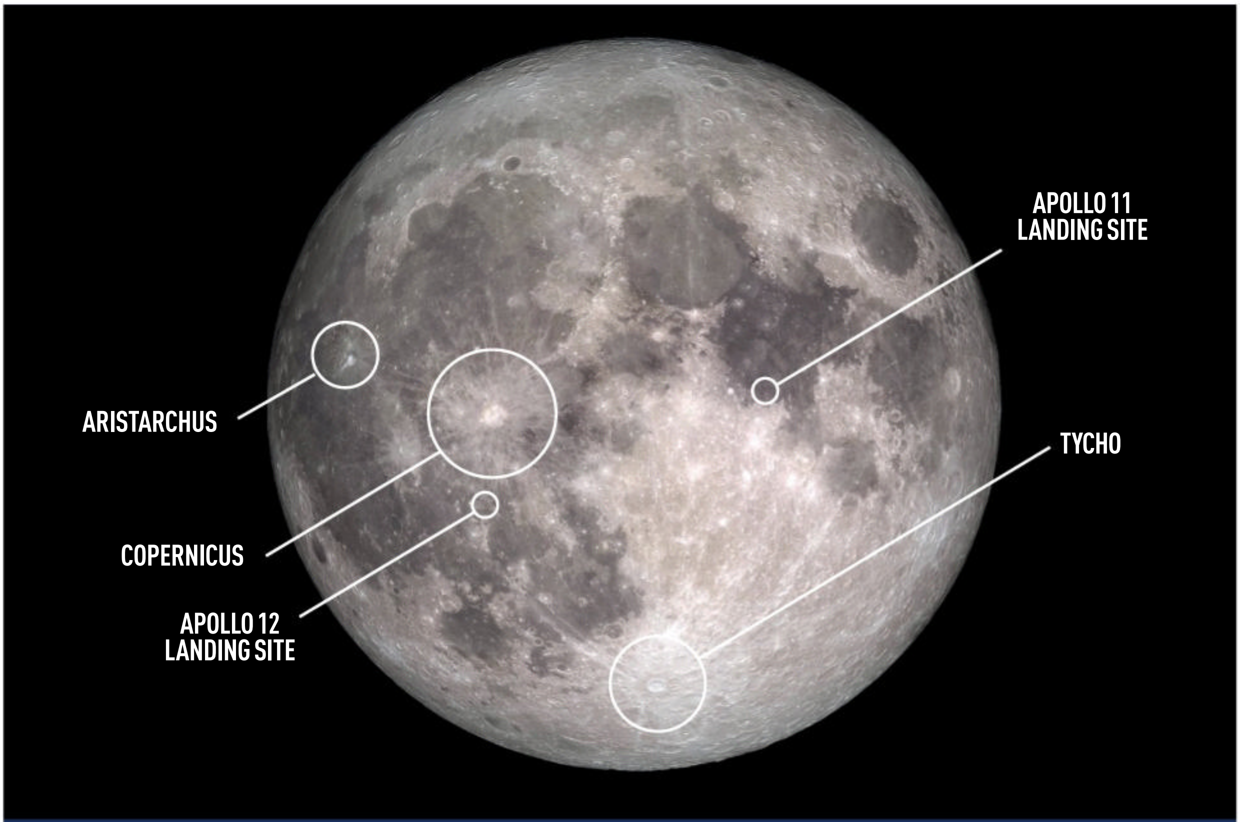
It isn't just the rocket that has to be tested – a massive amount of new technology will be required too. "We're doing everything from food technology, to modifying our toilets so that they're built to last, to the environmental control systems," says engineer Erika Alvarez, who is part of NASA's Artemis team.

To say it is a tricky task would be an understatement, which might make some people wonder: why bother going back at all? There is the chance to cash in on lunar resources. But if you ask NASA, it says its principle rationale is that returning to the moon is a vital precursor for a trip to Mars, where it wants to send a cadre of astronauts by the late 2030s.

The first people to visit Mars will face a nine-month trip to get there and they will have to stay for months before making the return journey. With that in mind, learning to set up an independent settlement on the moon will be essential before we can seriously contemplate a sojourn on the Red Planet. "The moon is a perfect platform to test all these technologies, the equipment, the maintenance and repairs – because from the moon, we can get back home," says Alvarez.

Some argue that sending people off world isn't worth the trouble. If the point is to explore and do science, send robots: they are much hardier and more adaptable than humans. They may not be able to interpret the landscape around them or do science quickly, but they can send pictures and data home.

However, as Dittmar says, perhaps the renewed thrust to send people back to moon is just human nature: our species loves to explore. "Why in the world would you get into something called a boat and go over water when you can't swim through it?" she says. "Why would you go through a mountain pass or over an ice bridge? There's something in our make-up; it makes sense to us biologically. All that's happened now is that our technology has evolved the same way it did to take us out of Africa and across oceans, and now it's evolved to take us off the planet. I don't see it as any different from the rest of human history." ∎



AMATEUR ASTRONOMY:
HOW TO SPOT THE APOLLO LANDING SITES AND DRAMATIC CRATERS ON THE MOON

The moon is our closest celestial neighbour. It is just 385,000 kilometres away, which means it is easy to see surface features using binoculars, and so get a glimpse into its history – and our own.

Unlike Earth, the moon has almost no atmosphere. This means there is nothing to slow down or burn up incoming rocks and dust, so everything hits the surface. And because the moon isn't geologically active, the signs of those impacts aren't erased as they are on Earth. The moon is entirely covered in craters, some billions of years old.

The best time to spot craters is two days either side of a full moon, when light from the sun highlights them clearly.

The first things to notice when looking at the moon are the dark and light areas. The dark parts, called maria, are basalt plains that formed from lava flows – evidence that the moon was once volcanic. The lighter parts are the highlands, made of lighter-coloured rock.

In the middle of the big maria to the left is Copernicus, a crater 93 kilometres wide. You might see long streaks radiating out from it. These were formed by material thrown out by an impact 800 million years ago. We know the age because Apollo 12 astronauts, who landed just to the south, took samples of this material.

You can also use Copernicus to find the Apollo 11 landing site. Look about a third of the moon's width to its right and you can imagine Neil Armstrong stepping out of Apollo 11's lunar module, Eagle, 50 years ago.

To the left of Copernicus is Aristarchus, the moon's brightest crater. Now look at the south of the moon to find Tycho, a giant crater nearly 5 kilometres deep.

NASA/GSFC

WHY NASA IS RETURNING TO THE MOON FOR THE WRONG REASONS

Former NASA deputy administrator Lori Garver helped create the now-booming private space industry. But she says NASA is still too focused on using its moon programme to provide jobs for US workers.

PROFILE
LORI GARVER

As deputy administrator of NASA between 2009 and 2013, Lori Garver's time at the agency was revolutionary. After a long history of NASA controlling all its activities itself, Garver set it on a new path, building up companies so that they could do some of the agency's work more efficiently and cheaply.

You played an important part in creating a private space industry. What initially motivated you?
At the time, NASA had a very full plate and the Space Shuttle programme was expensive. Freeing up budget from human space flight was a huge motivation; we wanted to offload some of the expensive routine activities.

Do you think there are good reasons to send people back to the moon now?
Human space flight can offer transformative change for us. In the long term, being a single-planet species puts humanity at greater risk of extinction than if we were a multi-planet species. So it would be good to aim to go to Mars in future, and the moon is a first step.

And is US human space flight in general on the right path?
At the moment, NASA is spending a lot of money on SLS [Space Launch System, a rocket designed to carry people back to the moon]. SLS is probably not sustainable at this cost, so we should be looking at systems to replace it.

The reason we are going back to the moon now is really because the building of SLS created jobs for US workers, and members of Congress with those jobs in their districts wanted to keep them. Some better reasons would be in order to inspire people, for reasons of geopolitics and for economic return. We ahould be going about it in a way that maximises those goals instead.

Lori Garver played an important role in kick-starting the space industry

NASA/BILL INGALLS

Did you expect commercial companies to have such a big part to play in the return to the moon?

I did not. Without Elon Musk and Jeff Bezos as outside visionaries who want to put their own capital at risk, this lunar programme would not be sustainable. They seem willing to put their own money in and not make money on contracts. That is something we at NASA never really envisioned.

Are there any downsides to allowing companies to operate on the moon?

The development of lunar and other celestial resources requires regulatory frameworks that aren't as fully developed. We need increased focus on that to manage private property rights and to make sure people are sharing limited resources successfully. All the reasons we have laws and regulations on Earth, we need to find ways to have in space. At a minimum, we need to not allow these companies to operate off the grid.

Do you see the military playing a role in lunar exploration?

I hope not. There are certainly people in the military who have an interest in it. But I'm not aware of why we would need it. Expanding military operations should not be a goal for society. I understand there's significant advantage to our national security from space activities. But let's hope a shooting match on the moon is not our future. ∎

WHY MILITARY FORCES SEE THE MOON AS A NEW STRATEGIC PRIORITY

The US Space Force is already taking steps to protect future bases on the moon. Could this lead to other powers like China escalating their own military activities up there too?

WITH renewed push for the moon, and the lucrative returns that might result, military interest is inevitably following. "The United States is certainly aware the moon could have tremendous long-term economic potential," says Peter Garretson, a defence expert at the American Foreign Policy Council, a US think tank. "The military doesn't want an outpost to be threatened due to the lack of a sheriff." Yet even in these tentative early stages, there are concerns that military activity could snowball. If we are to return to the moon, how much of a role, if any, are we comfortable with the armed forces playing?

US military interest in lunar space dates back to the dawn of the space age. In 1959, the US Army proposed a crewed military outpost on the moon called Project Horizon. Notions of such bases, as well as nuclear testing on the moon, had supporters during the cold war too.

Those proposals never gained traction, but recently there has been more concrete interest and action. The US and Chinese militaries have spoken about conducting surveillance beyond Earth orbit for years, says space policy expert Bleddyn Bowen at the University of Leicester, UK. This would include things like using satellites to track debris from rockets in order to prevent collisions between spacecraft in lunar orbit. "If the moon is going to be a busier place, you're going to need more infrastructure to support it," he says.

Evidence for this came in March, when a discarded rocket booster, believed to be of Chinese origin, hit the moon, having been untracked for years following its launch in 2014. "Eventually, there will be astronauts on the moon," says Vishnu Reddy, a space tracking expert at the University of Arizona. "The chance is very small of them getting hit by something. But we've clearly seen that it is a possibility." Part of the military's role in relation to the moon could be preventing such accidental impacts.

The US Space Force, the sixth branch of the country's military that was founded in 2019, is now taking action on this. In March, it announced it was developing the Cislunar Highway Patrol System (CHPS) satellite in collaboration with the Air Force Research Laboratory. The plan is for this craft to test technologies to track objects up to and beyond the orbit of the moon for the first time. Prototype proposals have been submitted, with a contract due to be awarded to a manufacturing company soon.

Experts agree that tracking of this sort will be useful. But it is "not clear why this has to be the military and not a civilian programme", says astronomer Aaron Boley at the University of British Columbia, Canada.

Having the US military involved in our future on the moon could lead to a scenario where the forces of other countries, such as China, feel the need to escalate their activity. There was an incident earlier this year in which US and Chinese satellites in a geostationary orbit about 36,000 kilometres above Earth came into close contact and manoeuvred to get a better look at each other.

"You've got the US and China each casting suspicions about what the other might do," says Brian Weeden at the Secure World Foundation, a US think tank that promotes the peaceful use of space. "That is going to send exactly the wrong signal."

Only the US appears to have made public its lunar military ambitions so far, though. "No one else has expressed a military interest in the moon," says Jonathan McDowell, an astronomer at the Harvard-Smithsonian Center for Astrophysics in Massachusetts. "There's a danger that the rhetoric that the US military is playing with will generate military interest in the moon where there really is no need for it."

While Russia has been relatively lacklustre in terms of moon exploration lately, China is generating concern among some Western observers. China's ongoing lunar programme – which has included sending a rover to the far side of the moon – has already raised some red flags, says Garretson, with the West struggling to figure out what to make of the intentions of a civilian-built but military-run effort.

China's equivalent of NASA is the China National Space Administration, a civilian organisation. But the body actually in charge of human space flight is the China Manned Space Engineering Office, which is part of the military. Similarly, infrastructure such as launch pads and satellites are mostly run by the People's Liberation Army. China has also sent up a communications satellite called Queqiao and Garretson says this could be used for military applications. ∎

ESA/FOSTER + PARTNERS

WHAT IT WILL TAKE TO BUILD A PERMANENT MOON BASE

The US wants to build a long-term human outpost on the moon by around 2030. Here is all the tech that will be needed, from a space station in lunar orbit to a way to avoid 'space hay fever'.

"APOLLO was awesome, but a lot of it was to just prove that we could do it," says NASA's Steve Creech. "I'm not saying it wasn't important, but this time we want to do it in a way that's sustainable and that leads to next steps." In other words, this isn't just about going back to the moon. It is the first glimmerings of what many hope will be a sustained campaign of human space exploration.

NASA's plans could hardly be bigger. They feature astronauts on moon buggies and long-term bases with power grids and mining operations. And with the first steps already being taken, this is set to happen by roughly the end of the decade. All of which seems wildly ambitious – and begs the question, what fresh technologies will such adventurous feats require?

Lunar astronauts could live in 3D-printed domes that protect them from radiation and dust

To begin with, the Artemis missions will largely be repeating feats managed during the space race. Artemis I orbited 130 kilometres above the moon's surface for six days, allowing the Orion craft – the capsule intended to carry astronauts – to be tested in space. Artemis II, planned for 2025, will involve a crewed fly-by of the moon. Then, in 2026, the third mission in the programme is set to see people land and walk on the moon again, including the first woman to do so. "I think that seeing women, people of colour, the next generation, walking on the moon can do a lot of the things that it did in the 1960s, can inspire people to go into science and drive the technical state of the art," says Lori Garver, a former deputy administrator of NASA.

From here, the plan is for things to change radically. For starters, NASA aims to put a space station known as Gateway in lunar orbit. The idea is that this will allow a reusable lander to shuttle between orbit and the surface, making trips to the moon's surface cheaper and easier. The agency has already contracted the aerospace company Northrop Grumman to build two founding components of Gateway: a place for astronauts to live, known as the Habitation and Logistics Outpost, and a segment to provide power and propulsion. Artemis IV, which may launch in the second half of the 2020s, will carry these components into lunar orbit. Artemis V, the last mission NASA officially has planned (with no set date as yet), will be the first to see humans drive a rover on the moon. It will also deliver a new refuelling module to Gateway, built by the European Space Agency and partner companies.

Aside from all that new infrastructure, the science carried out on these missions will be different too. The plan is for the Artemis landings to be near the moon's south pole, which is of particular interest because of its abundant water ice. Astronauts staying on the moon will need a local supply of drinking water, as it is too heavy to transport from Earth. What's more, water can be split into oxygen and hydrogen, the first being vital for breathing and the second for fuel to power the ›

WHAT WILL LIFE BE LIKE ON THE MOON?

The moon's south pole, 2037. NASA and its contractors have built a habitation staffed by a rotating crew of astronauts, much like the International Space Station was until it was shuttered in the 2020s. There is a power grid of solar panels and several rovers parked outside. When the crew look out of the windows, they can just make out the water ice mining station in permanent shadow at the bottom of the nearby crater.

Life here is no cakewalk. Because of the moon's slow rate of rotation, astronauts will face periods of two weeks of complete darkness and temperatures dipping below -173°C (-279°F), followed by two weeks of around-the-clock sunshine and temperatures above 100°C (212°F). It means sleep can be a challenge and going outside to make repairs and do science is dangerous.

The crew handle this by planning their outdoor adventures to coincide with the lunar dawn, when temperatures are more reasonable. Their suits are also specially designed to reflect sunlight and resist heat, plus they have cooling systems inside. One of the best things, they all agree, is that the suits are tailor-made, rather than coming in standard sizes like in the Apollo era.

The time delay for communications to Earth is just over a second, so they can place a video call home whenever they like and see their families' faces. Occasionally, rich space tourists pay them a visit and the astronauts have to smile for a selfie.

rockets that could potentially launch from our lunar staging post to Mars and elsewhere.

The moon's water ice is far colder than the ice cubes in your freezer and it is distributed through the lunar rock. Understanding how the ice behaves and how we can best make use of it is going to be crucial, and it will require a host of new technologies. Investigations are due to begin later this year, when the Nova-C lander – a partnership between NASA and US aerospace firm Intuitive Machines – will try drilling almost a metre into the lunar "soil" to extract and analyse the ice.

The next step will come when humans return to the moon as part of Artemis III. A key element of their mission will be to retrieve ice samples and bring them back to Earth, where they can be more thoroughly analysed. That might sound simple – we have freezers, after all. But we will need to invent a special kind of freezer. "The samples will have to be kept extremely cold at all times, so those freezers need to be able to be transported between all of our vehicles and stay cold," says Erika Alvarez, part of NASA's Artemis team.

It is not just ice in the moon's crust that scientists are interested in. China has recently announced that samples of the moon returned to Earth in 2020 through its Chang'e-5 mission contain a previously unknown mineral. This mineral contains phosphate, a key nutrient for plants, and helium-3, which could potentially be used as a fuel.

Eventually, the plan is to construct a surface habitat called Artemis Base Camp so that astronauts can remain on the moon's surface for days or perhaps even weeks, collecting samples and data. And though it might seem like a small step from spending a few hours on the surface to staying for a few days, it requires a huge leap in technology.

Before they can even begin to build a base, the explorers will need a power grid. Solar power will be possible, but the base will have to stay operational through periods of darkness lasting about two weeks. Temperatures during these periods can dip below -173°C (-279°F). "You've got to have a grid that can sustain itself in that environment, that can generate enough power to do everything from life support to literally keeping the lights on to operational support," says Mary Lynne Dittmar at private firm Axiom Space. NASA is working with the US departments of energy and defence to develop a small nuclear power plant for the base.

Once power is established, there is the problem of actually constructing the base. When it comes to space flight, mass is everything – it isn't feasible to send all the materials to build an entire base camp, along with tools, supplies and astronauts, to the moon. Instead, several teams of researchers are evaluating how we might make building materials from the resources that will be readily available on the moon. This might mean mining stone, making bricks from lunar dust or even 3D printing with materials made from dust.

The trouble is that handling moon dust is tricky in the extreme. Because there is no wind or rain to smooth the particles, they are spiky and electrostatically charged, meaning they stick to everything, including spacesuits and tools. We know from the Apollo missions that it is tough to keep moon dust out of airlocks – and once it is inside, it can be breathed in, causing "space hay fever". NASA is already working on dust mitigation strategies, from nanocoatings for equipment to special filtration systems for habitations. All of which is a reminder that everyday life for astronauts on the moon will be far from straightforward. ∎

"I GO TO WORK TO DO COOL THINGS WITH MY FRIENDS, LIKE GO TO THE MOON"

Christina Koch, who will become the first woman to go to the moon with the Artemis II mission, on what space smells like, why it is difficult to return to Earth and how astronauts play human bowling.

PROFILE CHRISTINA KOCH

In 2019, on astronaut Christina Koch's first mission to the International Space Station (ISS), the NASA astronaut lived in space for 328 days – the longest time any woman has spent there. On the Artemis II mission, scheduled for November, Koch will spend 10 days on a trip to circle the moon with three other astronauts.

What was it like to be up there on the ISS for so long? Did you feel cooped up?

I was very lucky that I got to spend almost 11 months on board the ISS as my first space flight mission. I never got cabin fever. It was pretty far into my mission before I realised, "I haven't felt the wind on my face in a long time, I miss that." There were definitely days where I would go over to our tiny greenhouse, which is about the size of a couple of shoe boxes, and just smell the plants. Just to smell something that was organic, that actually did a lot for me.

I've never really thought about the smell aspect – does the space station smell like anything? Body odour, maybe?

You know, if it does, we get nose blind to it very quickly. The main smell that I think most new folks notice is almost a metallic one. We sometimes say it's the smell of space. When we have a visiting cargo vehicle come and dock and we first open that hatch, there's a space in between the station and the cargo vehicle that has been exposed to just the open vacuum of space. It has this weird metallic smell.

How did it feel to break the record for the longest space flight by a woman?

A lot of people talk about this individual accomplishment of having a record. I like to think of it not so much as that, but that the milestone is important because it communicates where we are and what the state of the art is right now in human space exploration. I hope that the record I set is exceeded as quickly as possible.

I also used it as inspiration. Those days when I didn't necessarily feel up to it, I knew I had to bring my best and try to get the most out of every day because what ›

“Every person I’ve loved, every forest I’ve walked in, will be far away on that one planet”

I was doing was different from the usual ISS mission. It was an ultramarathon, not a marathon.

Doing that sort of thing is important for medical research on how long-term space flight affects women, right?
I think that I would characterise it as the long-term effects on any human, and the fact that I happen to be female could illuminate where there would be a difference. In general, anything we see that’s a difference between men and women, whether on the ground or in space-flight adaptation, is an area to explore.

Is this one reason it is so important to have a diverse astronaut corps?
Absolutely. Collectively, we’ve made the decision that it’s important to be representative of everyone that we are carrying dreams for as we explore. NASA made this decision many, many years ago, and that’s why now we have an astronaut corps that represents everyone. The reason that’s important is manyfold. Plenty of studies have shown that missions are more successful when you have a diverse group of people contributing to them. Not only will we discover more, get there more efficiently, learn more and be more successful because we’re diverse, but we will inspire a larger segment of the population when people look at the astronaut corps.

I know that there’s a lot of work to be done on the space station, but do the astronauts up there get to unwind and have a laugh sometimes too?
Human bowling is something that we do on our off time. We do have time off as astronauts: we have weekends, typically, and, of course, there is time after work. We work about 12 hours a day, five days a week, and then some extra hours on the weekend. But when we do have time off, we definitely take advantage of the fact that we are in microgravity. Human bowling is where one person kind of gets in a cannonball position and either someone throws them or they launch themselves off some handrails. Then the rest of the crew is sort of standing like the pins in bowling. And the idea is that you have to, you know, bowl with your body. There has also been human surfing.

Is that just one person standing on top of another?
Yes.

Now that you are back, are you looking forward to your next mission, travelling around the moon as part of the Artemis programme?
I’ve been excited about it for many years, and to be a part of it as a crew member is a complete dream come true. The moon has been something that has inspired me for my whole life, really. I love gazing at the moon, I always have, and I think seeing it up close will really bring that perspective that it is a real and separate body in open space.

I can only imagine what it’s going to be like to look back at Earth and see the whole thing out the window. To know that everything, every person we’ve ever loved, every forest I’ve ever walked in, is all far, far away on that one planet.

What has the training been like so far?
It’s been a lot of different things. There are a lot of people to meet. There are a lot of things to learn about, things that have been in the works for many, many, many years. So, part of what we’re doing is actually a lot of travel to meet the far-flung teams – every time we meet the teams, we learn both the technical side of

NASA

Christina Koch will become the first woman to go the moon on NASA's Artemis II mission

what they are doing and also their culture. We learn what we need to know to feel that sense of trust in the vehicle, and they learn what they need to know to see who their operators are going to be.

But then, of course, we have the real technical training, the hardcore stuff, which typically happens at the Johnson Space Center in Texas. It's been classroom work: a lot of background theoretical knowledge about the spacecraft, about the mission, about the orbital mechanics and about the science that we can do during the journey.

Now, we're moving into the phase where we get a little bit more hands-on. We're getting to play with the displays, we're getting to learn the flight software; eventually, we'll do full-length simulations with the mission control teams all over the world. And then there's the [full] hands-on stuff: there's getting in suits, getting into the vehicle, learning how we're going to get out of the vehicle if and when we need to, working with the recovery team. I think the biggest takeaway is how many people it takes to put together a mission like this and the awe of being a part of it.

Are you disappointed that you won't get to walk on the moon?

I am nothing but stoked to be a part of this mission. I am so excited that I'll get to watch some of my friends walk on the moon, that I will know those people, that I'll know the teams that got them there, that I will know the whole process that they've gone through in the Artemis programme.

I am just really excited that we are doing this, and to have a role to contribute is really just where the dream comes true for me. Every single day I wake up and come to work, I feel like I am going to work to do cool things with my friends, like go to the moon. ∎

CHAPTER 3

THE INNER SOLAR SYSTEM

Along with Earth, Mercury, Venus and Mars form the solar system's rocky planets, a stark contrast to the bloated gas giants that make up its outermost worlds. Even though the inner planets are relatively nearby, they are incredibly hard to visit.

The environments around Mercury and Venus are hostile to say the least. Only two spacecraft have ever made it to Mercury and of the numerous Venus landers, none survived longer than 90 minutes. Meanwhile, touching down on another planet's surface is a fragile business. Since 1971 there have been 20 attempts to land robots on Mars, over half of which have either crashed, fatally malfunctioned soon after landing or missed the planet altogether.

Remarkably, though, we have landed on and returned rocky time capsules from asteroids travelling through the inner solar system.

MISSION ICARUS: TOUCHING THE SUN

The Parker Solar Probe was sent to unlock the secrets of our star by flying into its fiery atmosphere – a mission that pushed technology to the limit.

OUR sun is no serene orb. Every now and then its fiery surface turns explosive, sending matter, energy and magnetism whirling into the surrounding vacuum.

In 1859, a particularly violent solar flare-up coincided with a huge electromagnetic storm in Earth's atmosphere. The interference caused polar auroras that could be seen as far south as the Caribbean and as far north as Auckland, New Zealand, and knocked out telegraphic systems.

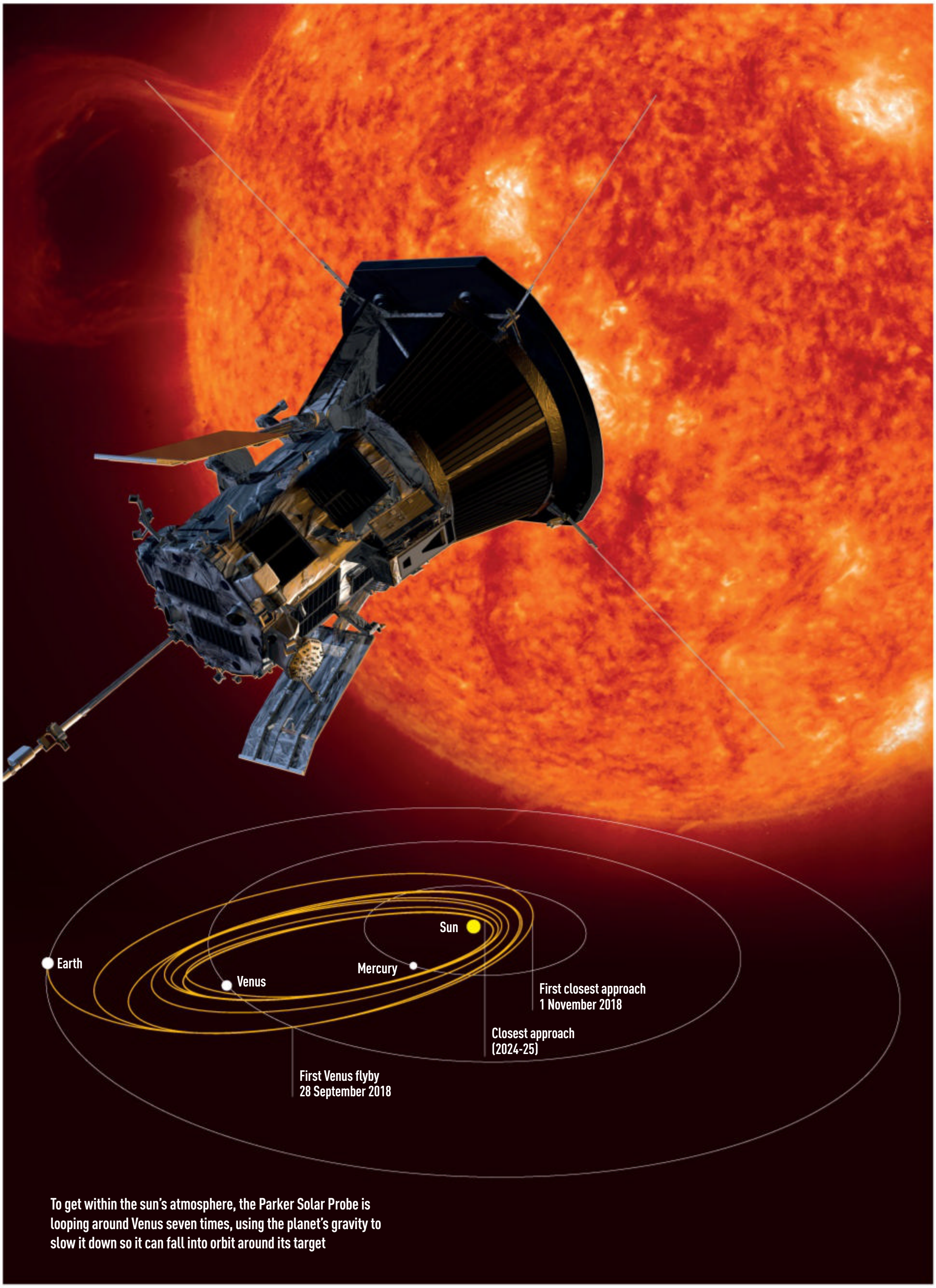
That was when we first grasped the power of solar storms on Earth. But what caused them remained unknown. In 1956, Eugene Parker, a young postdoctoral fellow at the University of Chicago, was investigating cosmic rays arriving at Earth from far off in the galaxy when an idea struck him. "The sun's atmosphere, the corona, is not tightly bound. Stuff can escape, and the whole thing acts like one big gaseous outward wind. It starts off very slow, but gets faster and faster, and by the time it's out at Earth, it's supersonic. It sweeps cosmic rays to Earth – and blows the comet tails in the opposite direction."

Fears of a repeat of the 1859 storm – one that might wreak havoc with modern power systems, satellites and communications networks – fuelled a growing desire to take a closer look at the solar wind. The details of this process remained enigmatic, and various missions were planned to fly into the solar wind to investigate. In 1976, the Helios-B spacecraft made it to within 42 million kilometres of the sun's surface, inside Mercury's orbit. But there was a fundamental technological barrier to getting any closer: no material existed that was lightweight yet heat-resistant enough to shield the probe's instruments from the sun. The magic material turned out to be carbon. Specifically, carbon technologies developed in the 2000s that were light and strong enough to withstand the sun's heat.

The Solar Probe Plus mission, approved in 2009, looked very different from previous proposed sorties to the sun. That was down to a shortage of plutonium radioisotope fuel for nuclear-powered spacecraft, which led NASA to favour purely solar-powered missions – and ironically that becomes a particular problem when you want to visit the sun.

"If you want to launch directly from Earth to the sun, you need 55 times more energy than to get to Mars," says mission scientist Yanping Guo. "It's more than twice even what you need to get to Pluto." One solution is to fly by other planets in order to gain an energy boost from their gravity. Jupiter, the most massive planet in the solar system, was the obvious choice for this mission, but it orbits so far out that the probe would lose out on solar power. Eventually, Guo found a trajectory with seven Venus flybys that passes the sun 26 times, getting closer and faster each time.

In May 2017, NASA renamed the probe after Parker. In April 2021, it became the first spacecraft to enter the upper atmosphere of the sun, called the corona. ∎



To get within the sun's atmosphere, the Parker Solar Probe is looping around Venus seven times, using the planet's gravity to slow it down so it can fall into orbit around its target

NASA/JOHNS HOPKINS APL/STEVE GRIBBEN PREVIOUS PAGE: NASA/JPL/CORNELL

MARC_HILTON/ISTOCK

AMATEUR ASTRONOMY:
HOW TO SEE THE NORTHERN LIGHTS

The northern lights are generated by the solar wind – a stream of charged particles travelling from the outer layer of the sun, or corona. Bursts of solar wind, called solar flares, slam into Earth's magnetic field, which acts like a shield around the planet that deflects most of the particles. But at its weakest points around the poles, some particles penetrate into the upper atmosphere, where they collide with and excite, or energise, gas molecules. As these molecules lose energy again, they release photons of light that make the auroras.

The type of excited molecule, along with the altitude of the collisions, determines the colour of each aurora. The most common are pale yellow and green from oxygen molecules around 120 to 180 kilometres up. Less frequent are red auroras, generated from oxygen around 200 km above the ground, while red-purple auroras come from nitrogen below 100 km.

The stronger the solar flare, the further south the northern lights will be visible. The particles take around a day to travel to Earth, so we can predict up to a day in advance how strong the aurora is likely to be. Keep an eye on forecasts (such as the US National Oceanic and Atmospheric Administration site) and aurora prediction apps (such as AuroraWatch UK) .

The level of activity can change quickly, so your best bet is to rely on live reports of solar activity. If you are unsure where to go, find somewhere dark and look towards the northern horizon. Then you need to wait and let your eyes adjust.

Don't expect to see the stunning, bright colours shown in photos. When you view them with the naked eye, auroras are much subtler and can be tricky to spot the first time you try. If you have a camera with a digital display, looking through the display can help confirm that you are seeing an aurora, as sometimes they can appear greenish-white to the eye, but very green in the camera.

MERCURY AND VENUS: A PAIR OF SIZZLING COALS

You could be forgiven for thinking these strange worlds were two circles of hell: Mercury, a black and blasted plain, and Venus, a sweltering world beset by rain of pure acid. So, what caused these seemingly Earth-like planets to become so resolutely, well, not?

THE biggest problem when it comes to planning a trip to Mercury is the sun. When your next-door neighbour is a star 6 million times heavier than you with a gravitational field 80 times stronger, visitors tend to get redirected.

If a spacecraft flies by Mercury too quickly, it will be trapped by the sun's powerful gravity and dragged to its doom. But even heading straight for the planet doesn't guarantee you will arrive. The sun has so much gravity that a direct mission to Mercury will always miss.

We didn't know how to get into orbit around Mercury until the mid-1980s, when Chen-Wan Yen at NASA's Jet Propulsion Laboratory in California figured it out. A spacecraft has to take the scenic route, with loops around Earth and Venus and multiple swoops past Mercury to slow it down before it can enter orbit.

The first probe to visit was Mariner 10, which flew past, rather than orbiting, just three times in 1974 and 1975. The second was Messenger, which orbited for four years from 2011. "We had Mariner 10 go by, and it was craters and all a little bit boring," says David Rothery at the Open University, UK. "We would still wonder if Mercury was boring if we hadn't had Messenger there to prove it wasn't."

One thing Messenger experienced directly was just how hot the planet gets. The orbiter had to periodically back away from Mercury just to keep its instruments cool – on the day side, the surface reaches temperatures of up to 430°C (806°F). And because there is barely any atmosphere to hold heat in and spread it around the planet, the temperature drops precipitously on the night side when the sun sets – down to about -175°C (-283°F). Day and night are drawn-out affairs, too: with an average of 176 Earth days elapsing between sunrises, one day is longer than the planet's year.

These temperature extremes mean life as we know it is almost impossible on Mercury. There are a few sunless craters near the poles that may have a small amount of water ice, but they are probably too cold for liquid water, with little or no oxygen. The low surface pressure and lack of air make it even less hospitable.

More problems come from within. Mercury has signs of what is known as explosive volcanism, a more dramatic type of eruption. Elements that boil at relatively low temperatures, known as volatiles, form gas bubbles in lava, which pop at the surface to spew hot liquid rock in all directions. Most of these eruptions seem to have happened about 3.8 billion years ago, when much of Mercury's interior was still molten from the heat of formation.

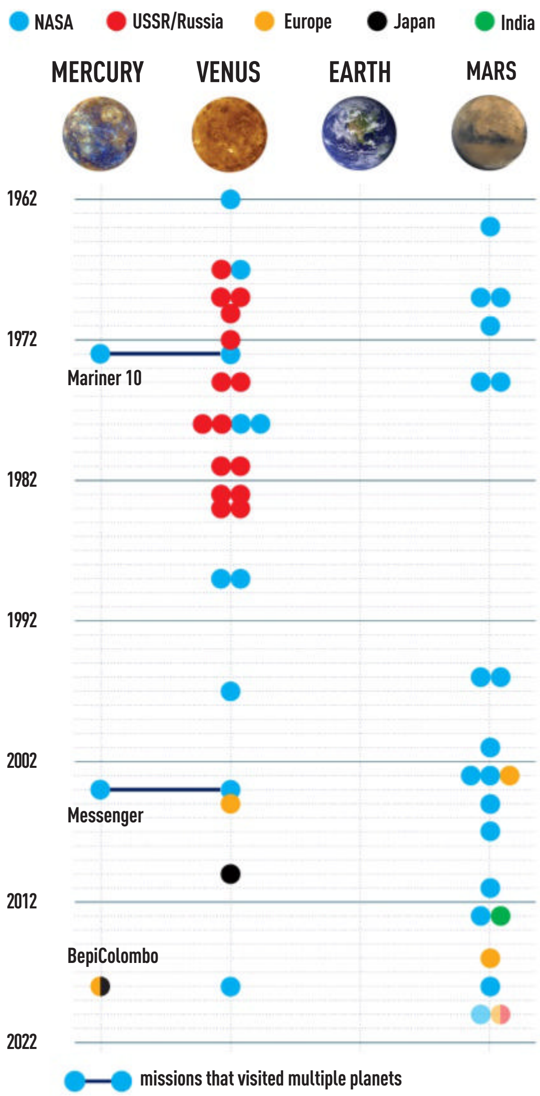
In theory, most volatile elements on Mercury's surface should have already boiled away due to its proximity to the sun. But they are still there. On a planet with no liquid water and little weather, these volatiles play a key role in shaping Mercury's surface features. In addition to powering its volcanoes, they are also responsible for Mercury's most un-Earth-like attribute. Instead of an atmosphere, the tiny planet has an exosphere, a thin and tenuous layer of particles floating above the surface.

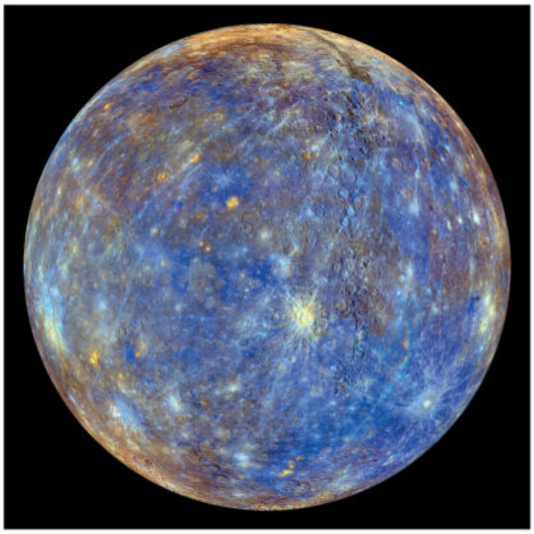
The exosphere is mostly hydrogen and oxygen, with some helium, sodium and potassium as well. It probably forms when charged particles from the sun sneak through the planet's magnetic field and hit the surface, sending tiny particles of dust and gas flying.

You read that right: Mercury is slowly shrinking. The process isn't only powered by evaporation, either. As its molten core began to cool, the planet started to solidify, causing its surface to contract. Cliffs on the surface that can be up to about 1000 kilometres long and 3 kilometres high show that its diameter has shrunk by several kilometres since its crust formed, crumpling the landscape. As Mercury's surface is all one shell rather than several tectonic plates, these cliffs probably couldn't have formed any other way.

But despite millions of years of cooling, some of the core is still liquid. Part of the reason it has taken so long to freeze may be simply that the core is enormous. It takes up 85 per cent of Mercury's radius – far more than any other planet we know of. Dig just a few hundred kilometres through the crust and you will hit molten iron-rich core. On Earth, you would have to dig almost 3000 kilometres to reach the outer edge of the core.

Exploration of our solar system used to be mainly about Venus, but in recent years, Mars has been prioritised. Of the four rocky planets, Mercury remains relatively unloved





NASA/GSFC

Young craters appear light blue or white on this image of Mercury

This thin veneer of rock over a huge core, combined with the unexpected volatiles, has led some researchers to conclude that Mercury may have formed further from the sun and then smashed into another, larger protoplanet as it migrated inward, stripping off its rocky outer layer. Without this hit and run, Mercury might be a much bigger planet, and one more structurally similar to Earth.

Planetary scientists are still scratching their heads over the mysteries Messenger revealed. Which is where BepiColombo comes in. The hope is that it will answer some of those questions. BepiColombo consists of two orbiters that will separate when they reach Mercury and provide the most comprehensive global view we have ever had of the strange little world. It launched in 2018, but because of the convoluted path necessary to skim safely into orbit, it won't arrive until the end of 2025.

Meanwhile, Venus has been unloved of late. "Venus is sort of the middle child," says Tracy Gregg of the University at Buffalo in New York, less loved than it siblings Mars and the gas giants. Of the 27 successful visits since 1962, only five occurred after 1990. That means our knowledge is even less up to date than it is for Mercury. It isn't that Venus is particularly hard to get to – it is just hard to learn about once you get there.

"The Soviet landers lasted between an hour and an hour and a half on the surface before, essentially, they cooked," says Gregg. Surface temperatures are around 470°C (878°F), with crushing pressure from the heavy atmosphere 90 times that at sea level on Earth.

Venus's inhospitable conditions have very different origins to Mercury's. Venus is hot because of a runaway greenhouse effect – its thick carbon dioxide atmosphere traps heat near the surface. That thick haze, which inexplicably rotates 60 times faster than the solid planet, means that the heat gets distributed all around the world instead of radiating away into the chill of space at night. Unlike Mercury, there is no cold side.

Venus is a place of mysteries. From radar data, we can see that it has what appear to be volcanic landforms: channels carved by lava, plains of volcanic rock and in excess of 1600 major volcanoes – more than anywhere else in the solar system, even though there is no evidence that they are active now. It is also home to the longest channel in the solar system, which once carried lava nearly 7000 kilometres. But nobody knows where the lava came from or where it went after creating the channel.

There are also strange bright areas of terrain called tesserae, which tend to be full of long ridges and troughs that form when the crust shifts due to tectonic activity. There have been hints from landers that these areas may be rich in silica, like continental crust on Earth.

If Venus and Earth formed close to where they are now, they should have about the same amount of water, whether they formed with it or got it from meteorites later on. There is no obvious reason for Venus to be so different, aside from maybe that a lack of plate tectonics made it difficult to sequester carbon dioxide in rocks.

Early in its history, Venus may even have been pleasant for life, with surface water and a less dense atmosphere. Not now. "Being on the surface is like diving in the ocean at a depth of around 1 kilometre, and it's also like an incinerator," says Pedro Machado at the Institute of Astrophysics and Space Sciences in Portugal. "There are better places to go for a holiday." ∎

To get to Mars, we will need to blast off from Earth with more supplies than we have ever put in space before, traverse millions of kilometres of deadly interplanetary nothingness and land safely at the other end. It is daunting, but it isn't out of the question. Here is our step-by-step guide.

MISSION TO MARS: THE COMPLETE GUIDE TO GETTING TO THE RED PLANET

COKADA/ISTOCK

Humans have launched many spacecraft to Mars since the 1960s – whether to pass by, orbit, land on the surface or more recently to rove around – with varying success

- US
- USSR/Russia
- Japan
- Europe
- China
- India

- Successful
- Unsuccessful
- Passing probe
- Orbiter
- Lander
- Rover

1960s

Mars 1
Missed Mars by 200,000 kilometres

Mariner 4
Took 22 pictures from a range of 10,000 km, the first "close-ups" of another world

Mariner 6
Flew past at a range of 3431 km and returned images

1970s

Mariner 9
First spacecraft to successfully orbit another planet

Mars 2
Orbiter successful but lander struck the surface before it could deploy its parachute

Mars 3
Landed successfully but fell silent shortly afterwards

Mars 6
Struck the surface travelling at 600 metres per second

Viking 1 and 2
Landed safely with instruments to measure water, heat and soil chemistry, bringing the first comprehensive information from Mars's surface

1. LEAVING EARTH

When Earth and Mars are at their closest, they are about 55 million kilometres apart. That sounds like a lot. But in terms of the propulsion systems needed, travelling that distance through space isn't actually too big an ask of our existing rocket technology.

Once you are far enough from Earth, its pull drops considerably and you could cruise to Mars using a reduced thrust. The journey would take about nine months, a little longer than an astronaut's standard six-month stint on the International Space Station (ISS). We don't need to dream up new types of engines or worry about things like solar sails, which accelerate very slowly. All we need is a big rocket pointed in the right direction.

Decades of space exploration have taught us a few things, chief among them being how to build big rockets. There are seven types of rocket in operation that could make it to Mars. The most powerful of these, SpaceX's Falcon Heavy, could shuttle about 18.5 tonnes there. That is more than enough for any lander or rover, but a human mission will be heavier. A crew of six, along with food and water to last their journey there and back, weighs in at a minimum of 20 tonnes. In 2017, a NASA report estimated that once you factor in scientific equipment and the kit needed to keep explorers alive on the surface – like a power generator and a place to live – a more realistic figure would be about 100 tonnes.

That isn't unthinkable. Two rockets developed recently, NASA's Space Launch System (SLS) and SpaceX's Big Falcon Rocket (BFR), are more powerful than anything that has been launched before. SLS should be able to carry at least 45 tonnes of cargo to Mars, and BFR is expected to haul more than 100 tonnes.

In other words, building bigger, better rockets is something we know how to do. And we could always lighten the load by sending some equipment ahead of the humans.

2. IN TRANSIT

It might seem as though humans have got to grips with surviving off-planet. After all, the ISS is permanently crewed. But as space exploration goes, visiting the space station is like camping in your back garden. You might feel like you are away from home, but your parents are still bringing you sandwiches. If you are going to Mars, you need to take your own sandwiches. ›

Except it isn't just food you have got to worry about. If the spacecraft breaks, you must have the spare parts and tools to fix it. If you get sick, you need the right medicine. But packing for every eventuality isn't possible, given that extra weight means more fuel and more expense. What do you do?

Part of the solution will be to take 3D printers that can produce parts on demand. The ISS already has one on board and NASA has been experimenting with it. So a Mars trip could pack a printer and raw material, rather than a bunch of parts that might not be needed.

Stocking the medicine cabinet is trickier. Our experience on the space station shows germs can thrive in spacecraft. And studies have shown that bacteria growing in simulated microgravity can develop resistance to a broad-spectrum antibiotic, and they retain that resistance for longer than they would on Earth. There are projects in the works to mitigate this, including antibacterial coatings for surfaces that might get dirty, like toilet doors. There is also a suggestion that astronauts could bring along raw pharmaceutical ingredients instead of fully formulated medications and manufacture their own drugs on demand. A prototype system for automatically synthesising simple medicines has already been tested in space.

Whether or not astronauts get sick, they will feel the physical effects of space travel. Without the pull of gravity to contend with, muscles and bones start to waste away. Studies show that astronauts can lose up to 20 per cent of their muscle mass in under a fortnight, even with daily workouts. The good news is that this may not matter much on Mars because its gravity is so much lower than Earth's – walking on the Red Planet would be far easier. Still, we would want to counteract the effects as much as possible, and astronauts would probably be tasked with hours of daily exercise and special diets. They might also have to wear muscle-compression suits.

As well as missing Earth's gravity, astronauts won't be shielded by its magnetic field, which diverts harmful cosmic radiation. NASA limits radiation exposure for male astronauts to about the equivalent of 286,000 chest X-rays, and around 20 per cent less than this for women, whose bodies may be more susceptible to radiation damage. Astronauts on a Mars mission would hit 60 per cent of that limit on the shortest possible return journey, without taking into account time on the surface.

That goes for the mental health risks, too. Being so far from Earth – far enough that home becomes just another point of light in the sky – could be psychologically challenging. You need a special type of person to cope with it.

3. WHO DO WE SEND?

The people we send to Mars will have to meet all the requirements that astronauts do now, including passing strenuous physical and psychological tests. But their skills will have to go beyond that. On the way to Mars, nobody can quit the team and nobody can be added. The handful of people on board will be totally responsible for keeping the mission aloft.

Certain roles like engineers, doctors and scientists will be indispensable. But it won't make sense to look for perfect astronauts – rather, we need the perfect team of astronauts. "You're trying to put together a toolbox, and you wouldn't fill a toolbox with hammers even if they're all the best hammers in the world," says Kim Binsted at the University of Hawai'i.

Binsted knows what she is talking about, as chief of the Hawai'i Space Exploration Analog and Simulation, in which crews of four to six people live as if they are on Mars. Participants stay for months at a time, donning mock spacesuits when they go outside and enduring a 20-minute communication lag with "Earth".

One thing that consistently causes conflict is when one or two team members feel different from the others. It could be differences in gender, nationality or even music preference. A crew with three men and one woman, or one person who wants to blast Metallica at all hours, might crumble because they don't feel like they are all on the same footing.

Getting a team mission ready will probably involve more intensive group training than astronauts undergo now. The crew will have to learn to deal with each other's personality quirks to defuse even small interpersonal conflicts.

4. LANDING AND LIVING ON MARS

With nine months of empty space and avoided arguments behind them, the travellers are about to face the most dangerous part of their journey. The trouble with landing on Mars is that its atmosphere is almost non-existent – it is 160 times less dense than Earth's, on average. This means that parachutes don't create enough drag to slow down spacecraft, as they do when landing on Earth. We could use boosters to slow down, like the Apollo astronauts did when they landed on the moon. But because gravity on Mars is stronger than that on the moon, we would need a lot more boosters. This means we will probably need a combination of boosters and something to create drag.

This approach has succeeded for a 1-tonne robot, but it won't be so easy for a heavier craft, which is why researchers are working on an improved way to land.

One is NASA's Hypersonic Inflatable Aerodynamic

1980s

Phobos 2

Designed to explore Mars's two moons, Phobos and Deimos, and land on Phobos, it snapped 37 pictures of Phobos before it stopped transmitting

1990s

Mars Observer

Built to measure Mars's atmosphere and magnetic field, it fell silent before entering orbit

Mars Global Surveyor

Mapped the whole surface and the thermal structure of the atmosphere until 2006

Mars Pathfinder/Sojourner

First successful Mars rover, driving about 100 metres

Nozomi

Intended to orbit, but flew past the planet at a range of 1000 km

Mars Polar Lander

Communication lost on landing

2000s

Beagle 2

Landed, but failed to unfold its solar panels

Spirit

Roved for 7.7 km before getting stuck in some dirt in 2010

Opportunity

The record-breaking rover covered over 45 km before contact was finally lost in 2018

Rosetta

Designed to rendezvous with a comet, the probe skimmed past Mars at a range of 250 km

Mars Reconnaissance Orbiter

Still active

Phoenix

Made first successful landing in a polar region, active for five months

Decelerators, a series of landing devices that use fabric strengthened with Kevlar to form a blow-up structure that is more rigid than a parachute and so creates more drag. The agency has tested small scale models of it on Earth.

Yet the really difficult question isn't how we land, but where. A site near either of the poles would seem the obvious choice because this is where we know there is underground water ice – and possibly an underground lake of liquid water – which would serve as a crucial resource. Humans use a lot of water and it is very heavy, so the amount we could take to Mars would be limited. Plus, many proposed Mars missions involve using water to make rocket fuel to get the explorers home.

The trouble is the pole areas get as cold as -195°C (-319°F) and are prone to storms that make landing even harder. The equatorial region mostly stays above -100°C (-148°F) and can reach 20°C (68°F). It also has more sunlight that astronauts could harvest for solar power, rarely gets storms and has all sorts of interesting terrain to explore. But it doesn't seem to have much, if any, accessible water.

It is a tricky problem, but for the first missions, it may be simplest to land somewhere predictable, where rovers have already explored. Once they are down, the explorers will be sticking around for a while. Even if they aren't establishing a permanent settlement, they will have to wait months at a minimum for Earth and Mars to come into alignment again so they can travel home in a matter of months rather than years. There is no visiting Mars without setting up a base.

The base will have to deal with the variety of interesting ways in which Mars can kill you. Apart from the aforementioned gnawing cold, there is the constant risk of being hit by micrometeorites, which often don't burn up in the wispy atmosphere. Then there is the radiation from space, which isn't deflected away because Mars has no planet-wide magnetic field. And with so little atmosphere, the pressure is incredibly low, almost akin to deep space.

The simplest protection from these risks may be the spacecraft that got our explorers here. But the landing craft itself would probably make for cramped quarters. Another option would be to bring their shelter or the materials to build it with them. NASA is running a competition to design 3D-printed habitats, and there have been many entries. A number of them use pieces of the landing craft in their design, but they all also require other building materials, which adds weight to the launch craft. The entries get extra points if they use resources already on the Martian surface, which has inspired plans to make bricks of compressed Martian soil and build igloo-like shelters. NASA has given › contracts to several groups studying the best way to make such bricks using precisely engineered replica Mars dust. But even so, building a home on Mars will probably require sending a few packages of building materials on ahead.

It might be possible to rope in the Martian crust itself as a natural radiation shield. One proposal would see humans setting up their habitats in the cylindrical caves created by ancient lava flows. We have seen the entrances to such caves on Mars in satellite images and studied similar structures here. On Earth, these caves are generally about 30 metres wide, but research suggests that on Mars, with its much lower gravity, they could be eight times wider and stretch for miles. One day they could accommodate a whole street of habitats.

The intrepid astronauts will have other pressing needs to think about. Food can be freeze-dried, seeds can be packed, oxygen can be taken in tanks if it can't be scrubbed from the Martian atmosphere once there.

But water is less easy. Even if the astronauts have landed in a location with plenty of it beneath the surface, they will need to have brought heavy mining equipment to reach it. And there's no guarantee that it will be potable once it is out of the ground. Even if the water is safe to drink, it will be full of fine dust. So the astronauts will have to bring sophisticated filtration systems with them.

That goes for the spacesuits too: they will have to be excellent at keeping dust out, especially as Martian soil may be full of chemicals that can be deadly if inhaled or swallowed. NASA is already working on next-generation spacesuits and special coating materials that would counter the dust problem.

5. HOME TIME

Some people may be hoping that we will settle on Mars permanently in the long term. But all serious Mars mission plans currently involve bringing the explorers back. This means the astronauts need to endure another launch, another nine-month journey, another landing. Luckily, it will be easier the second time. Mars's thin atmosphere and its weaker gravity will mean getting into space won't be as tough. The journey itself will be equally long, but the familiar azure glow of our home world will grow stronger by the day. The landing will be simple, aided by parachutes and Earth's thick atmosphere.

When the explorers peek their heads out of their capsule, they will be splashed by the cool water of our abundant oceans and enveloped in the chatter of other people. They will be home. Back on Mars, the swirling dust will have already covered their footprints. But their habitat will still be standing, ready and waiting for the next visitors. ∎

2010s

Yinghuo-1
Stranded in Earth orbit after thrusters failed to burn

Phobos-Grunt
Intended as a sample return mission to Phobos, it was launched with Yinghuo-1 and stranded with it in Earth orbit

Curiosity
Still active, this car-sized rover has driven more than 18 km on Mars, investigating its geology to see whether its past conditions could have supported life

Mangalyaan
A successful technology demonstration mission that made India the first Asian nation to reach Mars orbit

MAVEN
Designed to study the evolution of Mars's atmosphere, still in orbit functioning as a communications relay

2020s

ExoMars Trace Gas Orbiter
Still in orbit, this European-Russian project was designed to measure methane and other gases in the atmosphere that could be signatures of life

Schiaparelli
Delivered by the Exomars orbiter, it crashed while attempting to land

InSight
Designed to study Mars's deep interior and seismic activity, successfully landed in November 2018

Mars2020
The Perserverance rover found volcanic rocks, organic matter, and signs of flowing water

Tianwen-1
China's first mission to land on Mars found evidence of an ancient ocean on what is now a vast dried-up plain

INTERVIEW

HOW OUR GOLDEN AGE OF ASTEROID EXPLORATION COULD REVEAL LIFE'S ORIGINS

What did NASA's OSIRIS-REx mission to sample Bennu discover? Mission leader Dante Lauretta says the asteroid could hold clues about how life began.

PROFILE
DANTE LAURETTA

Dante Lauretta is a planetary scientist at the University of Arizona. He led NASA's OSIRIS-REx mission, which brought back a sample of the asteroid Bennu.

You watched from a helicopter as the OSIRIS-REx samples landed. How tense was it?

I got up at 1.30 that morning because we had some routine work to do on the spacecraft. I wear a ring that measures my heart rate and I remember it was already 120 beats per minute! This was 20 years of my career, all depending on everything going smoothly on that day.

Later, I was in a helicopter, waiting for the capsule to come down. The capsule got pretty low and there should have been a drag parachute opening, but no one was calling it. I was a mess emotionally, thinking that this was going to be a disaster. But then the air force officer I was with was calling the main chute and, before I could process it, the capsule was safely on the ground. All this stress was released – years and years of anxiety and worrying and effort, pouring your heart into a mission – all of that lifted and I just broke into tears. It was relief, enormous relief.

Compared with planets and moons, asteroids might seem dusty and boring. Why is there so much interest in them?

Asteroids hold an enormous wealth of information, because they are literally the oldest rocks in the solar system. They represent the very first solid material out of which all the beautiful planets grew. That's why we find them so fascinating. They are the things that grew together to make up the planets, and the ones that ›

NASA/BILL INGALLS

Dante Lauretta led the team that brought back a sample of asteroid Bennu

are left are kind of the stragglers that survived the chaos of the early solar system.

We have had several asteroid sample-and-return missions already. Where does OSIRIS-REx fit into the story?

Well, it's the largest sample of asteroidal material ever returned to Earth, by a lot. We have in excess of 120 grams, more than twice what we promised. So that's super exciting for us.

This story started off two decades ago when we in the community were pushing to have a sample-and-return mission to a carbon-rich asteroid, so we could explore origin-of-life issues. We pitched it to NASA, the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA). And in the end, NASA and JAXA both funded missions, so it was a double victory. The Japanese missions became Hayabusa [which visited an asteroid called Itokawa] and Hayabusa 2 [which sampled the asteroid Ryugu], and we became very close teams.

As a community, we are ecstatic that we got these three opportunities. The samples are similar yet distinct, so there's interesting things to learn there. Why is Ryugu different than Bennu? Did they come from the same asteroid family? There's a good chance that they did and we're sampling various regions of a much, much larger world.

What have you learned from the material from Bennu so far?

When you look at the material, most of it looks dark, like charcoal, but there is also some really bright stuff, which, to me, is the most exciting thing we got. Let me try to explain.

One of the first things we did was analysis using a technique called X-ray diffraction, which gives you peaks on a graph that correspond to a known mineral. The sample of Bennu is mostly made up of water-bearing clay, specifically minerals called serpentines. There's the same rock type on Earth, which forms when mantle rock hits ocean water. Then we also found that we have this magnesium-rich phosphate mineral, and this is what makes up those bright sections that I mentioned. This is really rare and it's also a weird type of phosphate that I have never seen before. It's very, very uncommon in geologic settings.

Can you tell me more about why the bright stuff is so interesting?

The thing about the phosphate material is that it looks very odd. It appears like a thin skin that looks like it has been deposited on the material. I was really puzzled by this, so I put out a call to the community, asking: "Has anybody seen this in geologic environments?" I heard from a group that detected sodium phosphate particles in the plumes of water erupting from Enceladus [a moon of Saturn] during the Cassini mission.

So if I put it all together, Bennu samples are hydrated, organic-rich serpentines from the early solar system. Serpentines on Earth, at least, form when rocks from the mantle are forced upwards into the seabed and react with water, in a reaction that releases heat – and it was probably a similar process on Bennu's

ENCOUNTERS WITH ASTEROIDS

In our solar system, the processes of planet formation left quite a few offcuts. One of the known regions these cluster in is the asteroid belt between the orbits of Mars and Jupiter, whose 20,000-odd rocky bodies range from just a few metres across to the dwarf planet Ceres. Here is a rundown of our missions to study asteroids, past, present and future

HAYABUSA JAXA
Launched: 2003
The first attempt at an asteroid sample-and-return mission brought back less than a milligram of material from asteroid Itokawa in 2010.

HAYABUSA 2 JAXA
Launched: 2014
Returned in 2020 with 5.4 grams of material from Ryugu.

OSIRIS-REx NASA
Launched: 2016
Brought back about 120 grams of material from asteroid Bennu in September 2023.

PSYCHE NASA
Launched: 2023
In transit towards Psyche, which is thought to be a metallic asteroid. It should arrive in 2029, but won't bring back samples.

MARTIAN MOONS EXPLORATION (MMX) JAXA
Due to launch: 2026
MMX will travel to the Red Planet's two moons, Phobos and Deimos, and collect a sample from the former to return to Earth.

MBR EXPLORER
UNITED ARAB EMIRATES SPACE AGENCY
Due to launch: 2028
This mission, currently in development, plans to visit seven asteroids in the belt between Mars and Jupiter, as well as dropping a lander on Justitia, a 50-kilometre-wide asteroid in the asteroid belt.

parent asteroid. So we clearly had a set of rocks that were interacting with a carbonated fluid. That's a huge result to me.

I would say my working hypothesis – and you know, if we can prove it, it's huge – is that Bennu samples are rocks from an ancient ocean world. You would have had phosphate enrichment in the fluid and, ultimately, evaporation and precipitation of that phosphate material.

Phosphate is a key building block in biology, right?

That's right, phospholipids make our cell walls and adenosine triphosphate is the primary energy molecule for all life on Earth. Phosphate molecules also form the backbone of DNA and RNA, and so are critical to our genetic material.

Did you find anything else interesting?

We can also see these things I call nano-globules all over the place. These are spheres with walls of carbon and nitrogen, sometimes empty and sometimes with other phases of mineral or rock inside them. They're enormously abundant. We see them all over this material.

These are exciting from an origin-of-life perspective. These could be like a protocell. They might be telling us something important, at least about compartmentalisation. If you can get separation of chemical systems, that's the first step towards a cell and that's where metabolism could maybe start to originate. ∎

CHAPTER 4

TO THE GAS GIANTS AND BEYOND

We have orbited Mercury, we have roved across Mars, we have even landed on Venus. In comparison to our study of the rocky planets, our exploration of the outer solar system, particularly the ice giants of Uranus and Neptune, has been surface-level at best.

Missions to the outer solar system require more planning and patience, but the results are worth it. From underground oceans on Jupiter's moons to an atmosphere around Pluto, our exploration of these icy reaches has already yielded clues to the origins of the planets and the possibility of life elsewhere.

JUPITER: HOW THE SOLAR SYSTEM'S GIANT MADE EARTH RIPE FOR LIFE

Jupiter is named after the mightiest of the Roman gods for good reason. This behemoth shaped our solar system and paved the way for our existence.

WITH such a cornucopia of delight and intrigue, Jupiter was an obvious destination for our first ventures into the outer solar system. Four brief encounters with the planet came in the 1970s, courtesy of the passing probes Pioneer 10, Pioneer 11 and Voyagers 1 and 2. They gave us our first glimpses of its swirling gases, powerful magnetic field and delicate rings, as well as a closer look at its most iconic feature – the "Great Red Spot", a vast storm that has raged since at least 1830.

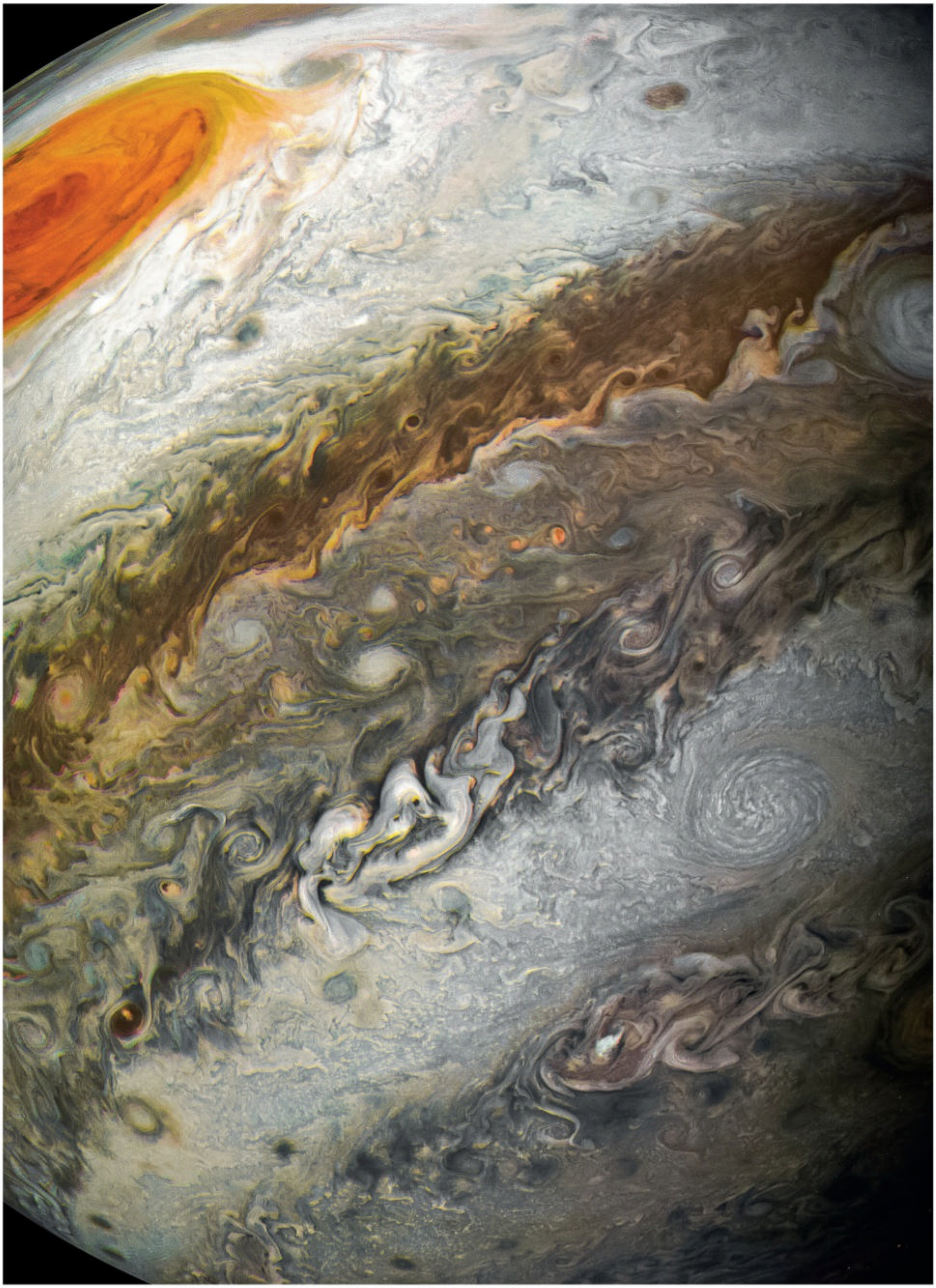
In 1995, NASA's Galileo, the first craft designed to orbit Jupiter, arrived after a six-year journey from Earth. In the following eight years, it gave us our first intimate view of the planet and its moons, including the four discovered by its namesake.

As far as the planet itself was concerned, the deepest insights came from a probe that the Galileo spacecraft dropped into Jupiter's atmosphere on 7 December 1995. Reaching an entry speed in excess of 170,000 kilometres per hour, it sent data for 57 minutes, detecting winds of up to 500 kilometres per hour, a strange absence of lightning compared with similar storms on Earth, and evidence that the energy driving the atmospheric convulsions was heat upwelling from its interior.

With its fuel running low, in 2003, Galileo was sent to plunge into Jupiter's atmosphere and burn up. According to the probe, the planet's atmosphere seemed to have far less water in it than we expected for a body at its position in the solar system – though it might have been that the Galileo observations were just made at a particularly dry spot. Jupiter continues to intrigue us, as the planet's origin and early history are of huge significance for the wider history of the solar system.

One thing we are fairly certain about is that Jupiter was the firstborn of the solar system planets, and that it was born small. About 4.6 billion years ago, a huge cloud of dust and gas collapsed to form the sun. Just a million years later, the leftovers of this cloud gave birth to the beginnings of Jupiter. Over the following few million years, this rocky core grew bigger and grabbed hold of the surrounding gas to build the swirling giant that we know today, consisting mainly of hydrogen and helium.

But that is probably not where the story ended. Jupiter's apparent lack of water isn't the solar system's ›



NASA/JPL-CALTECH/SWRI/MSSS/KEVIN M. GILL PREVIOUS PAGE: NASA/JPL only planetary mystery. Take Mars: it is small, only just over half the diameter of Earth, despite orbiting where there should have been plenty of planet-building material. Then there are Uranus and Neptune, the two ice giant planets furthest from the sun. Here we have the opposite problem: they can't have formed where they are now, because there simply wasn't enough material there to make worlds that large.

The only way we can explain the size and distribution of the planets as they are now is if they formed somewhere else and migrated to their current positions. To move whole worlds around, you need something big to give them a gravitational shove – something like Jupiter.

This starts with a scenario called the grand tack model. This postulates that once Jupiter had grown beyond a certain size, increased friction with the disc of dust and gas that formed all the planets slowed it down. This caused it to fall towards the sun, to around where Mars is now, its huge gravity sweeping planet-building material out of its way. Jupiter itself was saved from a cataclysmic end crashing into the sun only by the slightly later formation of Saturn, the solar system's second, only marginally smaller, giant: its increasing gravity pulled Jupiter back from the brink.

Jupiter's gravitational bulldozing is our best guess for why Mars ended up so small. To explain Uranus and Neptune, we need a second hypothesis. It is called the Nice model, after the French city where the team that came up with it in 2005 was based. It says that the ice giants probably formed at least about 25 per cent closer to the sun than they are now, near Saturn's current orbit. The Kuiper belt, a region of icy dwarf planets and comets where Pluto resides, was probably much closer then too, about where Neptune is now.

But about 4 billion years ago, Jupiter's powerful gravity destabilised the orbits of the ice giants, pushing them outwards. This model has a lot going for it besides explaining Uranus and Neptune. The movements of these planets in turn flung rocks from the Kuiper belt back in towards Jupiter, many of which swung around the gassy behemoth and were catapulted back again to far beyond their original positions. This is our best guess for explaining the Oort cloud, a reservoir of rocks thought to encircle the solar system and from which lonesome cometary travellers occasionally reach us.

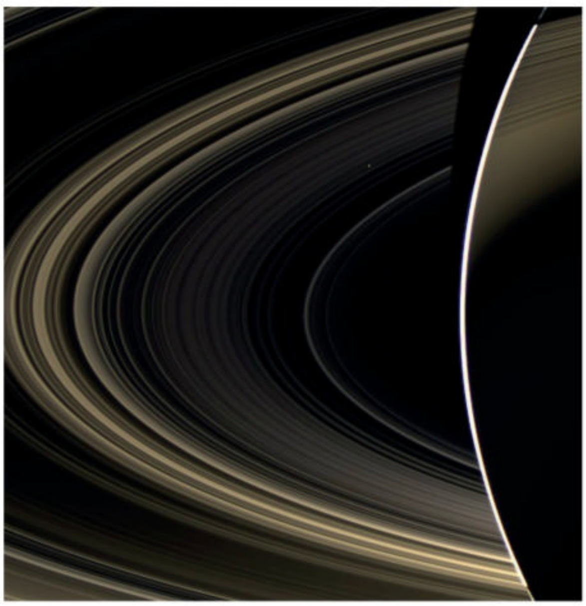
Other rocks flung inwards – along with complex chemicals and water – probably stuck around in the inner solar system, perhaps explaining how planets like Earth got water when the environment they originally formed in was probably too hot. If so, we might be able to credit the gas giant with life as we know it. ▮

JUPITER'S MOONS

When, in 1610, Galileo Galilei discovered four moons circling Jupiter through his newly invented telescope, they were the first bodies conclusively shown to be orbiting a planet other than Earth. That broke a world view that had persisted for more than 2000 years, and helped get Galileo into a lot of hot water with the religious authorities of his day. They didn't know the half of it. At last count, Jupiter has 95 moons, more than any other planet. But the four original "Galilean" moons – Io, Europa, Ganymede and Callisto – remain the showstoppers.

CASSINI'S GRAND FINALE: THE SPACECRAFT THAT UNVEILED SATURN

In 13 years orbiting Saturn, the Cassini probe has exposed many wonders, from magical rings to loony moons and giant polar hurricanes. Here are our top picks.



NASA/JPL-CALTECH/SPACE SCIENCE INSTITUTE

How the intricate patterns in Saturn's rings are sculpted still puzzles astronomers today

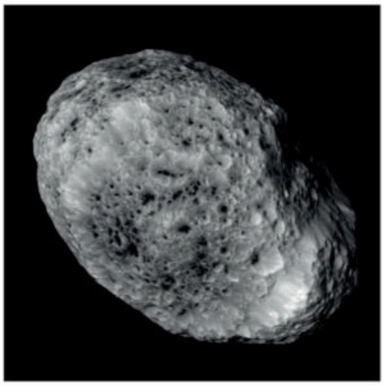
THE RINGS

After a six-and-a-half-year journey, Cassini entered orbit around Saturn on 1 July 2004 – and immediately encountered the planet's signature feature, its rings. Pictures collected by the Voyager probes when they flew past Saturn in 1980 and 1981 suggested the planet was girdled by about 10,000 rings, each a cloud of particles tightly confined to a narrow orbit.

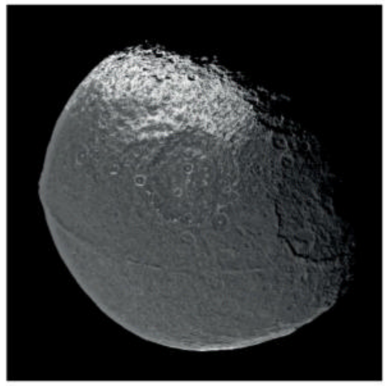
The rings are also complex: Cassini's images have revealed clumps, holes, gaps and other structures. Some wave-like features are due to gravitational interactions with the moons embedded in the rings, but the origin of others is unclear.

The rings probably formed initially when a large moon came too close to Saturn and was ripped apart by gravitational forces. Larry Esposito, principal investigator for Cassini's ultraviolet imaging spectrograph, says this was probably early in the solar system's history, and that the rings have gradually spread since then, perhaps forming moons in the process. Others think the rings go through cycles: moons collide forming new rings that coalesce into new moons which eventually collide again, with the current rings as little as 100 million years old.

Enceladus



Hyperion



Iapetus

NASA/JPL-CALTECH/SPACE SCIENCE INSTITUTE

ENCELADUS

Before Cassini, researchers had expected this icy, 500-kilometre-diameter moon to be frozen solid. But on an early flyby in February 2005, the spacecraft's magnetometer "sensed something unusual going on with its magnetic field", says Cassini project scientist Linda Spilker of the Jet Propulsion Laboratory in Pasadena, California.

A later pass showed that the south pole was much warmer than expected, and was spouting geysers of salty water into space. Enceladus circles Saturn twice for every orbit of the larger moon Dione, inducing a gravitational interaction that melts ice inside both moons. The process squeezes Enceladus, ejecting jets of water from large fracture zones near its south pole. Cassini measured the composition of these jets, detecting raw materials for life including salt, water, carbon dioxide, methane, other organic molecules and, most recently, hydrogen, which is an ideal energy source for life.

Silica found in the jets can be produced only in water close to boiling point, indicating that hydrothermal vents are also present in the subsurface ocean – making the icy moon a hot target in the search for life.

HYPERION

Trapped in a gravitational resonance with Titan, Hyperion tumbles chaotically in orbit. Subject of an early flyby in September 2005, its light, porous-looking surface resembles a battered sponge, but no one quite knows why. One possibility is that it is a fragment of a larger object shattered in a past collision. The dark zones look lower than the light-coloured ridges, perhaps because they absorbed more sunlight, causing ices below them to evaporate and the dark layer to sink down.

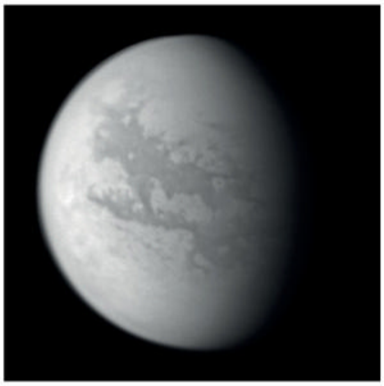
IAPETUS

At first glance, an equatorial ridge girdling Iapetus looks like a moulding mark on a factory-fresh rubber ball. A Cassini flyby in 2007 revealed that the ridge is as heavily cratered as the rest of the 1500-kilometre-diameter moon's surface, so it must have formed long ago. Iapetus's surface is also oddly two-toned, with a darker leading edge. This is caused by gravitational forces that lock the moon into position around Saturn, causing its front face to sweep up dust.

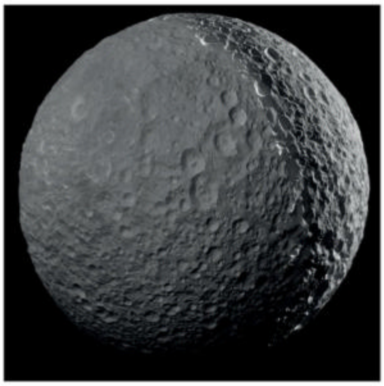
TITAN

When Voyager 1 passed Titan in 1980, it couldn't see the surface of Saturn's largest moon: solar ultraviolet radiation drives reactions between nitrogen and methane molecules in its atmosphere that yield a thick, orange-brown gunk. The purpose of Cassini's Huygens lander, built by the European Space Agency, was to find out what lay beneath. Voyager had discovered that the temperature and pressure on Titan's surface would allow liquid methane. Huygens, released on 14 January 2005, was made to withstand a wet or dry landing.

Photos taken during the lander's 150-minute descent showed networks of branching streams possibly carved by liquid methane. But the touchdown was hard, on a cobblestone-strewn flood plain near



Titan



Mimas

Pan

Titan's equator like "something you might see in Death Valley", says Alexander Hayes at Cornell University in Ithaca, New York. But at around -180°C (-292°F), it was much colder.

Huygens transmitted data from the surface for 72 minutes until its battery failed. In the years since, Cassini has probed Titan's atmosphere and mapped its surface on successive flybys, confirming the presence of liquid methane. In radar observations a few weeks apart, it found evidence that methane showers had soaked the soil, then evaporated – the first proof of precipitation beyond Earth.

Titan's landscape is eerily calm, with methane seas and lakes that are "fantastically flat", says Hayes. They are more transparent than water lakes: a radar echo from one was reflected from its bottom, 160 metres down. Bright "magic islands", which appear briefly in the dark lakes before disappearing, are thought to be nitrogen bubbling out of solution.

Perhaps oddest of all, Titan has two ocean levels. Beneath the hydrocarbon seas on the surface, under a shell of water ice, lies salty liquid water. This hidden ocean is, says Hayes, "the most accessible laboratory for prebiotic chemistry in the solar system" – a potential habitat for life.

MIMAS

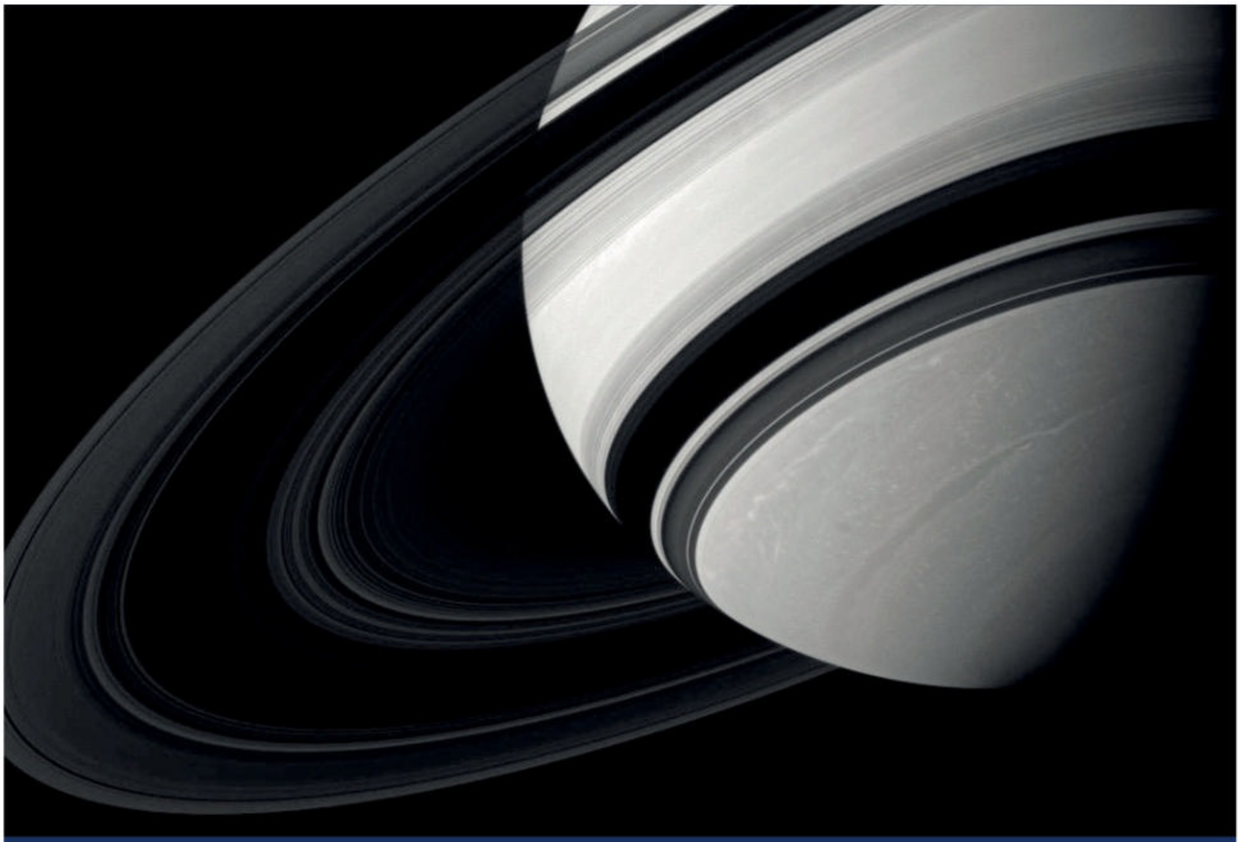
At 396 kilometres in diameter, Mimas is the smallest known rounded body in the solar system. Seen closest by Cassini in February 2010, it isn't completely round, however: one side is dominated by the 130-kilometre Herschel crater with walls 5 kilometres high. The giant pit makes Mimas look eerily like the planet-destroying Death Star in the *Star Wars* movies. It is, however, extremely vulnerable: made principally of water ice, cracks on its opposite side show that a past impact came close to shattering it.

HURRICANES ON SATURN

Hurricanes on Earth tend to go towards the poles, but those on Saturn are fixed there. They have central eyes and eye-wall clouds like terrestrial hurricanes, and spin in the same way, but at 4000 kilometres across, three of them side by side would span Earth's diameter. Terrestrial hurricanes are powered by heat released from warm ocean surfaces. There's nothing like that on Saturn, so what powers its storms remains a mystery.

PAN

Fat, round, ravioli-shaped Pan orbits in a gap in Saturn's A-ring, the outermost of the large, bright rings. Its central core is icy, but ring particles accumulate on a strip around its circumference, fattening Pan out to a 35-kilometre diameter. Revealed in great detail in images taken in March 2017, this belt is cratered, with signs of a small landslide pulled downhill by the moon's gravity. Atlas, another moon in the A-ring, is similar, but its skirt shows no craters and looks fluffier. The moons' growth may be limited by a gravitational tug of war between them and Saturn: if ring particles pile too high on Pan's equator, the planet's gravity tugs them off again. ∎



NASA/JPL-CALTECH/SPACE SCIENCE INSTITUTE

AMATEUR ASTRONOMY: HOW TO SPOT SATURN'S RINGS THROUGH A TELESCOPE

Seeing Saturn's cartoon-like rings up close can be an awe-inspiring experience

People will often say that you can see Saturn's rings through any small telescope, or even binoculars. While that is true, you really need a telescope with at least 40 times magnification to clearly see the detail of the rings as separate from the planet. And the bigger the telescope, the better.

You don't need any equipment to see Saturn itself though. To find Saturn, look east just after sunset, and you will spot a bright "star". Look closely and you will see it isn't flickering. Use a free stargazing app to make sure you know exactly where Saturn is from your part of the world, because it will change over time.

Once you have found the planet, point your telescope in its direction and focus it. You might be tempted to magnify your telescope as much as possible with your choice of eyepiece, but try to resist this urge – too much magnification will just increase the distortion caused by light bending on its way through our atmosphere, making the image appear blurry.

Through smaller telescopes, Saturn's rings will appear as a cream-coloured fuzzy line coming out from a central yellowy blob. With larger telescopes, you might be able to make out the black band of the Cassini Division, the gap between the A and B rings.

I think that Saturn through a telescope looks almost cartoon-like, and some say it is the most three-dimensional-looking object you can view in the night sky, because of the shadow the rings cast on the planet's surface.

FORGOTTEN GIANTS: WHY IT IS TIME TO REVISIT URANUS AND NEPTUNE

A fleeting glimpse of the ice giants some 30 years ago hinted at very weird science that could tell us a lot about exoplanets.

A FEW billion kilometres from here, two cerulean marbles hang in the blackness of space. Neptune and Uranus are not the most distant objects in the solar system. They aren't the biggest or the smallest. They don't have the brightest colours. But they do hold the greatest mysteries.

Our only close look at the ice giants Neptune and Uranus came more than 30 years ago when the Voyager 2 spacecraft hurtled past on its way out of the solar system. It snapped a few pictures, then the planets faded from view. "Everything we know up close about these planets and their moons is based on that single flyby," says NASA scientist Amy Simon.

Here are the biggest questions another trip to the ice giants could answer.

Why is Uranus too cold?

When Voyager 2 buzzed past Uranus, its heat sensors picked up no signal at all. That doesn't make sense if this ice giant emits heat in the way we think planets do.

As far as we know, gas, dust and eventually rocks smash together during planet formation and that locks up heat in their cores. The heat then radiates out over billions of years. How much heat is coming out at any given time depends on what the planet is made of and how old it is.

We can estimate how much heat should be emanating from the ice giants by taking a cue from Saturn and Jupiter, which we have studied more extensively. Heat moves from their cores to their atmospheres of hydrogen and helium, gets shuffled around, and eventually escapes. The ice giants are colder and smaller than these planets, and their atmospheres include methane and ammonia as well as hydrogen and helium. But the same sort of heat dispersion process should apply.

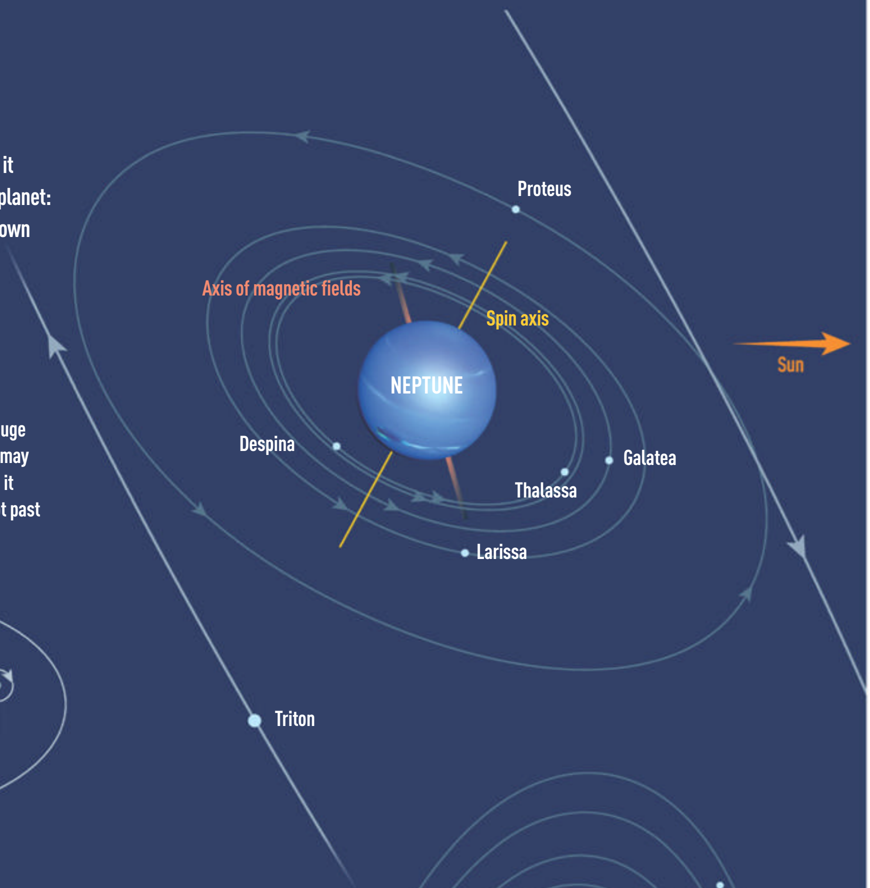
You might suspect Uranus's lack of a heat signal is because its interior is different from what we have so far guessed. But here's the weird thing: the models based on Jupiter and Saturn predict the heat output of Neptune rather neatly, just not that of Uranus.

Perhaps Neptune and Uranus are just different then? That is possible, but unlikely. They must have formed at around the same time and place to have accumulated the amount of hydrogen and helium we see in their atmospheres, suggesting their innards are similar.

An alternative idea is that Uranus's cold heart is related to its odd tilt. This could make its poles hotter than the equator and may have sped up the planet's loss of heat. Or it could be the opposite; the core is still warm but there is something that stops the heat ›

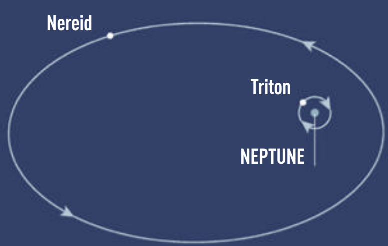
NEPTUNE

Like Uranus, Neptune's magnetic field is strangely skewed relative to its spin. But it has far fewer moons than a typical giant planet: just 14, of which the largest seven are shown



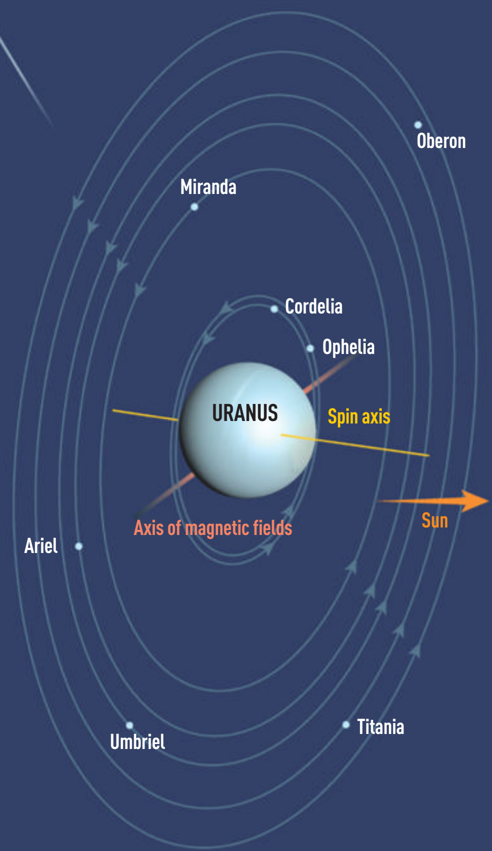
NEREID

Neptune's third largest moon, Nereid, has a huge and highly eccentric, or egg-shaped, orbit. It may have been pushed aside by Triton, or perhaps it was captured by Neptune's gravity as it swept past



URANUS

Most planets spin at right angles to the plane of their orbit, but Uranus rotates on its side. It also has 27 moons, some of which are highly mysterious. Seven of them are shown

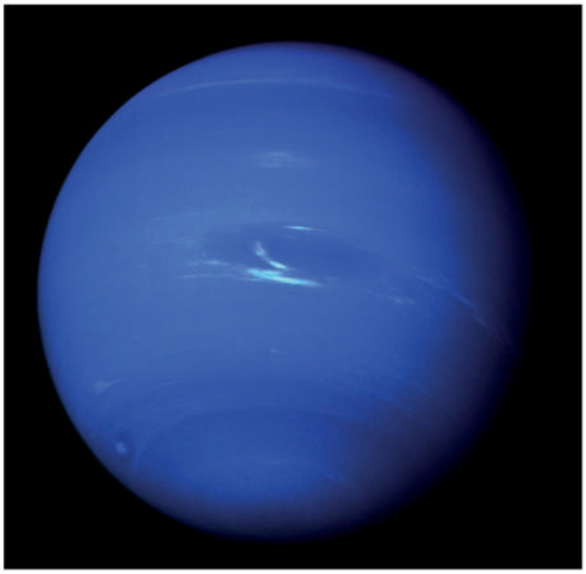


TITANIA AND OBERON

Both these moons appear to be heated by inner movements, suggesting there may be liquid oceans beneath their surfaces

CORDELIA AND OPHELIA

These two small moons act as "shepherds" to keep the planet's outermost ring thin and well-defined. Between them and Miranda is a swarm of smaller moons packed so closely together that they should have all crashed into one another by now


NASA/JPL

The Voyager probe's historic image of Neptune. The central, bright blue smudge is a giant storm

getting out for us to measure, such as slushy ice in the atmosphere.

We can't disprove any of the hypotheses because we know almost nothing about what's going on inside Uranus or Neptune. We know their size and mass, which tells us their density – but there are lots of ways to bake that.

Why are the magnetic fields lumpy?

A lack of heat wasn't the only strange reading Voyager 2 picked up. It also managed to briefly measure the ice giants' magnetic fields. They were like nothing we have ever seen.

Earth, Jupiter and Saturn all have magnetic fields with an alignment that roughly matches their spinning axis. Earth's magnetic field is like a bar magnet – the north pole is only 11 degrees off from the geological north pole, and it is a similar story at the south pole. Uranus's magnetic field is more complex. It has lumps and bumps pointing in different directions, and is totally skew-whiff, sitting at about a 45-degree angle from the spin axis. It is the same with Neptune. Even stranger, Voyager measurements showed that, for both planets, the centre of the magnetic field doesn't seem to sit in the middle of the planet.

Earth's magnetic field is generated by a swirling spherical skin of molten iron in its outer core, the motion of which is driven by the core's heat and corralled by the planet's rotation. It is hard to see how a process as symmetrical as this would create an off-centre field.

The dynamos that give rise to the ice giants' fields are probably very different, then. Our best guess is that the planets' interiors are made of layers of electrically conducting ices. Each layer may have different properties that mean they flow around each other in complex ways. In other words, the thing generating the magnetic field is not a single uniform sphere, but several interacting shells.

If that is true, it may help explain another bizarre feature of Uranus's magnetic field: that it seems to slam open and shut every day.

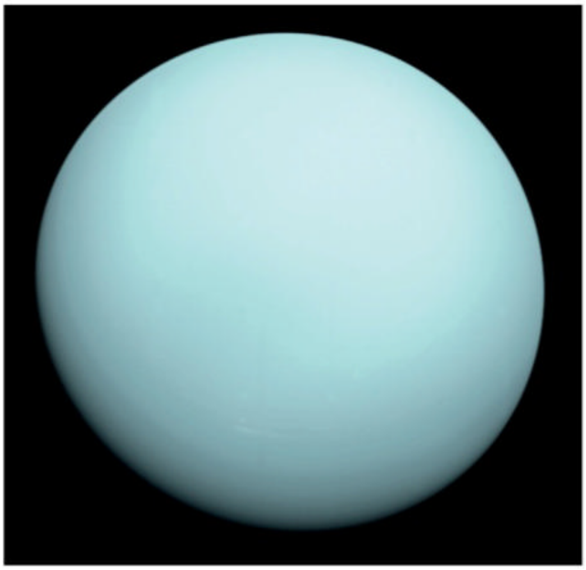
We can't even be sure that the magnetic fields are quite as they appear. We have only one measurement of each, and it is possible that they are constantly shifting and just happened to be off-centre when Voyager 2 whistled past.

Fields opening and shutting isn't unheard of. It happens at Earth's poles occasionally. When it does, it lets in particles from the solar wind that create super intense auroras. The chance of glimpsing something like that over Uranus is another tempting reason to visit.

Why does Uranus orbit sideways?

Most of the planets in our solar system rotate on an axis that is approximately at right angles to the plane of their orbits. They are like a series of spinning tops skittering on a table, all circling the sun in the same plane and spinning in the same direction. Even Neptune follows this pattern reasonably well.

Not Uranus. The spin of this frigid world is almost perpendicular to its orbital direction, with its spin axis close to the plane of its orbit. Most of its moons orbit in the same direction that it rotates, at a right angle to the plane of the solar system. Something must have happened when Uranus formed to make it so crooked. ›



NASA/JPL/CALTECH

Voyager 2 took this snap of Uranus in 1986 from a mere 9 million kilometres away

Most planetary scientists believe that it was an epic collision. For a single crash to knock a planet as large as Uranus off-kilter, the other object would have to be several times more massive than Earth. Or it could have been a series of collisions with smaller objects.

That doesn't explain why the moons are tilted too. Maybe the moons grew out of the rubble tossed into space by the collision, in a similar manner to how Earth's moon is believed to have formed. Then again, of the 27 moons, 18 of them orbit normally, around the planet's equator, and 9 follow less regular orbits. It is possible that the normal moons were around Uranus before the collision, whereas the others grew out of collision debris.

All this depends on Uranus having a solid core – otherwise it is hard to see how the collision narrative would work. We assume that is does, but we have no evidence. One way to tell would be to measure the planet's gravity from orbit – any areas with a strong pull could signify lumps and bumps on something solid.

Why do the ice giants even exist?

As if the curious magnetic fields and oddball temperatures weren't enough, there's another issue with the ice giants.

The trouble comes down to the window in which the ice giants could have formed. There is a period of about 3 million years after the birth of the sun when there was enough gas in the solar system's protoplanetary disc to build up the ice giants' thick atmospheres – after that, the solar wind had blown most of it away. But Neptune and Uranus both probably have a solid core and these might have taken as much as a billion years to accrete. After that, there would not have been enough gas left around to form their atmospheres.

One possibility is that the ice giants didn't form gradually, but in a short burst, with some gravitational glitch causing a cloud of dust to collapse quickly. The conditions under which anything like that might happen are unclear though.

A more probable explanation is that the ice giants were born closer to the sun before migrating to their current home. They would have grown more quickly there, because the cloud of dust was thicker. It is an attractive idea, seeing as we already think the early solar system involved planets pinballing around. Popular models of planet formation involve Jupiter either being born close to the sun or moving inwards in its youth. It could have absorbed or tossed aside huge rocks in the process, clearing the way for planets like Earth to survive unscathed, before moving outwards again.

It wouldn't be too difficult to get a handle on what happened if we sent a probe to the ice giants to sample the various chemicals in the atmosphere. The ratio of isotopes, variants of chemical elements with different masses, is a dead giveaway of where the planets formed and would help us reconstruct their movements.

We have never quite managed to measure Jupiter's isotopes, despite several missions there. But if we pulled it off for Neptune or Uranus, it would help narrow down the possible ways in which Jupiter moved around too; its awesome gravity would have been a major driver for the way the ice giants moved. In that sense, the mysteries of the ice giants aren't merely parochial oddities – they go to the heart of what makes our solar system the way it is. ∎

WE'RE HURTLING INTO A NEW REGION OF INTERSTELLAR SPACE. WHAT NOW?

As we speed towards a mysterious zone of interstellar space, new insights are revealing its exotic chemistry, strange waves and vast bubbles, and their ramifications for life on Earth.

WE ARE used to living in a thick soup of atmosphere. In a cubic centimetre of air, a volume the size of a six-sided die, there are trillions of atoms. Gas, dust, water vapour, viruses, pollen and more all waft around. Just beyond our atmosphere, however, in interplanetary space, the conditions are close to a perfect vacuum. Out there, the same volume contains, on average, just five atoms.

This matter mostly consists of charged particles streaming out from the sun as the solar wind. We have known for decades about this flow of material and how it creates a protective bubble around the solar system called the heliosphere. It cocoons us from high-energy cosmic rays shooting at us from deep space – and it is a good thing too, because those rays can damage the cells and DNA in living things. Radiation levels are eight to 10 times higher outside this zone. Much about this crucial area remained a mystery for a long time, though, not least where it ends and where interstellar space begins.

That changed thanks to two space probes, Voyager 1 and 2. They both launched in 1977 and were sent on different trajectories, with the principal aim of exploring the outer planets of the solar system. But once they had flown past them, they kept on going towards the inky blackness of interstellar space.

In 2012, Voyager 1 recorded a huge drop in the strength of the solar wind and a simultaneous rise in the number of incoming cosmic rays. This occurred › at 122 astronomical units (AU) from the sun (1 AU is the distance between Earth and the sun, about 150 million kilometres). This, scientists later declared, was the heliopause, the edge of the heliosphere. Voyager 2 had taken a longer route, heading out at a slightly different angle to its twin, but, in 2018, it also detected the heliopause at a similar distance from the sun.

There are still many mysteries about the heliopause, though. For instance, when researchers analysed data sent from Voyager 2 in 2019, they found it appeared to have a smoother passage through a thinner section of heliopause than Voyager 1. We don't know why.

Then there is the more fundamental question of the shape of the heliopause. Our solar system is moving through the surrounding interstellar medium, which pushes against the heliosphere and distorts it. For this reason, the leading nose of our heliosphere is widely agreed to be rounded. But the shape of its "tail" remains controversial. Many favour a simple teardrop form.

However, astronomer Merav Opher at Boston University in Massachusetts and her colleagues have been working on a NASA-funded project called Shield, using data from observations of the heliosphere to build computer models of it. This work led Opher to argue in 2021 that the heliosphere is shaped like a croissant, with a two-pronged tail. With more probes designed to observe the heliosphere set to launch in the coming years, Opher reckons the question could finally be settled.

As well as finding out where interstellar space starts, we are discovering more and more about what it contains. We know there is a scattering of atoms and dust and that the density of this medium can vary considerably throughout our galaxy. It was always thought that complex molecules couldn't exist in interstellar space, as they would surely be ripped apart by the barrage of powerful cosmic rays.

But in 1970, astronomers Robert Wilson and Arno Penzias – famed for their accidental discovery of the cosmic microwave background radiation, the afterglow of the big bang – saw a signature of carbon monoxide in the Orion Nebula, a gas-rich region of our galaxy. The discovery kick-started a new field, the study of molecules drifting in the interstellar medium. As of 2022, some 256 types had been found, mostly identified from the way they absorb specific wavelengths of passing radio waves.

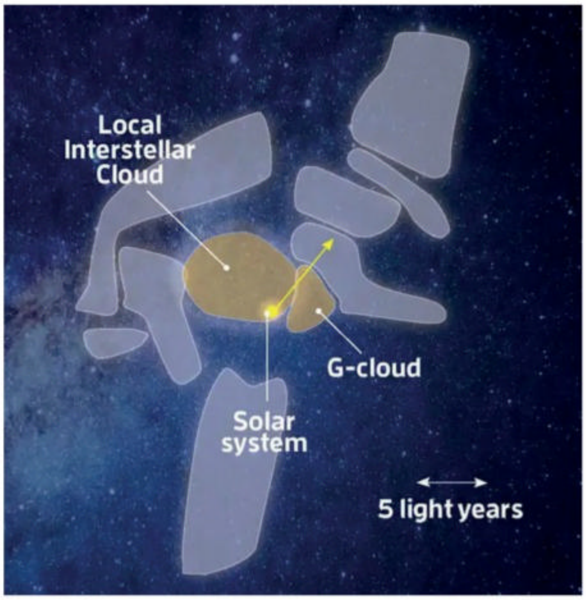
Some of these molecules are complex hydrocarbons. Even simple amino acids, the building blocks of proteins, have been spotted. That led astronomers to explore whether the ingredients of life could have been delivered to planets like Earth across interstellar space, either floating freely or on comets or asteroids, something that remains unanswered today.

Just as interstellar space isn't empty, it isn't a still, tranquil zone either. Instead, it is like an ocean full of waves. We learned this, again, from the Voyager probes. In 2021, when Stella Koch Ocker at Cornell University in New York and her colleagues analysed data sent by Voyager 1 from beyond the heliopause, they were surprised to find waves of radio activity washing over the spacecraft. These were caused by events from the sun seeping through the heliopause and interacting with the interstellar medium.

Interstellar space may have waves like an ocean, but it isn't an unbroken expanse. Instead, it is divided into many bubbles, each with its own character. This was originally recognised in 1992 by astronomer Rosine Lallement at the Paris Sciences et Lettres University in France.

By studying the motion of sodium gas in our corner of the galaxy, she found that the solar system was moving through a cloud of dust and gas about 10 light years across, now known as the Local Interstellar Cloud. She also realised we were heading out of that bubble and towards another one called the G-cloud. Within a year, detections of the flow of interstellar helium gas by NASA's Ulysses spacecraft would support the findings.

Insights from the Hubble Space Telescope have helped pinpoint our position more accurately by



The solar system resides in one of several vast bubbles of interstellar space. We are speeding towards a new bubble called the G-cloud and should reach its edge in about 2000 years

measuring the motion of our sun with respect to our neighbouring star system Alpha Centauri. This showed that our solar system entered the Local Interstellar Cloud about 60,000 years ago and will pass into the G-cloud in about 2000 years. In cosmic terms, we are right on the edge.

What happens when we enter this new bubble? The good news is that the G-cloud appears to have a similar density to our Local Interstellar Cloud, meaning few changes. The bad news is that the character of the boundary between the clouds is uncertain. It isn't clear if they are touching or if there is an intermediary region of different density between.

If we encounter a higher density region, that could push more heavily on our heliosphere, causing it to shrink and allowing harmful cosmic rays to penetrate deeper in towards the solar system's rocky planets like Earth. That would be unwelcome.

A higher flux of cosmic rays might increase Earth's cloud cover and cool our climate, and it could also cause more genetic mutations in cells as high-energy particles enter our bodies. "Earth would see the effects [of cosmic rays] much more than at present," says Jeffrey Linsky at the University of Colorado Boulder. On the other hand, if we enter a region of lower density, the heliosphere could expand, increasing the volume of space that is shielded from cosmic rays and possibly boosting the habitability of areas at the distant edges of the solar system.

On a grander scale, our 10-light-year-wide Local Interstellar Cloud resides in a much larger, irregularly shaped structure called the Local Bubble, which is 1000 light years across. This is a giant shell of expanding gas formed by more than a dozen stars exploding as supernovae, with a density around a tenth that of the space outside the Local Bubble. Recent estimates have suggested that our solar system entered this bubble about 5 million years ago, and we are now roughly at its centre. In another 8 million years, it is predicted we will reach its edge. ∎

CHAPTER 5

SPACE TELESCOPES

Some of our most ambitious space missions are telescopes. Unfolding delicate mirrors and keeping sensors running in the harsh depths of space is not for the faint-hearted.

The first major optical telescope in space, NASA's Hubble Space Telescope is famous for its beautiful images of distant galaxies. Its successor, the James Webb Space Telescope, recently began peering even further back in time – forcing us to rethink how galaxies and black holes formed in the universe's youth. Along with the Euclid space telescope, launched in 2023 to probe dark matter and dark energy in incredible detail, our understanding of the cosmos is about to be upturned.

TRAILBLAZING TELESCOPES: HUBBLE AND JWST

The Hubble Space Telescope and the James Webb Space Telescope have, in their own way, painted the cosmos in a radically new light.

HUBBLE'S launch in 1990 was motivated by the idea that the best view of space is from space itself. Astronomers attempting to get a good view of very distant objects in the universe have problems doing that from Earth's surface thanks to obstructions from clouds, light pollution and the distorting effects of the atmosphere. Building big telescopes on mountain tops is one solution, but Hubble offers an even better view.

Named after Edwin Hubble – the US astronomer who, in the 1920s, showed through observations of distant galaxies that the universe was expanding – Hubble's main light-collecting mirror is 2.4 metres in diameter. (By comparison, the current largest optical telescope on Earth's surface, the Gran Telescopio Canarias on La Palma in the Canary Islands, is 10.4 metres in diameter.) It observes in the visible, infrared and ultraviolet regions of the electromagnetic spectrum.

The observations it has made have increased our knowledge across the breadth of astronomy and cosmology. It has, for example, allowed us to pin down the expansion history of the universe better than ever before, including how it started in a big bang 13.8 billion years ago and has recently begun to expand ever faster thanks to the influence of a mysterious "dark energy". It has also shown that most, if not all, mature galaxies have black holes at their centres, and made key observations of distant outer solar-system bodies such as Pluto and Eris.

Hubble was last serviced back in 2009, and following the end of NASA's space-shuttle mission in 2011 it seems unlikely there will be another crewed servicing mission going there any time soon. Nevertheless, it looks in good nick, and could last well into the 2020s and perhaps beyond.

The James Webb Space Telescope (JWST) is NASA's successor to the Hubble Space Telescope. The ambitious space observatory took off from the European Spaceport launch site near Kourou, in French Guiana, on 25 December 2021 on a European Space Agency (ESA) Ariane 5 rocket, after a series of delays. Since the project was first envisioned in 1996, its costs have overrun from $0.5 billion to almost $10 billion. ›

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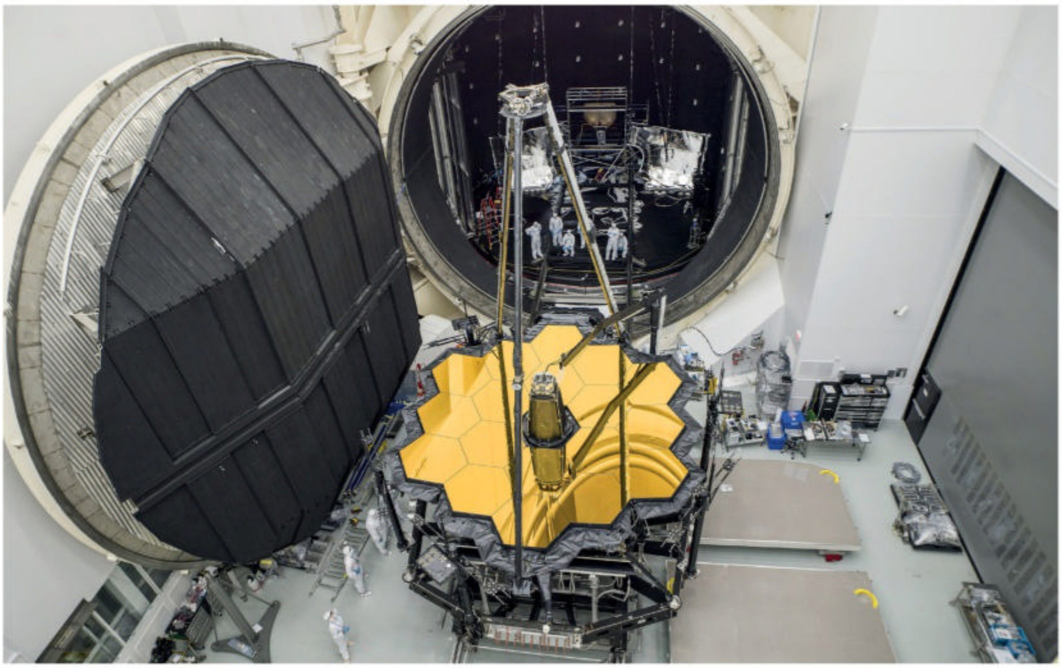

NASA

JWST's mirrors are prepared inside one of NASA's clean rooms

JWST was fully deployed on 8 January 2022 and reached its destination on 24 January. On 16 March 2022, it focused all its mirrors on a single star for the first time.

On 12 July 2022, NASA released JWST's first set of full-resolution science images, which included an image of the Carina Nebula, the Eight-Burst Nebula, a group of galaxies called Stephan's Quintet and a galaxy cluster stretching the light of the objects behind it. At the same time, NASA released an analysis of the composition of an exoplanet named WASP-96b and a picture of Jupiter.

JWST is further from Earth than Hubble, which orbits at an altitude of around 570 kilometres above Earth's surface. JWST sits in a Lagrange point between Earth and the sun, an area in which the gravitational pull between two orbiting bodies balances out, meaning something placed there can stay there with little effort. There are five of these in the Earth-sun system, and the one JWST will stay at sits 1.5 million kilometres from Earth, in the opposite direction to the sun, called Lagrangian point 2 or L2.

Although JWST is often described as a replacement for Hubble, its capabilities differ slightly compared with the iconic telescope that came before it. While the Hubble Space Telescope looks mostly in the visual and ultraviolet parts of the electromagnetic spectrum and can see a small portion of the infrared spectrum, JWST can image longer infrared wavelengths, offering an unprecedented view of the universe.

The telescope has a varied set of scientific goals, including examining nearby exoplanets, studying the earliest stars, observing supermassive black holes and looking for signs of cold dark matter. It will be used to study young galaxies, to answer questions of how galaxies assemble and to peer through clouds of dust to watch stars being formed. But it will also look much closer to home, studying objects within our solar system such as Mars, the gas giants, Pluto and even some asteroids and comets.

JWST is equipped with a set of 18 hexagonal mirrors arranged in a honeycomb shape 6.5 metres across, compared with Hubble's spherical 2.4-metre-diameter primary mirror. This means JWST has a 6.25-times-larger surface area to collect light compared with the Hubble Space Telescope. JWST has upgraded cameras and is protected by a sun shield 22 by 12 metres wide.

Light from objects in this distant part of the universe, like the earliest galaxies, is shifted towards the red end of the spectrum, which means we need infrared telescopes to observe them. JSWT will be able to peer far enough to see what the universe looked like around 100 million to 250 million years after the big bang, about 13.6 billion years ago, when the first stars and galaxies started to form. ∎

WHAT THE HUGE YOUNG GALAXIES SEEN BY JWST TELL US ABOUT THE UNIVERSE

The James Webb Space Telescope spotted six early galaxies that were so large they threatened to break our best theory of how the cosmos evolved. Did they?

WHEN physicists talk about a cosmological model, they are referring to a set of equations that describe the evolution of the universe. To build the prevailing story of how the cosmos we see today came to be, known as the standard model of cosmology, they started with Albert Einstein's general theory of relativity, which casts gravity as the result of mass warping space-time.

Those equations tell us that, although the universe expands overall, specific regions of space can become dense enough to pull matter together through gravity, forming galaxies. Cosmologists fed the equations into supercomputers, along with a list of "ingredients" that reflect the composition of the universe, and ran the simulations. By comparing the galaxies that pop out with our observations, they were able to tweak the model, over the course of decades, to better resemble what the universe actually looks like.

What we have ended up with is a model in which the universe was sculpted through a combination of gravity, familiar matter and two exotic ingredients. These exotic components are dark matter, which is required to provide a gravitational pull beyond that which known matter can muster, and dark energy, thought to be powering the accelerating expansion of the universe.

Both remain hypothetical, in the sense that we have yet to detect or otherwise identify either. But astronomers nevertheless reckon they have a handle on their characteristics because of how they affect the cosmos. In the case of dark matter, they believe it is composed of massive, sluggish particles that together outweigh normal matter by around 5:1. This is known as cold dark matter, or CDM. Dark energy, for its part, is assumed to be an unchanging energy field – an idea that Einstein toyed with in his equations under the guise of a parameter called lambda. So, the standard model of cosmology is known as lambda-CDM.

To be clear, lambda-CDM is remarkably successful. It does an excellent job of explaining the growth of galaxy clusters and other large-scale structures in the universe. But given the mysteries surrounding dark matter and dark energy, researchers are always on the lookout for fresh observations that would help them pin down the characteristics of those ingredients to improve their model.

That is why they were excited to see JWST's observations of young galaxies. But when Ivo Labbé at Swinburne University of Technology in Australia and his colleagues used tried-and-tested calculations to glean the masses of these objects based on their overall luminosity, they got more than they bargained for. They found the galaxies had grown so massive so quickly that they sit right on the edge of mathematical possibility in a lambda-CDM universe. ›

When Mike Boylan-Kolchin at the University of Texas at Austin got wind of Labbé's results, he immediately ran what he calls "a stress test" of lambda-CDM. This involved looking at how much matter it was possible to accumulate in a dark matter halo in the early universe – haloes being large clumps of dark matter that are thought to corral ordinary matter, usually in the form of gas, to create galaxies. He discovered that it was just possible to pull together something with the mass of the Milky Way.

However, to reproduce Labbé's observations, the galaxy would have had to convert essentially all of its atomic matter into stars. And that is a big ask, to put it mildly. "The galaxy would have to be forming stars even in the far outreaches of these collections of dark matter, where the gas is pretty diffuse and just starting to trickle in," says Boylan-Kolchin.

While astronomers expect a lot of stars to form in a galaxy's central region, the outskirts are usually too diffuse to ignite much activity at all. This drastically drags down the efficiency at which a galaxy converts its gas into stars. Typically, star formation in a large galaxy involves just 10 per cent of this gas. In the case of the JWST galaxies, Boylan-Kolchin found that these would have had to be running at 100 per cent star formation efficiency, converting all the gas. "That's very unrealistic," he says. "It is basically impossible."

The upshot is that the galaxies themselves appear to be impossible in the context of the universe as we thought we knew it. But their appearance wouldn't be the first observation that threatens to break the standard cosmological model. A discrepancy between the expansion rate of the universe as calculated in the relatively nearby universe versus what cosmologists see in the distant reaches of space has been simmering for years now. It is known as the Hubble tension, and if it turns out to be real, cosmologists will almost certainly have to drastically modify the lambda-CDM model to accommodate some sort of early burst of dark energy.

The anomalous young galaxies seemed to be pulling in the same direction. An early burst of dark energy would mean there had to be more dark matter and more ordinary matter in the universe than we thought. More dark matter means larger haloes, and larger haloes mean more efficient star formation.

The question is whether the calculations of the galactic masses stand up to scrutiny. "If these results are really right, there seems to be something seriously wrong [with traditional lambda-CDM]," says Boylan-Kolchin. "So we better confirm or reject these results as quickly as we can."

Trying to do so has engaged many astronomers, and one line of work has already pointed to a way to ease the discrepancy. To grasp how, first you have to understand that the standard way to estimate a young galaxy's mass is to look at its total brightness and calculate how many stars would be needed to make it that bright. While this sounds perfectly reasonable, it assumes you know how various factors influence star formation.

To better establish those factors, Charles Steinhardt at the Cosmic Dawn Center in Denmark has examined how big early galaxies should be expected to grow in light of the nuances of star formation in the early universe – an epoch in which the interplay between gravity and thermodynamics, or the laws of heat and energy, may not have been the same as today.

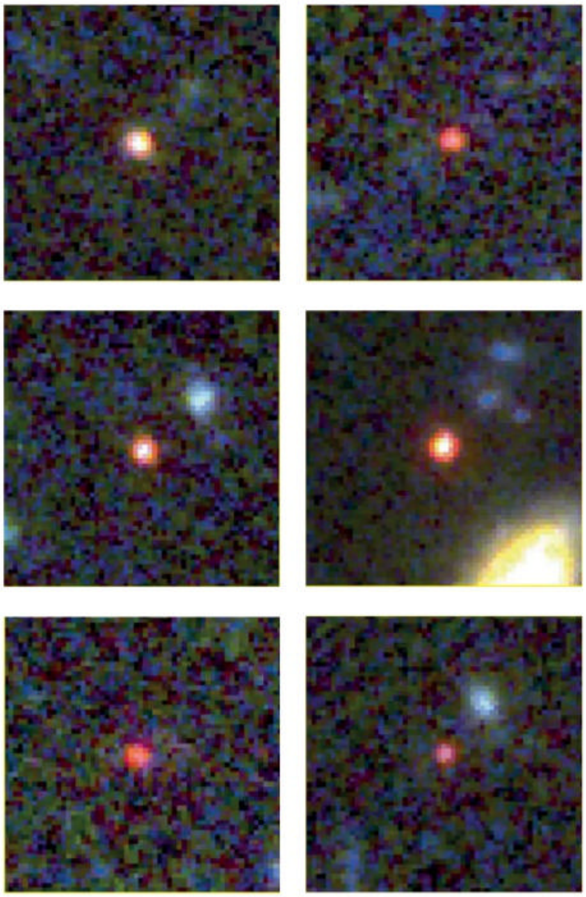
In star formation, the temperature of interstellar gas is crucial in determining the mass distribution of stars that form in a given cluster – that is, how many high-mass stars you get compared to low-mass stars – which is described by what astronomers call the "initial mass function".

The reason Steinhardt wanted to examine Labbé's galaxies is that the initial mass function astronomers universally apply is derived from the conditions in the Milky Way as it is today, whereas we know that star-forming gases would have been considerably hotter in the early universe. That would have inhibited the formation of low-mass stars, changing the initial mass function, the result of which would be a reduction of the mass of any given galaxy as a whole.

Sure enough, when he included such factors in his calculations, Steinhardt found that the masses of early galaxies decreased significantly. "We get the masses to come down for some of Labbé's galaxies by between a factor of 10 and 100," he says. The upshot is clear: "You might be able to still make them from the [dark matter] haloes that you can get under lambda-CDM."

That sounds a lot like another escape for cosmology-as-usual. But lambda-CDM isn't yet in the clear because Clara Giménez-Arteaga, a PhD student also at the Cosmic Dawn Center, has performed another analysis of other early galaxies spotted by JWST – not the six Labbé had looked at – and got a very different result.

She was able to take an alternative approach to estimating the mass of young galaxies thanks to JWST's unprecedented optics, which can resolve even these far-off star clusters into collections of pixels – rather



NASA, ESA, CSA, I. LABBE, G. BRAMMER

Six galaxies, seen 500 million to 800 million years after the big bang, imaged by JWST

than single pixels containing less detail. That means you can estimate the number of stars and their masses in each pixel, then add them up to compare them with the value from the overall luminosity approach that Labbé used. "Thinking about this beforehand, I thought I should get about the same answer," says Giménez-Arteaga. What she found, however, was surprising: each of the galaxies she looked at was between three and 10 times heavier than previously thought.

The reason is that, in effect, treating each galaxy as a single unresolved pixel, rather than as a collection of pixels, hides the fact that star formation may not be taking place uniformly across the galaxy. The unresolved method causes brighter, newer stars to outshine dimmer, older stars, masking them from view and lowering the estimated mass, says Giménez-Arteaga. By treating each individual pixel as its own region, astronomers can see the vast number of long-lived, low-mass stars that have been created in previous rounds of star formation. "The physical mechanism that makes this happen can only increase the resolved mass," she says.

Giménez-Arteaga is yet to apply this method to the galaxies Labbé analysed, but given that the technique has been shown to increase the calculated mass of similar early galaxies, it would almost certainly do the same for the six in question – and would therefore intensify the contradiction with lambda-CDM.

Clearly, cosmologists need to get the true measure of these suspicious galaxies. The fate of the universe, or at least our understanding of it, depends on the answer. The good news is that, unlike the Hubble tension, a case that seems set to rumble on, we can expect definitive answers in the not-too-distant future.

Almost all the analyses done so far rely on images of the galaxies, which require astronomers to estimate a number of quantities such as age, distance and mass. But to accurately pin these down, you need spectra – where the collected light from an object is split into its constituent wavelengths for more detailed analysis. This is the next step in the process and, fortunately, is precisely what JWST was made for.

Unlike its predecessor, the Hubble Space Telescope, JWST is designed to capture light from the really distant universe, which has been dramatically stretched into the infrared region by the expansion of the universe. "JWST offers, for the first time, good quality spectroscopy covering the crucial wavelength range," says Andrew Bunker at the University of Oxford, who › is a member of JWST's near-infrared spectroscopy instrument team.

With infrared spectroscopy, we can determine accurate distances and ages for the galaxies. Assuming that each galaxy is confirmed to be at the distance currently estimated – as most astronomers seem to confidently expect – spectroscopy will also allow us to test Steinhardt's ideas by investigating the temperature of the interstellar medium at each galaxy.

As a proof of concept, Bunker and his collaborators recently released a spectrum of a very distant galaxy that had shown as a faint red dot in earlier Hubble data and was earmarked for further investigation. The results exceeded anything he had dreamed of. "We never thought we'd get such a beautiful spectrum," he says.

The upshot is that the galaxy, which is only about 700 million years old, appears to have experienced a short yet intense burst of star formation, followed by a rapid slowdown about 10 to 20 million years before the time of observation. Particularly interesting, says Bunker, is that the mass they calculated came in at around 200 times smaller than the Labbé sample.

Bunker says this isn't a direct refutation of the idea that those six galaxies could break cosmology, because the galaxies he analysed are in a different part of the sky. "It's possible lambda-CDM is broken, but the jury is out until we have the spectroscopy," he says.

So, the plot continues to thicken. For now, lambda-CDM has a stay of execution. But even if it survives this current crisis, it will face the chop at some point, says Steinhardt. "Lambda-CDM is a placeholder," he adds, meaning that until we understand the true nature of dark matter and dark energy, we are simply using the most generic examples of both in the model. In that context, it is perhaps surprising that such a simple model has been able to explain the entire universe for so long.

And yet it seems clear, at this stage, that JWST's ability to peer into the furthest reaches of the cosmos means it is going to keep finding things that put lambda-CDM under pressure. "It has already been a game changer," says Bunker. "We're now routinely getting high-quality spectra for which we can infer the properties of galaxies just a few hundred million years after the big bang." ∎

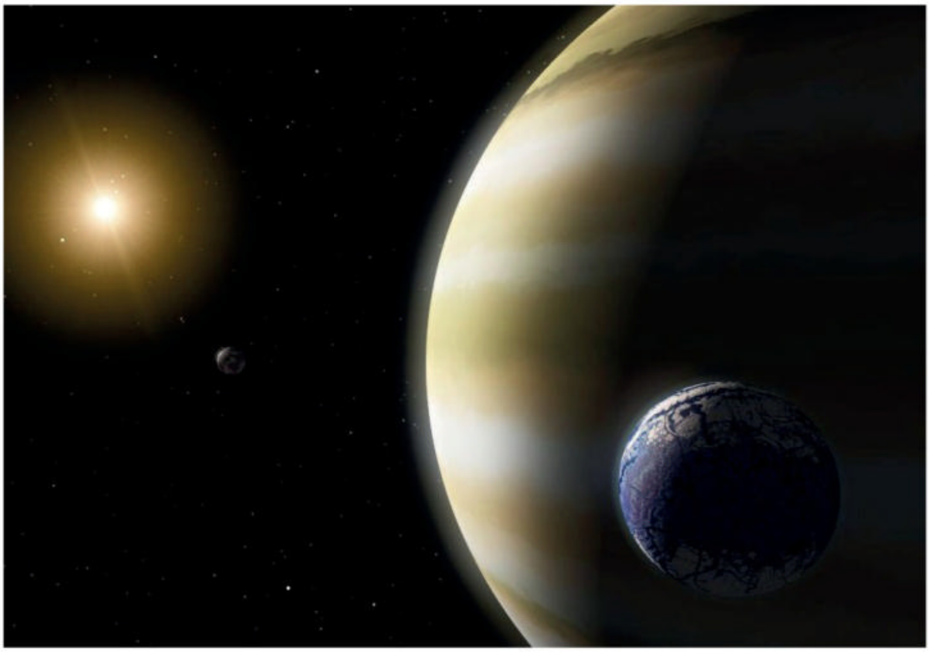
Five exomoon programmes have been picked for the James Webb Space Telescope, raising the hopes of finding moons around exoplanets for the first time.

WE'RE ABOUT TO FIND EXOMOONS AROUND FAR-OFF PLANETS

IF OUR solar system is anything to go by, moons are everywhere – six of our eight planets have them. Earth has a solitary and sizeable one, while Mars has two small, asteroid-like companions. The four giant planets host the most extensive satellite systems, with Saturn currently holding the record at around 150 known moons.

There isn't just one way to make a moon, either. Our own appears to be the result of a chance event that saw a Mars-sized object slam into us 4.5 billion years ago, its tidal effects playing a key role in the evolution of life on Earth since. The moons of Mars, on the other hand, are probably captured asteroids, while Jupiter and Saturn's may have formed in discs of debris around the planets.

Moons can come in all manner of configurations, too. Two of Saturn's – Janus and Epimetheus – almost share an orbit. But it could get weirder than that. "In principle, you could have crazy things like rings of moons around planets, like Saturn's rings but moons instead of tiny little particles," says Sean Raymond at the University of Bordeaux in France. Along with Juna



An artist's image of an Earth-like exomoon orbiting a gas giant planet in a distant star system

Kollmeier at Carnegie Observatories in California, Raymond has even postulated that, under the right conditions, moons could have their own moons. These are called moonmoons.

Astronomers started thinking about exomoons in earnest when the first exoplanets were discovered in the 1990s. Darren Williams, now at Pennsylvania State University, was a graduate student around this time. "Very quickly, the number ballooned from zero to 10," he says. "All of these planets were giant Jupiters. I said they're going to have moons, and some of the moons are going to be big enough to support life."

Moons could be intriguing locations to look for life if they are large enough to hold onto sizeable atmospheres. The cut-off for this is surprisingly small, barely one-tenth the mass of Earth, says Lisa Kaltenegger at Cornell University in New York. "There is no reason why an exomoon couldn't be inhabited," she says. And while planets are likely to need to orbit in a star's habitable zone to host liquid water and life, a moon could be heated by a planet in a much wider orbit around a star. "These moons could be much further out to be warm enough for life," says Kaltenegger. "It's much easier to keep them from freezing in the interior because of the tidal heating from the planet."

Take our solar system as an example. We know that Jupiter's tidal forces keep its four largest moons warmer than they would otherwise be, by squeezing them, which generates heat through friction. Saturn's atmosphere-laden moon Titan, meanwhile, is the only known place besides Earth with lakes and seas on its surface, albeit ones filled with liquid hydrocarbons instead of water.

A habitable moon orbiting a gas giant might have an amazing sky, especially if the moon were tidally locked – with one face always pointing towards the planet – like our moon is to Earth. One side of such a satellite would live under permanent planet-shine and never experience full night. "You could walk on that moon [from the far side to the planet side] and the planet would start to come into view," says Kaltenegger.

All of which is to say that exomoons are wondrous places. So how do we find them? And why are we yet to confirm a sighting?

Jean Schneider at the Paris Observatory was the first to tackle one of those questions. In 1999, astronomers had broken fresh ground by spotting an exoplanet using a new technique called the transit method – noticing the dip in a star's light as a planet passes in front of it – which has since become our predominant way of finding these worlds. In theory, thought Schneider, the same technique could reveal › exomoons. He worked out that an exomoon should cause a slight shift in a planet's transit depending on whether it is in front of or behind the planet as it crosses the star's face. These are now called transit timing variations. "It gives you the revolution period of the moon around the planet, and the amplitude of the variation gives you the mass of the moon," he says.

The first real attempt to search for a moon around a transiting exoplanet was made with the Hubble Space Telescope in 2001, with no luck. But the field of transiting exoplanets was revolutionised in 2009 with the launch of NASA's Kepler telescope, a wildly successful mission that found more than 2700 transiting worlds in its nine years of observation. It was as a result of these sightings that David Kipping at Columbia University in New York began to think seriously about the possibility of finding exomoons.

As the Kepler discoveries poured in, he and his colleague Alex Teachey at the Academia Sinica Institute of Astronomy and Astrophysics in Taiwan went through the data with a fine-tooth comb to look for exomoons. The problem was that many of Kepler's discoveries were hot Jupiters, gas giants on tight orbits around their stars. This appeared to rule out exomoons because the gravitational pull of the stars in such locations would be likely to rip away any moons.

As such, from an initial look at 300 Kepler planets in 2016, Kipping and Teachey came up almost empty-handed. "I remember being very depressed," says Kipping. "I went to Alex's office and I said, 'Is there anything in here at all?'" There were no clear exomoon signals.

The only potential hit the pair found was around a gas giant called Kepler-1625 b, which is 8200 light years from Earth and about the same size as Jupiter, but with a much greater mass. The pair were given time on Hubble in 2017 to observe the planet in more detail and they found a transit timing variation suggesting the presence of an exomoon, which they dubbed Kepler-1625 b I. To cause the signal, the moon would have to be huge, with a radius on a par with that of Neptune.

Unfortunately, upon further inspection, the data turned out to be inconclusive. No amount of analysis could unequivocally confirm the signal the pair had seen. "There's been some controversy," says Kipping. "I remain very sceptical myself."

Then, in 2022, Kipping and Teachey revealed a second exomoon candidate around a Jupiter-sized planet about 5600 light years away called Kepler-1708 b. This moon would be much smaller than the first candidate, but still huge compared with any in our solar system: a mini-Neptune or super-Earth-sized object more than twice the size of our planet. Kipping describes the candidate as "basically something we just couldn't kill… a persistent signal of an exomoon that we can't get rid of".

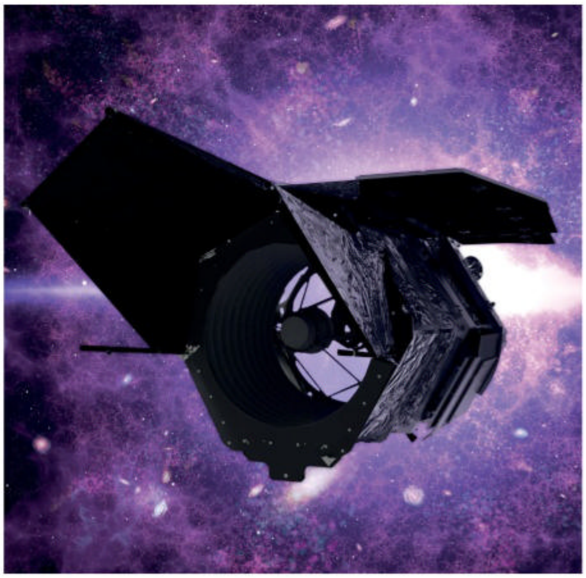
Not everyone agrees, however. In December 2023, René Heller at the Max Planck Institute for Solar System Research and Michael Hippke at the Sonneberg Observatory, both in Germany, published a paper refuting the existence of the two exomoons. Reanalysing the original data, Heller and Hippke said they couldn't find the same evidence as Kipping and Teachey. But Kipping says there were flaws in Heller and Hippke's analysis.

This back and forth shows how difficult it is to confirm an exomoon detection using Kepler and Hubble data, and Kipping's detections remain tentative at best. "They're not slam dunks, and in the exoplanet game, people are really used to slam dunks," says Teachey.

Finding out if the moons exist for certain would require further observations over many hours. Instead, a better bet may be to look elsewhere – around free-floating planets, for instance. Also known as rogue planets, these worlds have been spotted drifting through our galaxy by the likes of the James Webb Space Telescope (JWST), glowing from their residual heat – which could also provide energy for potential life. These wandering objects, likely to have been ejected from orbits around young stars, could perhaps be acting as roaming oases of habitability.

If these rogues have any large moons in orbit, spotting their transits should be possible. "You can monitor them in much the same way you would monitor a star for a transiting exoplanet, but instead of an exoplanet, you are seeing moons," says Melinda Soares-Furtado at the University of Wisconsin-Madison.

A NASA observatory set to launch in 2027 aims to do just that. The Nancy Grace Roman Space Telescope, known simply as Roman, will stare at portions of the sky for long periods. Its primary goal is to seek transiting planets, and it is expected to find as many as 100,000 of these. But Soares-Furtado and Mary Anne Limbach at the University of Michigan and their colleagues calculated in 2022 that the telescope will also be particularly sensitive to exomoons orbiting free-floating worlds in the Orion nebula. This is the closest region of intense star formation to Earth, where there are thought to be rogue planets. More than a



GSFC/SVS

The Roman Space Telescope will monitor stars for transiting planets

dozen transiting exomoons are likely to be detectable there if they exist, the researchers found, right down to the size of Jupiter's moon Callisto or Saturn's Titan.

Such discoveries would also give us a good handle on how prevalent exomoons are likely to be. "You can do large-scale statistics," says Soares-Furtado. If these moons turn out to be as numerous as we think, it could dramatically increase the number of locations where we might one day look for life. "It increases the number of places to look by around a factor of 100 if our solar system is not unique in the number of moons that we find here," says Soares-Furtado. This estimate is based on the fact that, in our solar system, there is around a factor of 100 more moons than planets.

The majority of exoplanets Roman is hoping to discover will be in orbit around stars. It will find them using yet another technique, one called microlensing, which looks for the bend in light from a distant star when a closer star and any accompanying planets pass between it and our line of sight. That method should be able to detect exomoons, too, "all the way down to about twice the mass of the moon, or the mass of Jupiter's moon Ganymede", says Scott Gaudi at the Ohio State University, who leads Roman's exoplanet team. It could even spot some moons comparable to our own around Earth-mass planets. "We're not going to get thousands of exomoons with Roman," he says. "But we're going to start to detect how common these things are."

The cadre of scientists looking for exomoons is small, probably because of how hard it is. But they are determined and innovative. Andrew Vanderburg at the Massachusetts Institute of Technology, for example, wants to detect exomoons in a totally different way, by noting the slight gravitational wobble in a planet caused by the presence of a moon. Upcoming big, ground-based telescopes, like the Extremely Large Telescope – expected to finish construction in Chile around 2028 – would be particularly suited to this technique. "If you can take observations of the planets themselves, getting light using direct imaging, you can look for moons," he says.

There are also grounds for optimism in new telescopes designed to look for exoplanet transits, only this time with enough accuracy to make an exomoon detection in a star system. An upcoming European Space Agency (ESA) instrument called Plato, set to launch in 2026, might be sensitive to moons down to the size of Earth, says Ana Heras at ESA in the Netherlands, who is the project scientist for the mission. NASA's Habitable Worlds Observatory, a proposed successor to JWST intending to launch in the 2040s to image Earth-like planets and hunt for life, might go even further – picking out the reflected light of exomoons as small as our moon in the light of those planets. "Habitable Worlds is absolutely incredible for exomoons," says Limbach.

All those plans are exciting, but they mean waiting years, if not decades, for any sightings. Luckily, there is a telescope already in use that could find moons as small as Europa, which is about 90 per cent of the size of Earth's moon. "JWST is the first telescope humanity has ever built that can find those moons," says Kipping.

Exomoon projects had never before been picked for JWST, but in the Cycle 3 selections announced on 29 February 2024, they finally made the cut. Five programmes related to exomoons were chosen, including two that will perform direct hunts for them.

One will study a Jupiter-sized planet orbiting a star called Kepler-167, which is about 1110 light-years from the solar system. The planet crosses the face of its star from our point of view once every 1000 days. Another programme, led by Emily Pass at Harvard University, will look for exomoons similar in size to our own moon orbiting two planets around the red dwarf star TOI-700, about 100 light years from Earth. The two planets are Earth-sized and in the habitable zone. ∎

HOW THE EUCLID SPACE TELESCOPE WILL PROBE THE DARK COSMOS

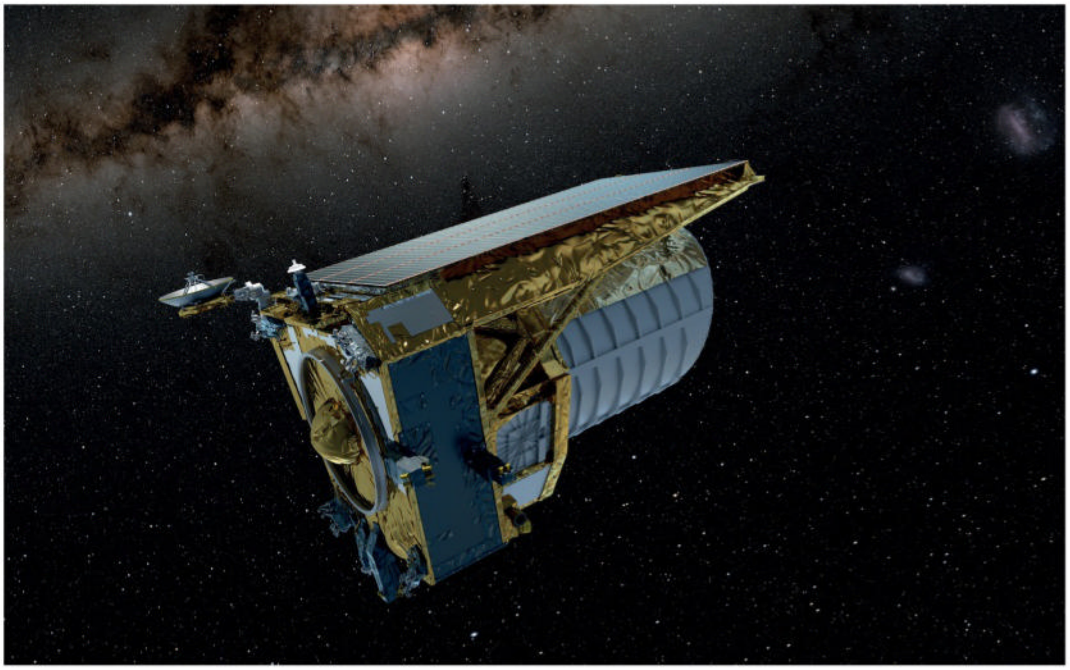
The European Space Agency's Euclid space telescope is on a mission to study the mysterious nature of dark energy and dark matter.

THE European Space Agency (ESA) launched its newest space telescope, Euclid, which blasted off from Cape Canaveral in Florida on 1 July 2023 and is now parked about 1.5 million kilometres from Earth. Over six years, it is expected to image about one-third of the sky, building the most detailed 3D map of the cosmos ever created, to help solve two of the biggest mysteries in the universe: dark energy and dark matter.

These two "dark" components make up more than 95 per cent per cent of the cosmos, but we cannot see them, hence their names, and know very little about what they could be made of. Astronomers infer the existence of dark matter from the behaviour of the matter that we can see, which acts as if there is some extra source of gravity holding everything together. Dark energy has the opposite effect, causing the accelerating expansion of the universe as a whole.

Euclid has two scientific instruments: a visible-light camera to measure the shape of galaxies, and a near-infrared detector to measure their brightness and

Euclid will catalogue billions of galaxies across different wavelengths of light


ESA

distance. While it isn't the first space telescope to use either of these types of instruments, it will be unusual in that it is planned to observe a huge swathe of space, cataloguing over a billion galaxies across more than one-third of the sky.

"With Hubble and the James Webb Space Telescope, those are great observatories for looking at very small regions with very high sensitivity, extraordinary detail – but it's a bit like looking at the sky through a tiny straw," says Mike Seiffert at NASA's Jet Propulsion Laboratory in California, a project scientists for Euclid. "With Euclid, we're less interested in the properties of individual galaxies and objects than we are in measuring a few properties of many, many galaxies."

Researchers will then use these properties to build two types of map of the universe. The first will use a phenomenon called gravitational lensing, in which relatively nearby matter warps and magnifies the light of objects behind it. The way this bends the apparent shapes of distant objects can tell us about the distribution of the nearby matter acting as the lens.

The distortions are usually tiny, but the huge amount of data Euclid is expected to collect during its six-year mission should allow researchers to use gravitational lensing to map out the distribution of matter – including dark matter, which we can't see any other way – in the universe. Knowing the distribution of dark matter more precisely will help us figure out how it behaves and may present clues as to what it is really made of.

The other type of map uses ripples in the matter distribution of the universe called baryon acoustic oscillations. These ripples first formed as sound waves soon after the big bang, when the cosmos was a hot, roiling soup of particles and radiation. Eventually, that soup cooled and the waves froze in place, remaining as slightly more dense regions where more galaxies tended to form as the universe expanded. Mapping those relic over-densities can be an extraordinarily effective way to look into how and why the expansion is accelerating.

"Seeing how those wrinkles in the early universe propagated forward and how dark energy affected that will help us understand the evolution of the universe and, really, how the universe works," says Seiffert. Euclid should start unravelling the mysteries of the cosmos soon. ∎

CHAPTER 6

SEARCHING FOR LIFE

For all of our landers, orbiters, spacewalks, sample return missions and space telescopes, there is one question we have yet to answer: is there any other life out there?

Finding signs of alien life has always been a goal of space exploration. But as we learn more about our own solar system, and begin to see exoplanets in more detail than ever before, it is becoming clear that a slam-dunk sign of life, a "biosignature", is going to be tricky to come by.

One thing is certain: there is no shortage of ideas about how we might find extraterrestrial life.

WHY HAVEN'T WE HEARD FROM ALIENS? THERE IS A REASON FOR THE SILENCE

The search for extraterrestrial intelligence has been going on for 60 years without success. Given the hurdles to interstellar communication, that's just a blink of an eye.

IN 1960, astronomer Frank Drake began an experiment. With a radio telescope, he studied two nearby sun-like stars, hoping to find signals that could only have been generated by life on planets orbiting these stars. He came up blank. In the six decades since Drake started the search for extraterrestrial intelligence (SETI), astronomers have kept listening, carefully and systematically. Still, we have heard nothing.

One possibility is that there simply are no aliens out there – that we truly are alone. But this seems unlikely, given the vastness of the cosmos, with hundreds of billions of galaxies containing hundreds of billions of stars, most of which have at least one planet orbiting them, at least according to our burgeoning knowledge of exoplanetary systems in our own galactic neighbourhood.

Jill Tarter, co-founder of the SETI Institute in California, says we haven't listened for long enough or looked hard enough to make any such sweeping statements yet. Astronomers have studied all kinds of electromagnetic radiation – light, radio waves, gamma rays – looking for signals. Such a search has to cover all directions and distances in space, plus the different ways a signal might manifest itself, such as shifts in polarisation, frequency, modulation and intensity. Tarter sees these parameters as a multi-dimensional ocean. "When SETI turned 50, we had explored one glass of water from that ocean. By the time it turned 60, it was more like a small hot tub," she says. "It's getting better and faster all the time, but there's a lot more to explore."

According to Beth Biller, an astronomer at the University of Edinburgh, UK, searching through time is the biggest challenge. Humans have only lived on Earth for the blink of an eye compared with the age of the universe, and we have only been broadcasting our presence with things like radio waves for just over a century.

"The civilisation that you want to contact has to exist at the same time as your own civilisation," says Biller, which given light's finite speed of travel, could be thousands, millions or billions of years in the past once their signals reach us, depending on how far away from Earth you are looking. "When you're talking about finding aliens, you just have to get a lot of timings correct," she says. Electromagnetic waves from other worlds will radiate in all directions, so the further ›

JOHN ELLINGSON / ALAMY STOCK PHOTO PREVIOUS PAGE: AERIALPERSPECTIVE WORKS/ISTOCK away we are, the fainter any signal will be. Even the closest neighbouring star system to Earth, Proxima Centauri, is more than 4 light years away, putting a big delay on any conversation.

Even if a transmitting alien civilisation were close enough, we might not see it. Around 70 per cent of exoplanets have been found using the transit method, which involves observing the light from stars periodically dimming when planets pass in front of them. A study published in June 2021 by Lisa Kaltenegger, an astronomer at Cornell University in New York, and her colleagues turned this logic around to ask how likely aliens would be to see us using this method.

They identified just over 2000 systems within about 300 light years of Earth that might see our planet in this way at some point between 5000 years ago and 5000 years from now. Within the list, there are seven stars with planets in the habitable "Goldilocks zone", where it is the right temperature for liquid water on the surface, of which four are close enough to have already received radio waves. Most of them lie in a heavily populated area of space so far unexplored by exoplanet surveys, at least until NASA's Transiting Exoplanet Survey Satellite (TESS) started operating in April 2021. "And yes, I gave them the star list to search for planets," says Kaltenegger.

Even a continued no-show might not tell us much. If alien life forms exist, it might be that intelligence or technology are rare. Perhaps technological civilisations are simply too combustible, liable to destroy themselves before they can make their presence unambiguously known. Perhaps they do know about us – but have decided to leave us alone.

Or perhaps we are simply looking for the wrong thing, our focus on electromagnetic signals reflecting the state of our current technology. Why not gravitational signals, say – or something else entirely? "We may have to discover new physics before we get it right," says Tarter. ∎

INTERVIEW

Space probes will be the first to explore the furthest reaches of our solar system and beyond. To make discoveries like finding alien life, they will need to think more like humans, says NASA's Steve Chien.

WHY NASA IS INVENTING CURIOUS AI FOR DEEP SPACE


AFLO CO. LTD. / ALAMY STOCK PHOTO

What is it like to work at the Jet Propulsion Laboratory?

I am unusual at JPL in that I haven't dreamed of working there since I was a child. However, I've had the tremendous opportunity to work on a number of incredible missions, including the European Space Agency's Rosetta and currently the Mars 2020 Perseverance rover, and that's what has kept me so very interested in working at JPL. I've been honoured to work with such amazing scientists and engineers.

What kind of intelligence does the Perseverance rover, currently exploring Mars, have? Is it a smart rover?

Well, smartness is a relative term. Perseverance can do much more than prior rovers, but it is still way behind what a human science and engineering team could do on Mars. For example, the rover can now, for certain instruments, "hunt for targets" given certain criteria such as colour, shape, distance from the rover. It will acquire wide field-of-view imagery, find targets within that which best match the criteria and then fire a laser to take a more detailed measurement.

Perseverance has more powerful navigation systems that allow it to drive faster and further, independently. But the progress is incremental and there's a long way to go. We are also working on software that will allow the Perseverance rover to adjust the plan sent from the ground [on Earth] in the event that activities are shorter or longer than anticipated, shuffling activities and adding and dropping activities to fit.

You have described your work as making space probes more curious. What do you mean by that?

The smarts we've been able to put on spacecraft and rovers thus far have been to recognise things we understand. To target specific types of rocks with a laser or to search for dust devils in a sequence of images, for example.

In the future, when we travel to the complete unknown, we will need to go beyond this. We'll need to look for patterns in data. For example, on Earth, we might look at overhead imagery and cluster it based on colour, texture, ruggedness and linear features. Based on these features, we might naturally discriminate between lakes, rivers, mountains, forests. But on another planet or moon, these might correspond to different types of sand dunes, oceans, vegetation and so on.

Why not send humans to investigate other planets and moons?

Humans are very sensitive, very fragile. Sending them to low Earth orbit requires an amazing endeavour, to the moon required an enormous endeavour and sending them to Mars is even more challenging. And those are all places where we're certain there isn't life.

If you look within the solar system, there are several places where we believe there could be life. Basically, the strategy is to look for liquid water. One of the most promising places is Europa, a moon of Jupiter. You can't really send people there because the Jupiter radiation is very harsh, plus you need a very long mission to go there. So, we have to send robots to look for life. But because of the distances involved, the communication is very difficult. The robots have to be smart enough to look on their own.

Can AI make probes and rovers recognise things in the same way a human does?

There's a central question of how smart machines need to be that's poking at the edges of artificial general intelligence. And that's what people talk about when they think of characters such as Data from *Star Trek* – something that could interact at a peer level with humans on a broad spread of topics, just like a human could.

›

PROFILE
STEVE CHIEN

Steve Chien is head of artificial intelligence at NASA's Jet Propulsion Laboratory. Throughout his career, he has worked on various missions including the Rosetta mission, and developed AI that is being used today by the Perseverance Mars rover. His main focus is the question of how to make AI more human.

We don't really need that in space. What we need is a specialised intelligence. A smart spacecraft doesn't need to know how to take a bus in Dublin, or how to book a flight. It needs to know very specific things, such as how its sensors work. It needs to know about the science that people want it to do.

So, AI is a way of stepping beyond just a probe sticking to a checklist?

Already the robotic missions are somewhat running themselves, autonomously, but we're just scratching the surface of the possible. A great example is that fantastic mission called New Horizons, which was run by a colleague of mine, Alan Stern. They did some amazing things – flew by Pluto, flew by the Kuiper belt object Arrokoth and did some incredible science. But they pre-planned how they would fly by those places.

What we'd like in the future is for the spacecraft to be smarter and look for certain things. It would look for satellites, for moons and moonlets and if it finds them, would take extra images of them. Plumes, little geysers, are a remarkable scientific phenomenon, so again the spacecraft would know to take more and more images of those.

How can we equip probes with these sorts of abilities?

It seems like this would be very easy, that you'd just tell the software to do that. But it turns out it's actually really complicated. You have to know how the spacecraft is moving, how and where to point, and most of all the spacecraft has to understand that "that's a plume".

These are all things that humans do very well. We walk around the world, and we say "that's a chair" or "that's rain falling". But making computers understand these things is not so easy. When you talk about curiosity, and you talk about wonder, the first steps to that are being able to spot what's unusual, what's different.

What we want to do is search intelligently, and we do that with things we call white lists and black lists. A white list contains specific things you're looking for. It might include sulphur, because sulphur is a sign of life, for example. A black list is where you're expecting to see certain things, but if we see something else, something we weren't expecting to see, that's interesting. You search, you see all of the things you expect, but – whoa! – you spot something you weren't ready for, like maybe a Martian runs past the lens. That is the big step towards intelligent curiosity – recognising that which is unusual and exciting.

How far away are we from an artificially intelligent probe that can truly make discoveries in the same way that humans do?

This is a very tough question. Already, there are machine-enabled discoveries being made every day. In these cases, the AI is amplifying the human intelligence, enabling the combined team to consider more plans, to find better plans.

Humans have a better strategic view, and the computer can run down leads and search, taking high-level direction from humans. A machine making an independent discovery? This is far less common. But there are cases, typically where the human grasp of the problem is limited by huge amounts of data. Even in these cases, the human-driven math and objective functions are a key part of the process.

As far as human-level competence in human-dominated fields, I do not see that in the near future, say in the next five or so years. But the pace of progress is astounding in some areas. I am unwilling to make any projections beyond five to 10 years, which makes me sound like an economist! ∎

HOW EXCITED SHOULD WE BE BY SIGNS OF LIFE SPOTTED ON ALIEN WORLDS?

We keep spotting molecular "biosignatures" in the atmospheres of planets beyond Earth, but it isn't clear if any of them can provide definitive evidence that we're not alone.

WHEN astrobiologists talk about seeking atmospheric biosignatures, they are referring to molecules known to be associated with life on Earth that we can detect from afar. We do this by looking at how the intensity of light from a host star at different wavelengths changes as a planet moves across its face, whereupon some of that light may be absorbed by the planet's atmosphere. Different types of molecule absorb light at characteristic wavelengths, and so if we see that the intensity of starlight diminishes at certain wavelengths during a transit, this indicates the presence of a given chemical.

We have never been better equipped for this search. Not only has the power of the James Webb Space Telescope to resolve spectra massively boosted our ability to probe the chemistry of worlds beyond our solar system, but we have ever more places to look for these exoplanets, too. There are currently more than 5500 such worlds confirmed, with a range of planetary types far more diverse than in our solar system. Better still, some of the most promising habitable candidates – planets intermediate in size between Earth and Neptune, with a rocky core and global oceans beneath a hydrogen-rich atmosphere, known as Hycean worlds – are also some of the easiest to study.

As for which molecules we want to see, for a long time it was all about water. NASA's astrobiology programme adopted an informal slogan: "Follow the water." We know liquid water is essential for all life on Earth, so the idea was that we should look for worlds with it on their surface. This gave rise to the idea of a "habitable zone" around a star in which planets orbit at the right distance to potentially have water in this form.

But this only gets you so far. "We assume life requires a liquid, and there's lots of reasons why water might be the best option," says Sarah Hörst, a planetary scientist at Johns Hopkins University in Maryland. "But water is one of the most abundant molecules in the universe." In general, its presence beyond Earth is therefore neither surprising nor automatically suggestive of life.

Seeing it in the atmospheres of small, rocky planets is different. Because atmospheric water molecules will be split by ultraviolet light from the parent star, it would only persist in rocky-planet atmospheres if it were continuously replenished by a surface source, such as oceans. So seeking water on exoplanets can narrow the options of where to look more closely – but it doesn't in itself amount to a reliable biosignature.

Oxygen has also long been considered a potential sign of life. As a very reactive element, it too will only persist in large amounts in an atmosphere if it is continually supplied afresh. On Earth, that happens mostly via photosynthesis in plants and bacteria – because of life, in other words – which explains why oxygen has been a favourite gas for astrobiological searches for decades. But that also gave rise to a "cottage industry" of people explaining how it might be produced by geological, photochemical or other non-living processes.

And then there is carbon dioxide. It isn't difficult to account for this in non-biological ways. Volcanoes on Earth spew it out aplenty. But the interest in detecting this molecule is more about establishing that there is carbon around from which complex organic molecules – and perhaps ultimately living organisms like the carbon-based ones on Earth – might be made. That is why the sighting of CO_2 bubbling out of Europa's sub-ice water ocean is intriguing. This chemical isn't thought to be stable on the Jovian moon's surface, so the source of it must be relatively recent.

A more plausible biosignature might be found in some combination of familiar gases on other worlds. Oxygen and methane, for instance, won't coexist in an atmosphere that is in chemical equilibrium – as they react to produce other substances – but only when some process, like life, is present to keep topping their levels up to maintain what researchers call a non-equilibrium state. The trouble is that every atmosphere is somewhat out of equilibrium, because the parent star is constantly dumping energy into it. You would need to see one that is wildly out of equilibrium, as on Earth, to get excited. If you add more molecules into the mix, the case that they were being made by life gets stronger.

But another, equally telling kind of biosignature might come from gases other than the common ones: molecules that, as far as we know on Earth, can't be created by anything other than life.

One is dimethyl sulphide (DMS), which, on our planet, is released into the air as a by-product of the metabolic reactions of some plankton. Hence the excitement around the recent announcement by Nikku Madhusudhan at the University of Cambridge and his colleagues of its detection in the atmosphere of exoplanet K2-18b, some 124 light years away in the constellation Leo.

Sara Seager, an astrobiologist at the Massachusetts Institute of Technology, says that if the detection checks out, it would be an exciting hint of life: "For now, it would be hard to explain DMS in any other way." However, any such excitement would be premature at this point, she adds, because the discovery remains highly tentative. She stresses that the first question to ask about such biosignature detections isn't "is it life?", but "is it real?".

Trying to detect such chemicals is complicated, especially for planets around red-dwarf stars like K2-18. Because they are dimmer than our own sun, drops in brightness due to planets passing in front of them are easier to see – that is why these stars are favoured as places to seek exoplanets. But Seager says red dwarfs also tend to have changeable surface spots like sunspots that complicate the starlight spectrum even before taking the atmospheres of transiting worlds into consideration. What's more, these stars are prone to solar flares that threaten to bake their planets, diminishing the prospects of life.

Searching red dwarf systems for biosignatures, then, is much like the old story of hunting for your lost car keys under a street lamp: we look not where is most likely, but where we are able to look.

Would finding one of these molecules in another world mean we have found life? "That is not clear," says Madhusudhan. On other worlds, we can't be confident that even molecules like DMS can't be generated by something other than life. "Just because it's only made biologically on Earth doesn't mean that's the only way to make it," says Hörst. "It's really hard to do this work without being Earth-centric." The problem is that we just don't – and maybe never will – know enough about the planetary environment on K2-18b to rule out all other possibilities. Are there volcanoes? Is there an ocean? Was there a recent comet impact on the surface? "We just don't have all of the information we need to be able to model the chemistry in exoplanet atmospheres," says Hörst.

But astrobiologists haven't given up on the idea that there could be definitive atmospheric biosignatures. Some think that we can use artificial intelligence to look for characteristic "life signals" in complex mixtures of molecules.

Others, meanwhile, reckon that measuring "molecular complexity" could do the trick, on the grounds that only life processes can produce such complexity above a certain threshold. ∎

NASA/JPL

AMATEUR ASTRONOMY: HOW TO SPOT JUPITER'S ICY MOONS

Jupiter's Galilean moons are promising places to look for life. Here is how to see them

The four biggest moons of Jupiter – Io, Europa, Ganymede and Callisto – are collectively known as the Galilean moons, because Galileo Galilei observed them in 1610, making them the first moons discovered beyond Earth. This was hundreds of years before Neptune, Uranus and Pluto were found. The fact they were discovered so long ago hopefully gives you some idea how easy it is to spot them, as long as you have access to a small telescope or large binoculars.

Your binoculars will need to have at least seven times magnification. Their power will be described by two numbers, like "12×36". The first is the magnification, so if this is a seven or above, you should be in luck

When Jupiter is visible, it is one of the brightest objects in the night sky. Use an astronomy app to figure out where the planet will appear in the sky. Once you have found it, look through your binoculars or telescope and you will see a few small spots of light very close to the planet. There will be up to four of these, and they will appear in a line. They might all be on one side of the planet or they might be on both sides. There might be fewer than four – in which case, some of the moons will either be in front of or behind Jupiter. The exact formation the moons appear in changes each day, depending on their paths of orbit around Jupiter. To work out what you have seen, you can use the Stellarium web software, plug in your location and time and zoom right into Jupiter.

Some of these icy moons are among the most promising places to look for life beyond Earth. This is why I love looking at them. The search for alien worlds doesn't need to involve distant exoplanets: we have exciting environments in our cosmic back garden.

HOW A RADICAL REDEFINITION OF LIFE COULD HELP US FIND ALIENS

Sara Imari Walker explains how Assembly Theory's definition of life might help us find it on other planets.

PROFILE SARA IMARI WALKER

Sara Imari Walker, a physicist and astrobiologist at Arizona State University, developed Assembly Theory with chemist Lee Cronin. She thinks that by pushing past cells and their chemistry to general principles about how complex objects come into existence, the theory can transform our understanding of what it is to be alive.

How do we define life at the moment?

A popular definition, often used by NASA, is that life is a self-sustaining chemical system capable of Darwinian evolution. Every word in there is problematic. I don't think life necessarily needs to be chemical. It's a much more abstract phenomenon. Life is about how information structures material objects and what objects are selected to exist, regardless of whether those things are chemical or not.

As for "self-sustaining", well, first you must define the boundary of the self. Parasites are interesting because they're not self-sustaining, but if you include their host then they are. Life depends on its environment. A lot of the issues with defining life always come from us wanting to draw a hard boundary. We want to be able to categorise things and put them in the life bin or the not-life bin. But there are always these challenging boundary cases. We shouldn't assume that we know what life is from the outset because that whole enterprise has failed over many decades.

Haven't we made some sense of what life is and how it began?

A lot of people focus on the RNA world scenario, for example, which posits that self-replicating RNA molecules appeared as a first step, before DNA or proteins. But they're still missing the bigger story about how complex chemical systems actually arise. This is a problem because we're building the answer we expect into the design of origin-of-life experiments. Everybody has narrowed in on the features of life that they think are important, but we haven't gotten to that deeper understanding that allows us to connect all these pieces together.

How are you getting to a deeper understanding?

A lot of people want to argue that the universe generates complexity for free. In standard physics, we think everything can happen spontaneously and life is just some very rare fluctuation. But the universe is this vast space of possible things. There are 118 known elements, and molecules are made from many of these elements, but there's not enough material in the entire universe to make even one copy of every possible molecule. And that's just counting simple molecules, I'm not including big molecules like DNA or proteins. So the likelihood of creating even a moderately complex object, say a DNA polymer, by randomly attaching atoms is exponentially low. If you try to create that twice it's almost impossible. There's never been a physics that has dealt specifically with this problem.

How does Assembly Theory try to deal with this?

The key conjecture of Assembly Theory is that the only way for us to observe complex objects is through a process of evolution and selection: where selection is based on things that have been built in the past, and they are used to build subsequent objects. This series of stages leads us to a "complexity threshold" and only above this do you see things that are products of life. Along with Lee Cronin at the University of Glasgow in the UK, our hypothesis is that life is the only physics that builds these high complexity objects. Sometimes I say that life is the physics that decides what gets to exist.

What do you mean by "objects"?

The fundamental objects in Assembly Theory are the emergent complex structures, not fundamental particles like quarks or electrons or photons. We define objects within an "assembly space", which contains all of the ways of building up an object from its basic building blocks. So an object like a molecule isn't defined by its three dimensional configuration that you might hold in your hand, and it's not defined by its mass or electric charge. The object is actually the ways of building the molecule. These histories, which converge on a particular structure that we see, are the object.

An electron can be made anywhere in the universe and has no history, so it's not a very interesting object. You are also a fundamental object, but with a lot of historical dependency. You might want to cite your age counting back to when you were born, but parts of you are billions of years older. The ribosomes that play a key role in translation of information from DNA to protein, for example, are believed to have been around on Earth for nearly 4 billion years. The specific molecules in your body aren't that old, but the lineage of these objects being reconstructed goes back that far.

From this perspective, we should think of ourselves as lineages of propagating information that temporarily finds itself aggregated in an individual. We are our history. So, we're reframing life by thinking about it as a temporally extended structure. It's a lineage, not an individual.

It seems intuitive that complex living objects are made from simpler objects. In what way is this an explanation for life?

We're saying that there's a different kind of complexity, which is assembled. On a meteorite you can have a chemical mixture of many molecules, but because none of them are produced in enough abundance you get this undifferentiated tar. From the perspective of Assembly Theory, no assembled structures have been selected out of that. It's a flat complexity that is very different to the kind of complexity we're talking about. According to Assembly Theory, this is why a meteorite has little to do with life.

Our key argument is that if something is hard to make, and requires many steps, then you're not going to see an abundance unless there was a selected pathway that makes it. In a meteorite, molecules with high assembly level are produced in such small amounts by random processes that they are undetectable. But if an object is alive, then selected pathways can reuse parts from the object's history to make an abundance of structures with high assembly. That's the only way to traverse this exponentially growing space of all possible things and so explain the existence of life. You have to trace out historically contingent paths, and we're trying to find out what the minimal number of steps needed to get there is.

What makes certain pathways "selected"?

If I was wildly conjecturing, I'd say there's a sort of force that moves objects through assembly space to generate higher assembly objects, which is why the biosphere ›

Sara Imari Walker has a new definition of what life is

evolved complexity over time. But I don't know if it's a force like in standard physics, we're trying to think about that. My intuition is that life is the physics that builds and grows possibility spaces. There's some sort of driving force that the universe is trying to explore in order to make as many objects as it can. It's trying to maximise the number of things that exist, and life is the way of doing that.

How are you testing this in the lab?

From our general theory about how objects assemble, we predicted that a threshold for life exists. Cronin and his team took a whole bunch of chemical samples from non-living and living materials. Using a mass spectrometer, which measures molecular fragments, they measured the "assembly index" of an object. This is the minimal shortest path required to build it.

The threshold for life seems to be an assembly index of about 15. We don't know if the number 15 is universal or specific to chemistry on Earth. But the fact that there is a threshold, above which we only observe molecules produced by life, is really significant.

We haven't found any non-living materials that have an assembly index above 15. This lack of false positives is unusual in origin-of-life science. When astrobiologists, like me, look for life, we seem to think that false positives are inevitable. We'll find atmospheric oxygen on an exoplanet, or amino acids on meteorites, even though there's no life there. This tells us that we've been looking at life wrong. If life is a real category of nature, and we understand the physics, there should be no false positives. It's either life or it's not.

So, you could you use this assembly index of life to search for alien life?

Yes. We're applying the idea of an assembly index of 15 to future flight instrumentation for NASA missions. NASA's Dragonfly mission, set to launch in 2027, will be the first to visit the surface of Saturn's moon Titan. It's a good example of the advantage of taking a more general approach to what life is because Titan is very different to Earth: the surface of Titan has hydrocarbon lakes. We don't expect anything like Earth life to evolve or live in this environment, so if we want to find out if life is on Titan, we need an agnostic technique. My group is now working on determining how we might be able to detect high-assembly molecules. We're working with NASA to ensure that their existing mass spectrometry instrumentation has high enough resolution to detect high assembly molecules.

Life detection on other planets or moons has so far been done by analogy to life on Earth, but this underestimates just how different alien life could be. Ultimately, I want to use Assembly Theory not just to detect life on other planets, but to predict what kind of life-assembling chemistries we expect to evolve on different planets.

How is Assembly Theory going to help you work out the origin of life, on Earth or elsewhere?

I actually think the origin of life was a planetary scale transition. The opposing, reductionist picture is that cells emerged in one environment, like at an isolated hydrothermal vent deep under the sea, and then they expanded over the entire planet.

My view is that geochemistry started to generate more complexity, which changed features of that geochemistry globally. Through these feedback loops, geochemistry transitioned to biochemistry and that led to cellular structures and eventually to humans. You can almost think of it as a condensation across scales from molecules to cells to ecosystems to the planetary scale, all at once.

Is there any way to test that idea?

We would need to build experiments that can explore diverse geochemistries to determine how different conditions could drive selection and the emergence of evolution. An analogy is in the Large Hadron Collider, which was built to explore the conditions at the start of our universe. We need to build a planetary geochemistry experiment to explore the conditions at the start of life.

We can do this with automated chemistry experiments done at scale, which we are working on with Cronin's team. The ultimate goal is to experimentally search enough of the chemical space of planets in the lab to observe a new origin-of-life event. That is, we want to discover alien life by making it from scratch in the lab. If we can do that, I think we can say we have solved what life is. ∎

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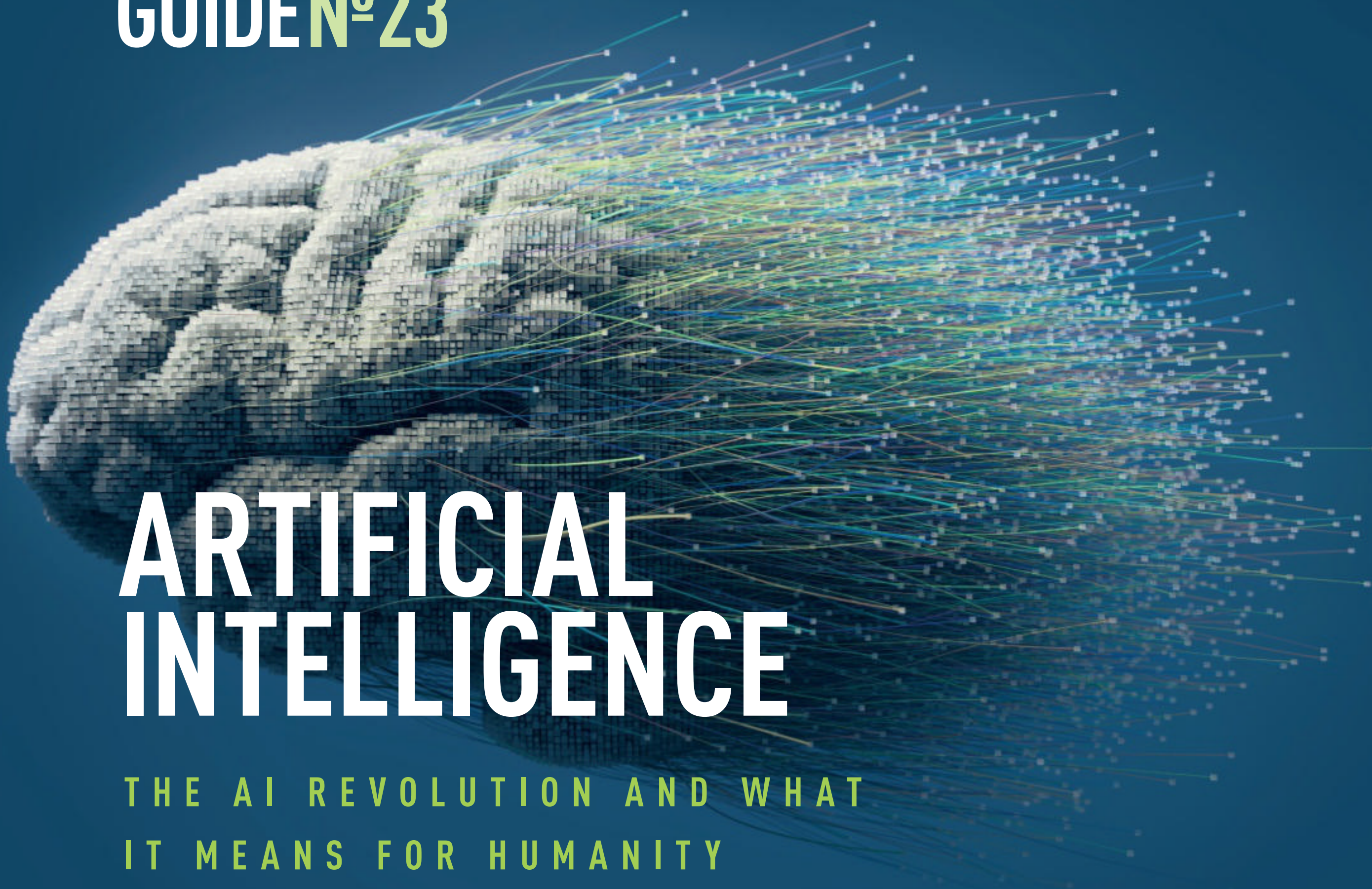

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