New Scientist

ESSENTIAL GUIDE №13

HOW THE SUN WORKS
EARTH AND THE MOON
THE PLANETS
THE UNKNOWN SOLAR SYSTEM
EXOPLANETS
AND MORE

THE SOLAR SYSTEM

A JOURNEY THROUGH OUR COSMIC NEIGHBOURHOOD – AND BEYOND

EDITED BY
STEPHEN BATTERSBY

NEW SCIENTIST ESSENTIAL GUIDE

THE SOLAR SYSTEM

OUR solar system isn't much in cosmic terms: a single star, just one of hundreds of billions in our galaxy – itself one of many billions in a practically unending universe – and its retinue of eight planets and assorted other hangers-on.

And yet what a wonderful place it is, harbour of many surprises and not a few mysteries. In this 13th *New Scientist Essential Guide*, we will take a peek behind the bright curtains of the sun's photosphere to investigate the mysteries of our star, ask what Earth and moon tell us about the formation of the solar system and consider what it would take to send people to Mars, as well as tour the gas and ice giants of the outer solar system and frigid moons and beyond. We will round off by visiting the other planetary systems we now know exist around other stars, guided by a central existential question – does life exist elsewhere?

And all this without leaving the ground. All titles in the *Essential Guide* series can be bought by visiting shop.newscientist.com; feedback is welcome at essentialguides@newscientist.com.

Stephen Battersby

NEW SCIENTIST ESSENTIAL GUIDES
NORTHCLIFFE HOUSE, 2 DERRY STREET, LONDON, W8 5TT
+44 (0)203 615 6500

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SERIES EDITOR Richard Webb
EDITOR Stephen Battersby
DESIGN Craig Mackie
SUBEDITOR Bethan Ackerley
PRODUCTION AND APP Joanne Keogh
TECHNICAL DEVELOPMENT (APP) Amardeep Sian
PUBLISHER Nina Wright
EDITOR-IN-CHIEF Emily Wilson
DISPLAY ADVERTISING +44 (0)203 615 6456 displayads@newscientist.com

ABOUT THE EDITOR
Stephen Battersby is a freelance writer and *New Scientist* consultant specialising in space, based in London

ADDITIONAL CONTRIBUTORS
Stephen Battersby, Lee Billings, Rebecca Boyle, Macgregor Campbell, Sophia Chen, Stuart Clark, Keith Cooper, Daniel Cossins, Leah Crane, Will Gater, Lisa Grossman, Jeff Hecht, Rowan Hooper, Layal Liverpool, Richard A. Lovett, Jason Arunn Murugesu, Jonathan O'Callaghan, Shannon Palus, John Pickrell, Simon Portegies Zwart, Sarah Rugheimer, Joshua Sokol, Sean C. Solomon, Natalie Starkey, Colin Stuart, Chanda Prescod-Weinstein, Richard Webb, Chelsea Whyte, Alex Wilkins

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CHAPTER 1

THE SUN

The sun dominates the solar system. It is our centre, our source of warmth, the origin of the word "solar" in "solar system", of course; and, in terms of sheer mass, it is overwhelming.

If the contents of this *Essential Guide* were in proportion to the mass of their subject matter, this chapter would run for well over 30,000 words, leaving a total of four words to be shared between the other four chapters on our solar system. Yet for all its dominance, our home star still holds many mysteries.

WHAT POWERS THE SUN?

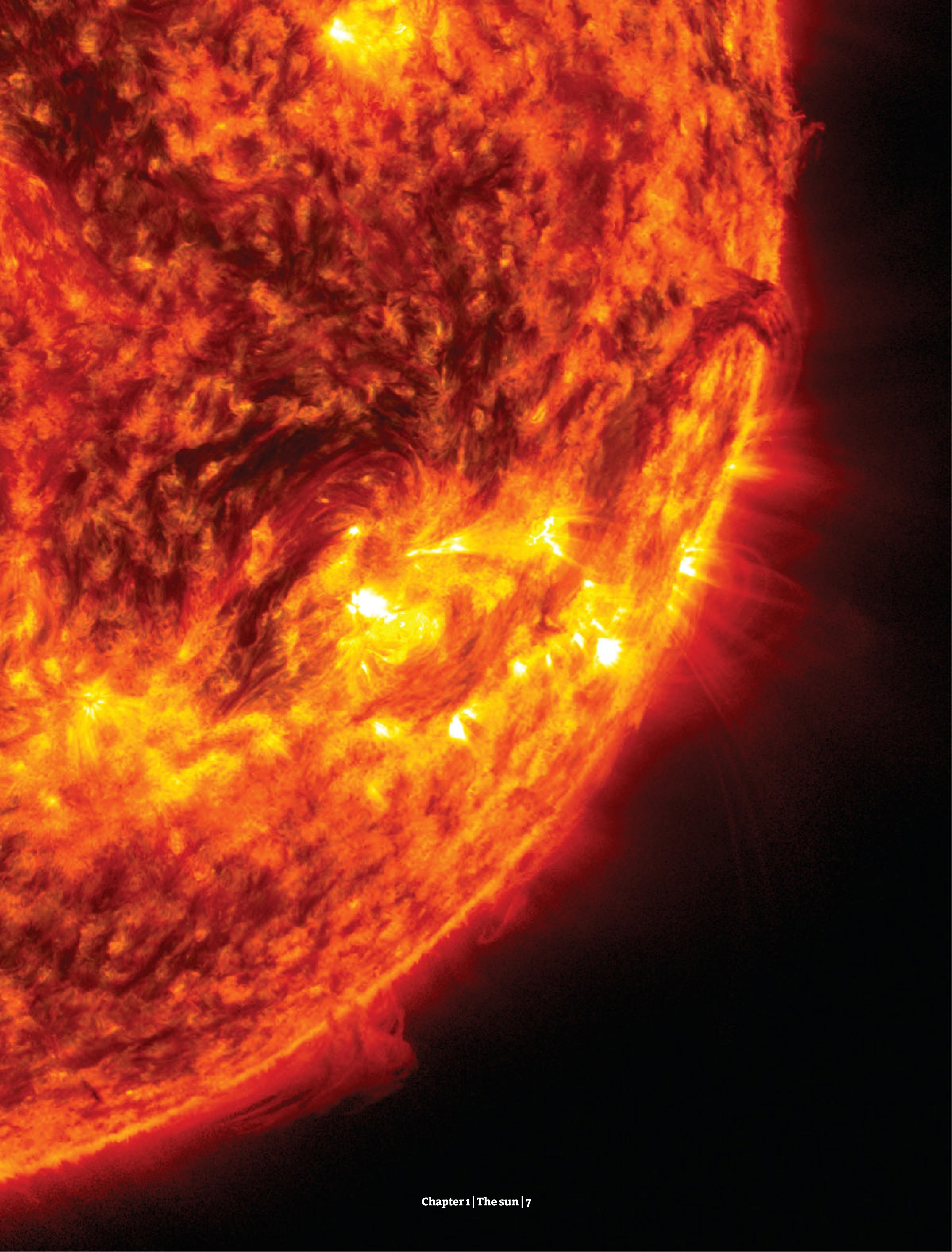
Although we understand the basics of how the sun shines, there appears to be something missing in there. It could be elements behaving in a way we didn't expect under crushing pressure. It could be an unexpected ingredient, perhaps dark matter. Or maybe we are just looking at the sun in the wrong way.

NASA/GODDARD SPACE FLIGHT CENTER

IN EVERY way, the sun is the odd one out. Unlike the solid or gaseous planets and other bodies around it, the sun is made of plasma – gas that has been ionised, with electrons stripped from its positively charged nuclei. The solar core, at ultra-high pressure and temperatures of around 15 million kelvin, is where nuclear fusion happens, the source of the sun's power. Above that is the radiative zone, where the heat generated in the core slowly percolates very slowly outwards and upwards.

Then comes the convective zone, where churning plasma somehow generates the sun's skittish, pulsating magnetic field. Sunlight comes to us from a thin skin called the photosphere, where sunspots blossom. Finally, the chromosphere and corona form the sun's atmosphere, which streams out into space, sometimes in cataclysmic eruptions known as coronal mass ejections.

Understanding the sun is important not just because it supplies the heat and light that sustain us. It is also our key to the wider universe, the reference against which we measure stars: their brightness, their age, how likely their solar systems are to support life. Mess with the sun, and the



consequences stretch as far as our telescopes can see.

Generally speaking, stars shine because gravity has pulled enough hydrogen plasma into such close quarters that its nuclei (protons) start to fuse together to make helium. Every star starts this way. When the hydrogen runs out, the helium starts fusing together, and so on, producing heavier and heavier elements. This is the source of much of the matter that makes up our planet and us.

It sounds like a simple matter of gluing protons together, but it isn't. The conditions have to be right. The plasma has to be hot and dense enough to get protons to fuse. Fusion happens in several stages and via several different reactions. The theories that describe how all this happens aren't the classical Newtonian physics that describes, for example, two football players colliding when they both want to control the ball. Instead, we need quantum mechanics and nuclear physics.

Whatever the complexities of the process, the end products are helium and heat. The energy in gamma-ray photons and the kinetic energy in other particles is passed on and outwards through the layers of the sun. Eventually, after tens of thousands of years, it reaches the outermost visible layer, the photosphere, which, at about 6000 kelvin, radiates life-giving sunlight (and some life-threatening ultraviolet light).

Almost all of the neutrinos, meanwhile, fly right out of the sun. A vanishingly small number are then snared in underground particle detectors on Earth, reassuring us that these once-theorised reactions are really happening in there. There are still some inconsistencies in scientific papers about solar fusion – it isn't simple to calculate how much energy is released in each reaction, and how frequently they occur, combining nuclear theory with nuclear experiments on Earth, but mostly this is a matter of filling in the details.

However, one recently discovered anomaly might be pointing to something quite peculiar happening deep in our parent star. There seems to be something missing.

There are two main ways to investigate what is inside the sun. Helioseismologists look at sound vibrations on the sun's surface, which give outward evidence of the vast quantities of energy being unleashed within. That energy depends on the sun's internal structure and ingredients. Then there are spectroscopists, who look at the light from the sun, splitting it into a range of wavelengths that reveal the barcodes of constituent elements.

For years, these two methods painted the same picture of the sun: a vast and dense ball of matter, made mostly of hydrogen and helium, that clumped together some 4.6 billion years ago and formed our solar system. Included in the mixture was a sprinkling of other elements carried by the explosions of larger, dying stars. Astronomers refer to all these heavier elements – which include carbon, oxygen, nitrogen, magnesium, iron and sulphur – as metals. Metals make up less than 2 per cent of the sun's total mass, but play a crucial role, shuttling energy from the core out to the surface.

In the late 1990s, Martin Asplund was a young researcher in Copenhagen, Denmark, when he first realised this picture wasn't quite right. He was studying

“Perhaps there is a shell of dark matter surrounding the core of the sun”

the motions of the outer layers of boiling stars, a necessary step towards performing more accurate spectroscopic calculations to unlock the light’s secrets. At the time, the mathematical imaginings of star surfaces used by spectroscopists were simplistic. In fact, they were literally one-dimensional, concerned only with the behaviour of an idealised solar surface possessing zero width. But the surface of the sun is decidedly three-dimensional. With a departmental supercomputer at his disposal, Asplund built a model that took height and width into account.

By 2009, he had startling results: a quarter of the metals we had counted on being there could no longer be found. They had simply vanished. If Asplund’s figures held up, helioseismology could no longer explain the behaviour of the sun. The quantities of helium on the solar surface didn’t tally; the outer layer became too thin; sound travelled through it at the wrong speed.

The easiest conclusion was that Asplund was wrong. In the hope of performing an independent cross-check, in 2017, a team examined the contents of the solar wind. The researchers found nothing to indicate that any matter was missing. Instead, they found indications of a total metallicity more or less on a par with what helioseismology predicts.

The hole is filled, but the filling makes no sense. The proportions of various elements are all wrong, different from anything anyone else has found, offering no definitive resolution.

So far, nobody has found a way to discount Asplund’s conclusions. And as his results have become widely accepted, they have had consequences well beyond the sun. As our closest and most accessible star, the sun informs our understanding of its cousins across the cosmos. Consequently, in the decade since his figures came out, Asplund’s work on the composition of the sun has rapidly become one of the most cited papers in astronomy. More and more heavy elements get blasted out into the universe as the millennia tick past, which informs us when stars were born and helps us understand their evolution. That, in turn, tells us how likely they are to have Earth-like planets sailing around them, and whether any of those planets could accommodate life.

As the effects rippled through astronomy, some solar physicists relished the opportunity to question long-standing beliefs. With so many simplifications and assumptions in our calculations about the sun, something else was bound to be going on. Doron Gazit, a physicist at the Hebrew University of Jerusalem, was one of those who spotted a way through the confusion: maybe Asplund’s metal tally was spot on, but the elements were misbehaving.

The key lies in a quality known as opacity, which dictates how much energy can pass through a given material. Heavier elements are more opaque than hydrogen and helium. For the spectral and helioseismology results to be reconciled, the opacity of the remaining elements inside the sun had to be increased: they must absorb more photons than had previously been thought possible.

You can think of an atom as a nucleus of protons and neutrons surrounded by electrons that orbit at › precisely defined energy levels. If an incoming photon has enough energy to cause an electron to jump energy levels, it is often absorbed and contributes to the atom's opacity. Otherwise, it passes straight through. Under the extreme temperatures and pressures of the solar core, the atoms would jiggle about more than normal. This motion would make some energy levels grow further apart, while others would come closer together. That expands the range of photons that any one atom could absorb, thereby offering a mechanism to increase the opacity.

The only way to test this would be to observe atoms interacting with light under temperatures and pressures similar to those in the sun, a seemingly impossible task – but not for Jim Bailey at Sandia National Laboratories in New Mexico. At the lab's Z Pulsed Power Facility, or Z machine for short, matter can be exposed to some of the highest temperatures and pressures on the planet for the briefest fraction of a second.

A run of experiments whose results were published in 2015 revealed that in such situations, iron does indeed have a higher opacity than thought – although not enough to explain away the hole on its own. The iron in these experiments represents the conditions that exist in just one spot inside the sun. It would take forever to recreate the rest of the sun's interior piece by piece, so now it is up to theorists to work out whether the rest of the metals could have seen their opacity increase too. But whether those refined models will push the opacity in the right direction overall is hard to say.

If not, perhaps another kind of matter is picking up the slack for the missing elements. After all, spectroscopy only detects matter capable of absorbing or emitting radiation. Dark matter, of the kind that makes up about 27 per cent of our known universe, does neither. This makes dark matter an outside candidate for filling the new-found hole at the sun's centre.

Like all other forms of matter, the dark stuff should experience the pull of gravity. On our galaxy's slow journey through space, any dark matter we bumped into would be likely to find itself drawn to the centre of the sun. Once in place, there are all sorts of tricks it could pull to explain the helioseismology results. Perhaps the mysterious stuff is its own antiparticle, releasing energy when it collides with itself. Or if not, perhaps there is a shell of dark matter surrounding the core of the sun. It would get pretty hot and, from time to time, particles would break away, travelling to the boiling outside and transporting energy with them.

The easiest way to resolve the controversy would be to produce an independent measurement of the sun's insides – one more conclusive than earlier attempts to test the solar wind. That knockout punch could come from neutrinos, lightweight particles produced as shrapnel in the fusion reactions taking place inside the sun.

Every second, some 65 billion solar neutrinos are passing through any given square centimetre on Earth, travelling at nearly light speed. The vast majority are created when hydrogen nuclei collide, but 1 in 100, or thereabouts, are born during heavier fusion processes involving atoms of carbon, nitrogen and oxygen. By measuring the amount of these "CNO" neutrinos that reach a given spot on Earth, you can work out the exact number spilling out of the sun – and from that, how many of these heavy elements are there creating them.

Such a direct probe would allow us to bypass all the theory and solve the missing matter problem.

Unfortunately, CNO neutrinos are especially hard to detect. Our best hope is in a Canadian detector called SNO+, equipped with a massive tank of fluid primed to give off pinpricks of blue light when a neutrino passes through it. The neutrinos could confirm that Asplund's numbers are correct. They could reveal that he is wrong and that the hole never existed at all. Or they could worsen the confusion surrounding our home star. ▮

THE MYSTERY OF THE SOLAR CORONA

While the sun's visible surface warms us, its elusive, ultra-hot atmosphere is a growing danger to human society, so we have sent spacecraft to brave this tumultuous sphere.

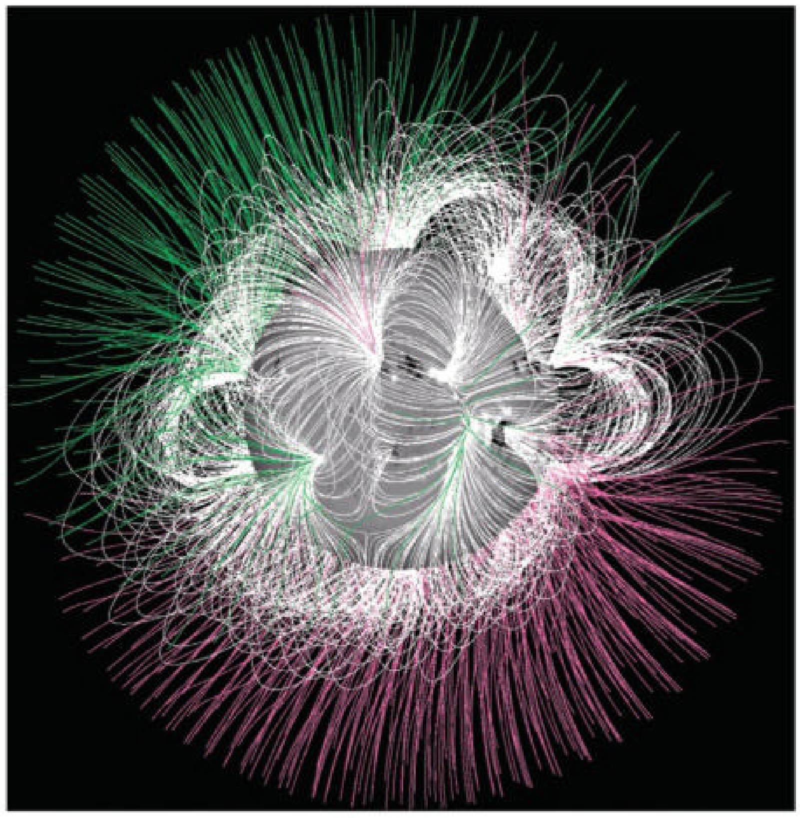
THE solar corona is made of strands of plasma millions of kilometres long that look like flames dancing in a circle around the sun. It is the star attraction of any total solar eclipse. But here's the thing: you would expect that the corona, being one of the outermost layers of the sun and so one of the furthest from the nuclear fusion in the core, would be relatively cool. Normally, the further you go from a heat source, the cooler it gets. A marshmallow will toast faster when it is closer to a campfire flame than when it is further away. Not so with the sun. Its surface is a mere 6000°C, but the corona, despite being further out, reaches more than 1 million°C. We still don't know why.

Theories centre on the sun's complex magnetic field. One option is a steady heating by magnetic waves flowing up from below. Another is the more violent heating from solar flares: explosions in the sun's atmosphere that happen when tangled magnetic fields suddenly snap into a new shape, a process called magnetic reconnection. Big showy flares don't carry enough energy to make the corona that hot, but much smaller nanoflares might be important.

In 2017, a team analysed data from a rocket-based X-ray telescope called FOXSI-2, which spent just 6.5 minutes staring at the sun. Over an active region of the sun with no obvious flares, the team saw 15 high-energy X-ray photons that were probably produced by material at 10 million degrees Celsius. If the corona had a uniform, steady heat source – as alternative theories suggest, with magnetic waves carrying the heat up from below – plasma wouldn't get that warm.

Other magnetic phenomena are almost certainly involved, including bizarre solar tornadoes: swirling plasma columns reaching from the surface into the upper atmosphere. Much of the energy that heats the corona appears to come from the transition region – the area between the sun's corona and the chromosphere below. Tornadoes, magnetic braids, plasma jets and strange phenomena called spicules are all thought to play some role in bringing energy from the lower regions of the sun and depositing it higher up. But no one knows exactly how. NASA's Interface Region Imaging Spectrograph mission has been observing this region since 2013, and physicists try to simulate these energy exchanges using models in the hope that they will yield clues that scientists can look for on the real sun. ›

Understanding the sun's magnetic field could explain why the corona gets so hot



LEFT: NASA/GODDARD SPACE FLIGHT CENTER RIGHT: NASA

Computer visualisations might paint a clearer picture – and quite artistically, too. In one simulation, astrophysicist Nicholeen Viall at the NASA Goddard Space Flight Center in Maryland added colour to data coming in from NASA's Solar Dynamics Observatory (SDO), which observed the sun's coronal plasma in 10 different wavelengths that each correspond to a temperature. The result is a swirling movie reminiscent of a painting by Vincent Van Gogh. But Viall's visualisation suggested the atmospheric plasma was cooling, not heating. This may be because the heating is happening faster than SDO can detect.

Despite the searing temperatures in the corona, there is rain – of a sort. Though this was predicted about 40 years ago, we couldn't see or study it until our telescopes became powerful enough to spot it happening. It works a bit like the water cycle on Earth, where vapour warms, rises, forms clouds, cools enough to condense into a liquid and falls back to the ground as precipitation. The big difference is that the plasma in the corona doesn't change from gas to liquid, it simply cools enough to fall back down to the solar surface. This all happens very quickly and on a gargantuan scale, with plasma droplets the size of countries growing in a matter of minutes, then plunging at a rate of 200,000 kilometres an hour from heights of more than 60,000 kilometres – about one-sixth the distance from Earth to the moon.

Of rather more concern to us is the weather heading in the other direction. We have known of the existence of a steady wind of charged particles emanating from the upper corona for 60-odd years. But on top of this, every now and then, the sun's fiery surface turns explosive, sending knots of plasma and showers of energetic particles flying outwards, sometimes towards Earth.

It is all connected to the sun's magnetic field, generated in the churning convective zone of the star. Different parts of the sun spin at different rates: while a day at the equator lasts around 25 Earth days, regions close to the poles take a few days longer to make a complete rotation. This uneven spin leads to distortion in the sun's magnetic field. As the equator spins, it drags the magnetic field that connects the sun's poles. This stretches and winds up the sun's magnetic field – building tension, like twisting a rubber band. Eventually, the magnetic field can snap, generating solar flares or huge outbursts of plasma called coronal mass ejections (CMEs).

This activity follows a cycle that lasts roughly 11 Earth years, in which the magnetic field grows, then weakens, and finally reverses its direction.

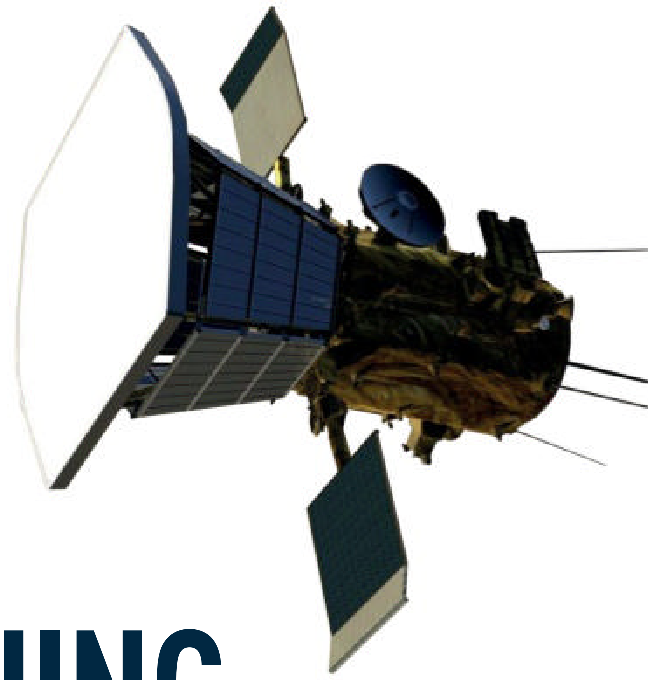
During a solar minimum, the field is weak. There are few flares or sunspots, the dark patches on the sun's surface that mark a strong local magnetic field. At the same time, the solar wind streams from the poles at a much greater speed, so there is more pressure pushing against material from interstellar space. This has the knock-on effect of changing the size of the huge magnetic bubble of charged particles, called the heliosphere, that the sun blows around itself, reaching to way out beyond Pluto.

During a maximum, the sun's magnetic fields are more knotted up. More sunspots burst out and there are more flares and CMEs. When a CME hits Earth, it can cause a geomagnetic storm, damaging satellites, interfering with communications and GPS, and even causing electrical blackouts in rare cases.

In 1859, a particularly violent solar flare-up known as the Carrington event coincided with a huge electromagnetic storm around Earth. It 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. Another such event might wreak havoc with modern power systems, satellites and communications networks.

This is one reason why scientists want to better understand the sun's mercurial magnetism. The strength of each coming cycle is hard to predict. We don't even know why cycles should last 11 years. The sun's output of solar wind, X-rays, ultraviolet and visible light also change through each solar cycle. Solar cycles have some effect on climate, with low solar activity tending to lead to cold winters in northern Europe and the US and mild winters over southern Europe, for example – although the effect is very small compared with the global warming of the past few decades.

We now understand what is going on a little better thanks to a space-borne instrument called TIM, launched by NASA in 2003. TIM keeps tabs on the spectrum of energy the sun emits and detects subtle changes in energy output so scientists can distinguish between human causes of climate change and purely natural causes we can't control. The European Space Agency's Solar Orbiter mission could also help. Flying within 45 million kilometres of the sun, it will photograph the solar poles for the first time, which should help scientists understand how the sun generates a magnetic field and may give insights into why magnetic polarity flips so frequently. And as the next section details, NASA's Parker Solar Probe is already even closer, plunging into the corona to seek answers to these questions. ▮



TOUCHING THE SUN

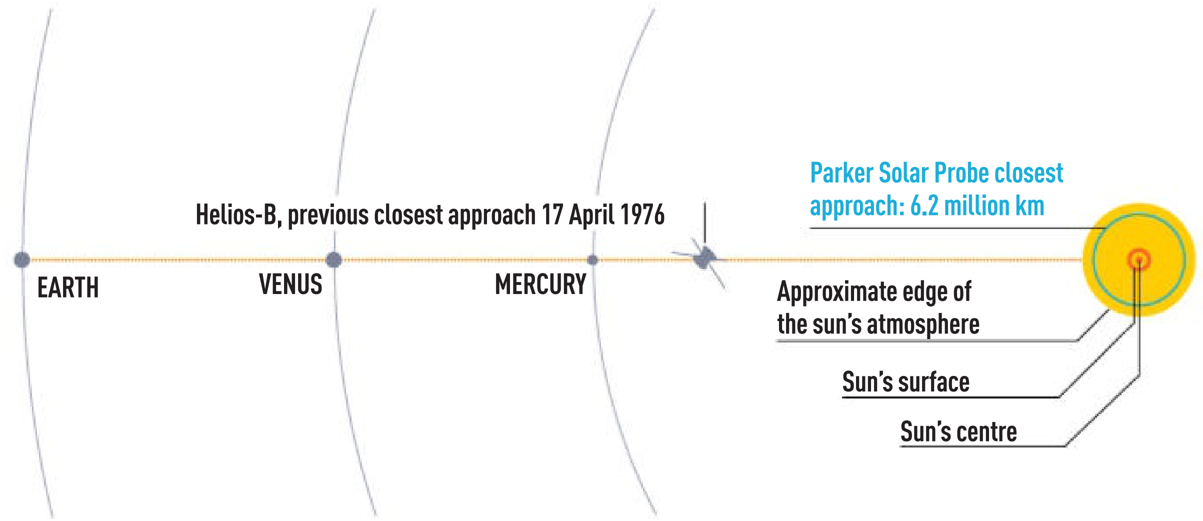
Fears of a repeat of the 1859 solar storm known as the Carrington event have fuelled a growing desire to take a closer look at solar wind and its birthplace in the corona. The Parker Solar Probe was designed to do just that, as some of those involved in the project explain.

IN 1956, Eugene Parker was a young postdoc at the University of Chicago. He was investigating cosmic rays arriving at Earth from far off in the galaxy when an idea struck him.

"We knew cosmic rays were correlated with the sun's magnetic activity, but the timing of the cosmic rays on our detectors during one particularly violent solar flare showed that the particles were moving very freely from sun to Earth. Around the same time, astronomers were noting that comet tails always pointed away from the sun, and that, too, was very difficult to explain.

"One day in 1958, it occurred to me this was all very simple. The sun's atmosphere, the corona, is not tightly bound. Stuff can escape, and the whole thing acts like

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



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.

"I came in for a lot of flak for the idea, but no one could find anything wrong with the mathematics. Then, in 1962, they launched Mariner 2 to Venus, the first mission into interplanetary space. What it saw could hardly be denied. The transformation was very quick: people were saying we always knew there was a solar wind. You know how it goes. I never criticised."

Various missions have been planned to fly into the solar wind to investigate it. In 1976, the Helios-B spacecraft made it to within 60 solar radii (or 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, says Andy Driesman, an engineer on NASA's Parker Solar Probe.

"As close to the sun as we wanted to get the probe, there would be almost 3 million watts of heat energy on its front surface, and we had to make sure there would only be 30 watts on the back side. There are some high-temperature metals that could make the protective shield, but they are too heavy to launch.

"The magic material is carbon. In the 1980s, you began to see carbon technologies in your golf clubs and tennis rackets. In the early 2000s, we took things one step further, making carbon materials light enough and strong enough to withstand the sun's heat, and coating them so they are not so black and absorb less heat. Carbon is very brittle and fragile, and a lot of work went into making a heat shield that could survive

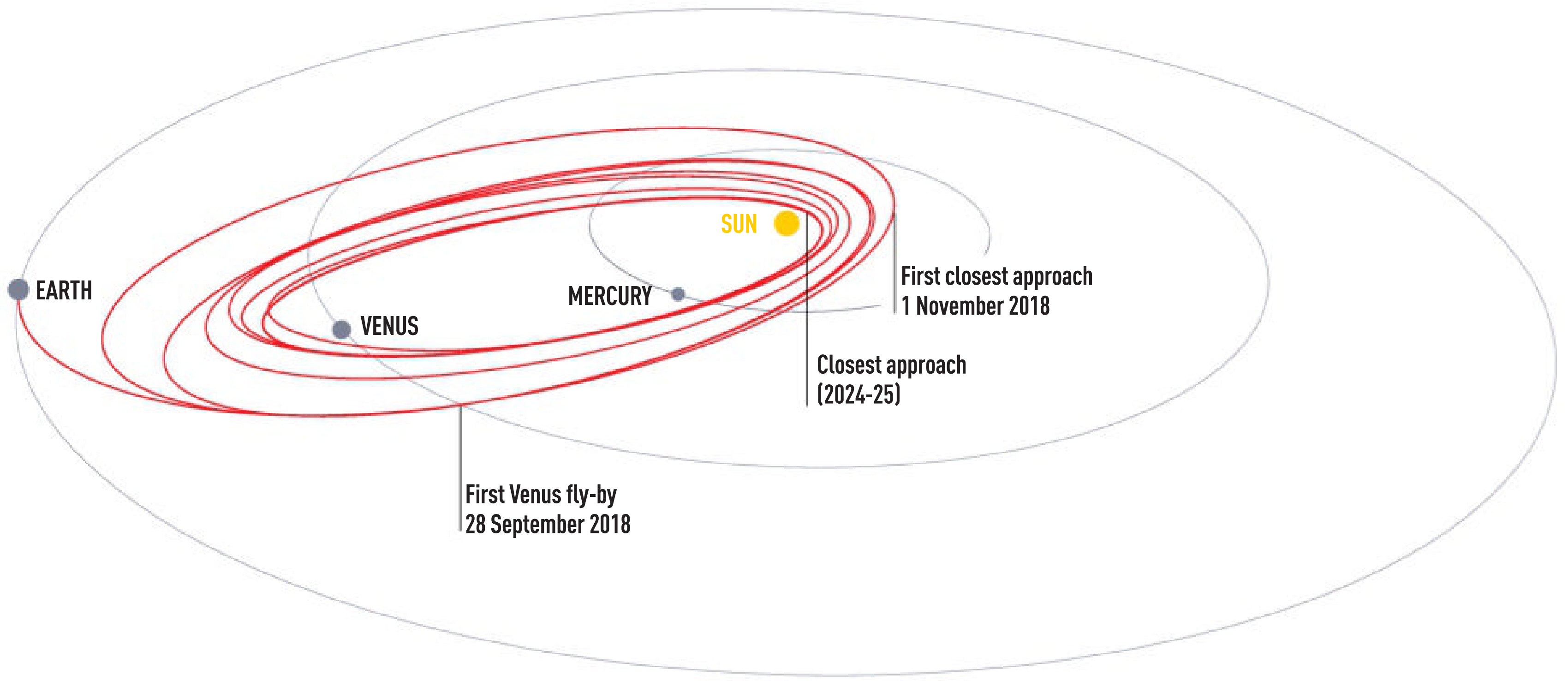
LONG-LOST SOLAR SIBLINGS

The sun may be all alone now, with its closest neighbour 4.2 light years away, but that wasn't always the case. Once upon a time, it had close family. After their birth in the same cloud of dust and gas that formed our solar system, they would have scattered hundreds of light years apart in the Milky Way.

In May 2014, astronomers reported finding the first of these long-lost siblings: a star called HD 162826. "It looks like the sun, but a little bit bluer," says Ivan Ramirez at the University of Texas at Austin, who led the study. It is warmer than the sun and 15 per cent more massive. The star is about 110 light years away, and you can see it with the aid of a pair of binoculars in the left arm of the constellation Hercules.

To find its family ties, Ramirez's team combed through galactic archaeology studies, which model the motions of the Milky Way. The search area was narrowed to 30 stars, and then these were examined closely to find a family resemblance. Only HD 162826 had a similar chemical make-up to the sun. Another team found that the star is the same age as the sun, as would be expected for two stars born together.

Locating solar siblings could tell astronomers more about the birth of our solar system, including what conditions were like when the sun and planets formed.



the launch environment. When we finally thought we had a solution, we went back to NASA and NASA said, OK, go forward, you're now a mission."

The Solar Probe Plus mission, as it was known 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 this becomes a particular problem when you want to visit the sun. Mission scientist Yanping Guo had to find a way to solve it.

"When you launch a spacecraft from Earth, it possesses Earth's orbital velocity, about 30 kilometres a second. To get to the sun, you have to cancel out most of that, slow it down so it can fall in under gravity. That takes a lot of energy. If you want to launch directly from Earth to the sun, you need 55 times more energy than to get to Mars. It's more than twice even what you need to get to Pluto," she says.

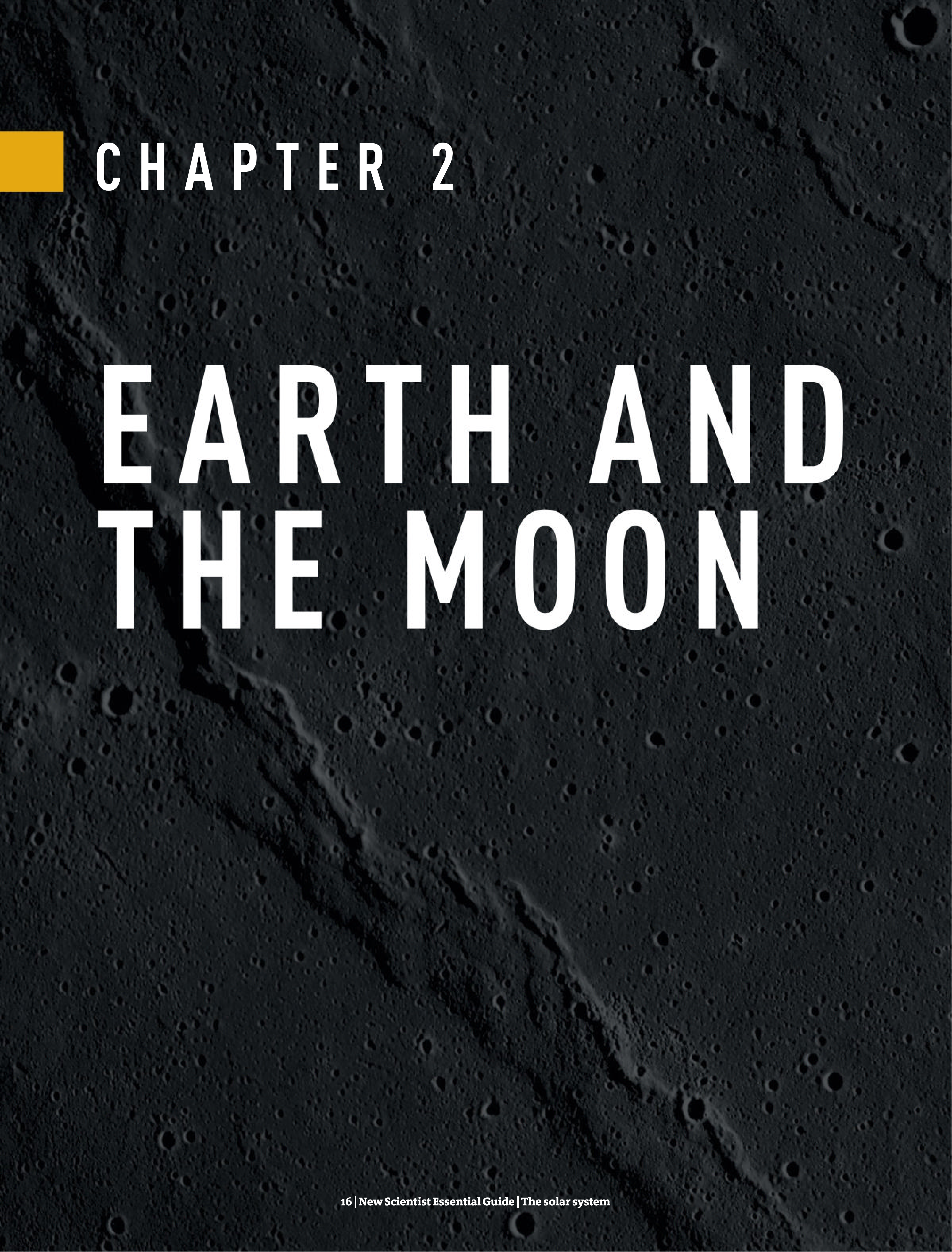
"For five decades, we had been studying this problem on and off, and had come to the same conclusion: to get to the sun, you need a Jupiter gravity assist. Instead of going directly to the sun, you launch out to Jupiter, and use its gravity to reduce the spacecraft's speed so it falls inwards. But at Jupiter's distance, solar power won't work: you need nuclear.

"Everyone said the problem was impossible, but I started looking at whether you might use the gravity of the inner planets instead. Venus is much smaller than Jupiter, so its gravity assist is much less. You can fly by multiple times, each time losing some velocity and falling in closer to the sun, but that means manoeuvring to pass Venus in the right orbit each time, which is tricky and uses up fuel. Eventually, I found a trajectory with seven Venus assists that passes the sun 26 times, each time closer (see diagram, above). The closer the probe falls, the faster it gets. At its fastest, it will be travelling at 200 kilometres a second – the fastest spacecraft ever."

In May 2017, NASA renamed the probe after Eugene Parker, the first living scientist to be so honoured. He died in March 2022, but not before, in April 2021, the Parker probe became the first spacecraft to enter the atmosphere of the sun. It passed through the Alfvén critical surface, the boundary where plasma ceases to be trapped by the sun and the corona becomes the solar wind. The spacecraft entered the corona on its eighth close pass of the sun, when it was only about 13 million kilometres from the centre of the star.

Until the probe entered the region, researchers weren't sure exactly how far from the sun the Alfvén critical surface would be, or what it would be like, but they knew that its presence could be measured by changes in the magnetic field and a slowing of plasma motion below the surface. The Parker Solar Probe's measurements confirmed this, and demonstrated that the critical surface wasn't a smooth bubble around the sun, but rather a wrinkled edge.

Studying this surface could help us understand how the sun spits out charged particles that can pose issues for satellites and space explorers, and maybe even predict those outbursts. It is also a step towards understanding other stars beyond our solar system. The probe should continue circling ever closer to the sun well into 2025, repeatedly breaking its own records for the fastest-moving spacecraft and the closest spacecraft to the sun. ∎



CHAPTER 2

EARTH AND THE MOON

Earth and its pale lunar companion are the only worlds with human footprints. They are special in many other ways, too. Nowhere else, for example, does such a huge moon orbit such a small planet.

That could be connected to another phenomenon, unique to Earth as far as we know: the presence of small quantities of matter that organise themselves into complex, dynamic forms, apparently defying the laws of thermodynamics. And besides the curiosity we call life, these two worlds could hold the key to understanding the formation of the whole solar system.

THE PALE BLUE DOT

Earth is, as far as we know, unique in harbouring life. But if we were looking at our planet from afar, would we be able to discern life's imprint? A seminal experiment over three decades ago gave us the answer.

NASA/JPL-CALTECH
PREVIOUS PAGE: NASA

WHEN the Space Shuttle Challenger blew up 73 seconds into its flight on a January morning in 1986, the consequences rippled through the space industry. One lesser-known casualty was the Galileo mission to Jupiter, a $1 billion NASA spacecraft designed to orbit the giant planet, study its many moons and drop a probe into its atmosphere.

→ Page 54 has more on Jupiter and its moons

Galileo had been due to begin this journey sitting on the tip of a Centaur rocket stage, which would power it to Jupiter after it was hefted into space inside a Space Shuttle's cargo bay. But in the wake of the disaster, NASA decided that launching an unlit Centaur rocket using the shuttle's booster was just too risky.

No other set-up was powerful enough to lift the Galileo spacecraft into orbit attached to this rocket stage, so the Centaur was ditched, leaving the mission team to find another way to get to Jupiter. The solution was gravitational slingshots that would send Galileo around Venus and twice past Earth to build up enough speed to hurl it at Jupiter. This workaround set the stage for one of the most inspired experiments in space science.

Galileo blasted off on its circuitous journey aboard the shuttle Atlantis on 18 October 1989. Only then did one of the project scientists, astronomer Carl Sagan, come up with an extraordinary idea: using an Earth fly-by as an opportunity to point Galileo's instruments at our planet, to see if they could discern signs of intelligent life solely from the data sent back. At the time, NASA spacecraft had flown by upwards of 60 planets and moons, and none had spotted any hint of life. "If we find signs of life on Earth, it means the negative results we find elsewhere really are ›

significant," Sagan said in a television broadcast. NASA liked his plan.

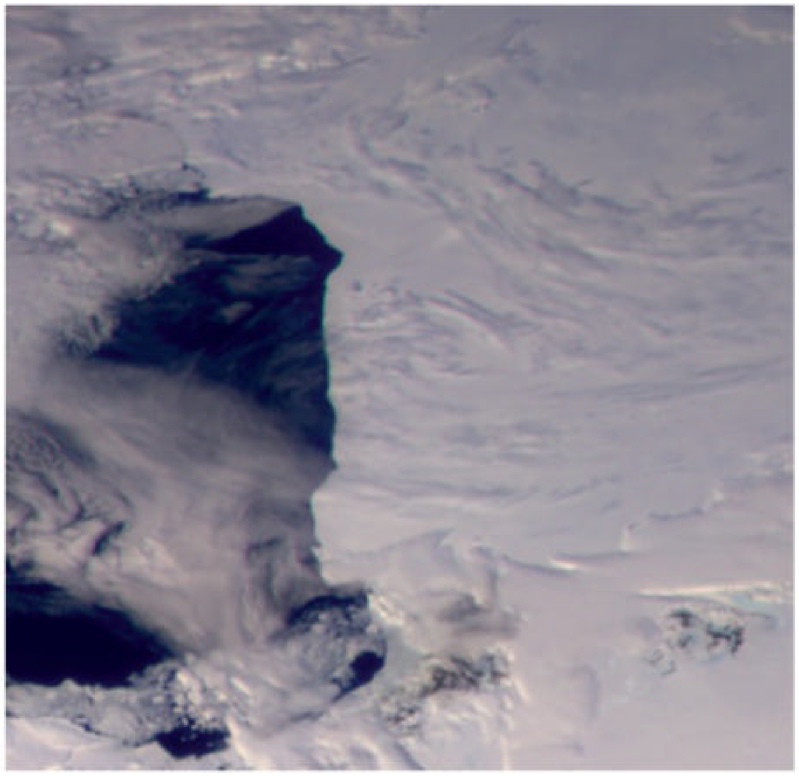
As it happened, Galileo approached Earth first-time round from its night-time side, flying past on 8 December 1990. It got to just 960 kilometres above the Caribbean Sea – 40 times closer than a geostationary satellite. Its imaging system and three spectrometers were trained on Earth in the visible, ultraviolet, infrared and radio regions of the spectrum. The data would be treated as if collected from an alien planet, and the presence of living organisms would be "the hypothesis of last resort" for the life-hunting detectives. At such close range, how difficult could it be to spot telltale signs of life?

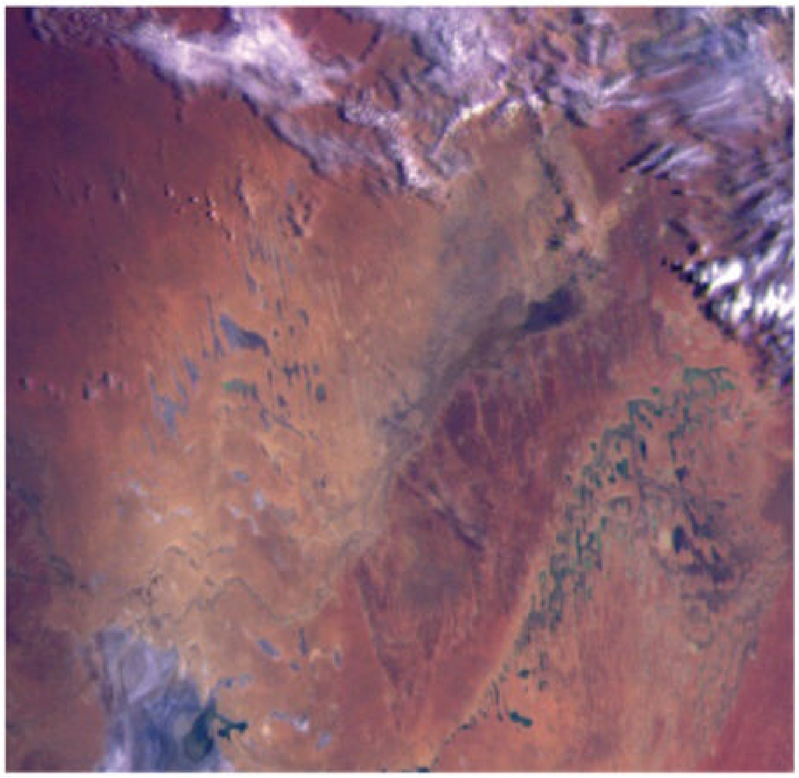
"They struggled hard to find any proof at all to start with," says Don Gurnett. He was a senior member of the team who ran the spacecraft's plasma wave spectrometer, which detected radio waves.

With its 1980s technology, Galileo's photographic resolution was just 1 kilometre per pixel at best when it reached Earth's day-lit side. That meant only artificial, geometric structures with a scale greater than that would show up – cities, swathes of agricultural fields and so on. Unfortunately, its highest-resolution images were of Australia and Antarctica, both of which are sparsely inhabited (see photos, right). Australia's coastal agriculture offered a hint of something, but wasn't judged "sufficiently distinctive to be... indicative of intelligent life". Ouch. The life detectives were off to a poor start with this, their only eyewitness, but the good news was that Earth clearly had water galore, in all its forms. Liquid water is probably necessary for the existence of life, but not sufficient.

There were further lines of enquiry. Galileo also spotted that Earth's atmosphere contains methane, for example. Methane isn't an unambiguous sign of life, but sunlight breaks it down, so any left over from the formation of the solar system should have long ago disappeared – something on the surface must be producing it. We know that much of Earth's methane comes from bacterial respiration, rice farming and, lest we forget, belching cows. But methane is also generated by volcanic activity, so it could have been a red herring.

The high level of oxygen in the atmosphere was tantalising too. This very reactive gas ought to form more stable compounds over time, so something





JPL NASA

In 1990, the Galileo spacecraft took pictures of Earth to see if it was possible to spot signs of life, a proxy for looking for life on alien planets

on the surface must have been pumping it out.

Earth's land masses provided another important clue. Much of the planet's surface was covered with a green pigment that strongly absorbed light in the red part of the spectrum. Crucially, the team reported, this pigment corresponded to "no plausible mineral". The pigment – chlorophyll – puts a cliff-like dip in the spectrum of light Earth reflects. Astrobiologists now call this the "red edge " and think its presence is uniquely indicative of the light-harvesting molecules involved in photosynthesis.

The red edge, combined with the other leads, pointed strongly towards life on Earth – but not necessarily the intelligent kind. "Most of the evidence uncovered by Galileo would have been discovered by a similar fly-by spacecraft as long ago as about 2 billion years," the team noted.

One last clue blew the case wide open. Gurnett's plasma wave spectrometer picked up narrow-band radio transmissions coming from the surface (though Galileo couldn't "tune in" to them). "You just don't see natural radio signals looking like that," says Gurnett. "We were picking up taxi communications from South America."

This was the smoking gun. "Of all Galileo science measurements, these signals provide the only indication of intelligent, technological life on Earth," the team wrote in their paper "A search for life on Earth from the Galileo spacecraft", a *Nature* cover story in 1993.

Surprisingly, the paper caused little excitement at the time, but three decades on, that view has changed. "I thought of it as a novelty at the time, but now as a seminal paper," says Jim Green, head of planetary science at NASA HQ in Washington DC. "Carl Sagan was ahead of his time, probably by a decade or more." The discovery of exoplanets orbiting sun-like stars has inspired a new generation of astronomers looking for signs of life in the atmospheres and on the surfaces of far-off planets. The question there is whether starlight passing through the atmospheres of these distant worlds betray signature "edges", or other features that can't easily be explained away without invoking life, just as Galileo's fly-by did with Sagan's "pale blue dot". ∎

→ Page 91 has more on the search for exoplanetary life

GOLDILOCKS PLANET

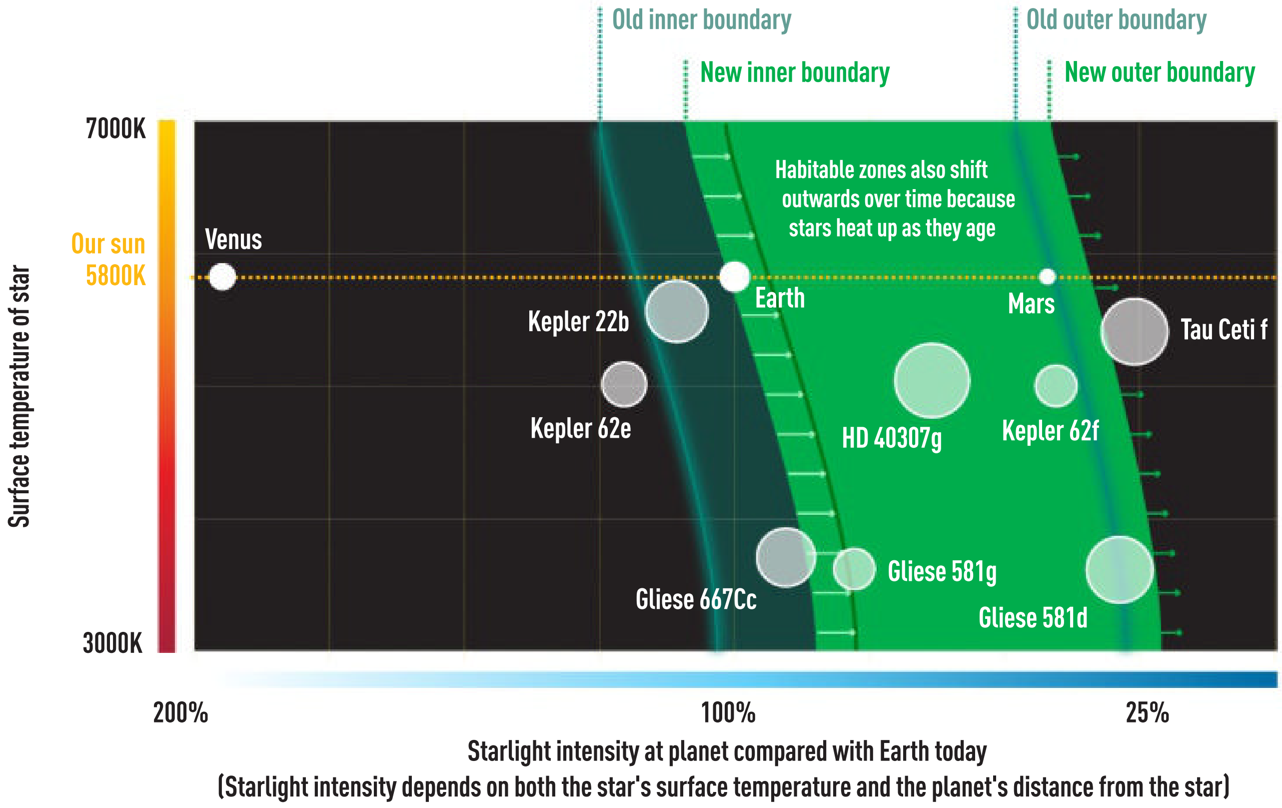
Earth's hospitable climate is due to its privileged place in the solar system, poised between fire and ice. But that position looks increasingly precarious.

OUR planet's abundant life is invariably constructed from carbon and reliant on liquid water. There are good reasons to believe that, as it is on Earth, so it is in the heavens. Carbon and water are two of the most common substances in the universe. In tandem, they provide an extravagance of durable chemical products unmatched by any other obvious combination of elements.

If life does need liquid water, then any habitable planet must occupy a slim sliver of the space surrounding a star. Too close to the thermonuclear furnace and water will evaporate away. Too far and it will freeze, consigning life to a frigid fate. Where exactly these boundaries are in a given planetary system depends on a star's brightness. Earth seems to be snugly sandwiched in the sun's sweet zone: the best of all possible worlds, at least in our solar system. The laws of physics as we understand them are the same throughout the universe, so presumably any other small, rocky planet in a similarly temperate orbit could also be a Goldilocks world.

If only it were that simple. Estimating where the Goldilocks zone lies depends on other assumptions about a potentially habitable planet's nature besides the presence of liquid water. Based on its position in the solar system alone, Earth's average surface ›

A star's habitable zone is the region around it in which an Earth-like planet can have liquid water. New calculations have shifted that zone outwards, altering our view of the habitability of many exoplanets, and putting Earth at risk from an ageing sun sooner than we thought



temperature should be well below freezing. Our saviour is a heat-trapping atmosphere, laced with the greenhouse gases carbon dioxide and water vapour. Such an atmosphere is thought to be a typical result of the way rocky planets form. If Earth's comfort blanket were much thicker or thinner, however, or had a different chemical make-up, the planet could rapidly cease to be so amenable to life.

Our neighbour Venus illustrates the point. Venus seems to have started out habitable, with a relatively Earth-like ocean and atmosphere. Its proximity to the sun rapidly turned those blessings into a curse. More water began to evaporate from the oceans into the atmosphere, where its heat-retaining qualities caused temperatures to rise still further. The result was a runaway greenhouse effect that sterilised the planet, as all the CO_2 was baked out of its crust and into its atmosphere.

→ Page 39 has more on Venus

In 1993, geoscientist James Kasting at Pennsylvania State University in State College set out to pin down a lot more precisely where the Goldilocks boundaries lie. He and his colleagues examined how varying the intensities and wavelengths of sunlight falling on an idealised Earth affected its atmosphere and surface temperature. Increasing the incident sunlight by some 10 per cent – equivalent to moving Earth inwards from its present position of 1 astronomical unit (AU) from the sun to 0.95 AU – produced a temperature rise that sent a huge amount of water vapour soaring high into the atmosphere, where it dissipated into outer space. Over tens of millions to hundreds of millions of years, such a "moist greenhouse" would entirely desiccate Earth and eradicate all surface life.

When Kasting tried to pinpoint the habitable zone's outer limit – the point where the fall in temperature is enough to cause irrecoverable global glaciations – he found it to be about 1.67 AU from the sun, slightly beyond the orbit of Mars. Already, these early calculations began to crack Earth's Goldilocks facade. Earth isn't in the centre of the Goldilocks zone, but well towards its inner edge. In 2013, working with Kasting and a few others, Ravi Kumar Kopparapu at Penn State University updated the calculations for the first time in two decades, including new measurements of how water vapour and CO_2 absorb certain wavelengths of infrared light. Rerunning the models showed that the habitable zone lies slightly further out than we had assumed (see graphic, above). The inner edge of the solar system's habitable zone moves out from 0.95 AU to 0.99 AU. In other words, were Earth just 1 per cent closer to the sun, its water could begin to steam off into space as a moist-greenhouse effect kicks in. Rather than being at a comfortable distance from the edge of the Goldilocks zone, we are teetering on the brink.

That portends an alarming future. As our sun ages, it is fusing hydrogen at higher and higher temperatures and becoming more luminous, pushing the inner edge of the Goldilocks zone outwards. But it is hard to pin down doomsday because of several uncertainties about the climate, such as the feedback effects of clouds. These could cut Earth's habitable lifespan from about 1 billion to only a few hundred million years.

One uncertainty may now lie with us humans. Thanks largely to our burning of fossil fuels, the atmosphere's CO_2 content is now about 420 parts per million, up from a pre-industrial average of 280 ppm. Might further greenhouse emissions push us over the edge, eventually to follow Venus's destiny?

So far, calculations are somewhat reassuring. If we managed to burn most of the planet's economically recoverable fossil fuel reserves, not merely doubling atmospheric CO_2 but increasing it by a factor of 8 or 16, the worst outcome would be only a moderately moist greenhouse. To go further, and trigger a runaway greenhouse, we would have to reach CO_2 concentrations of around 30,000 ppm, according to calculations by geochemist Colin Goldblatt at the University of Victoria in British Columbia, Canada. If we really try to turn Earth into Venus, we could – by using our fossil fuel resources to cook up a lot of limestone to release even more carbon.

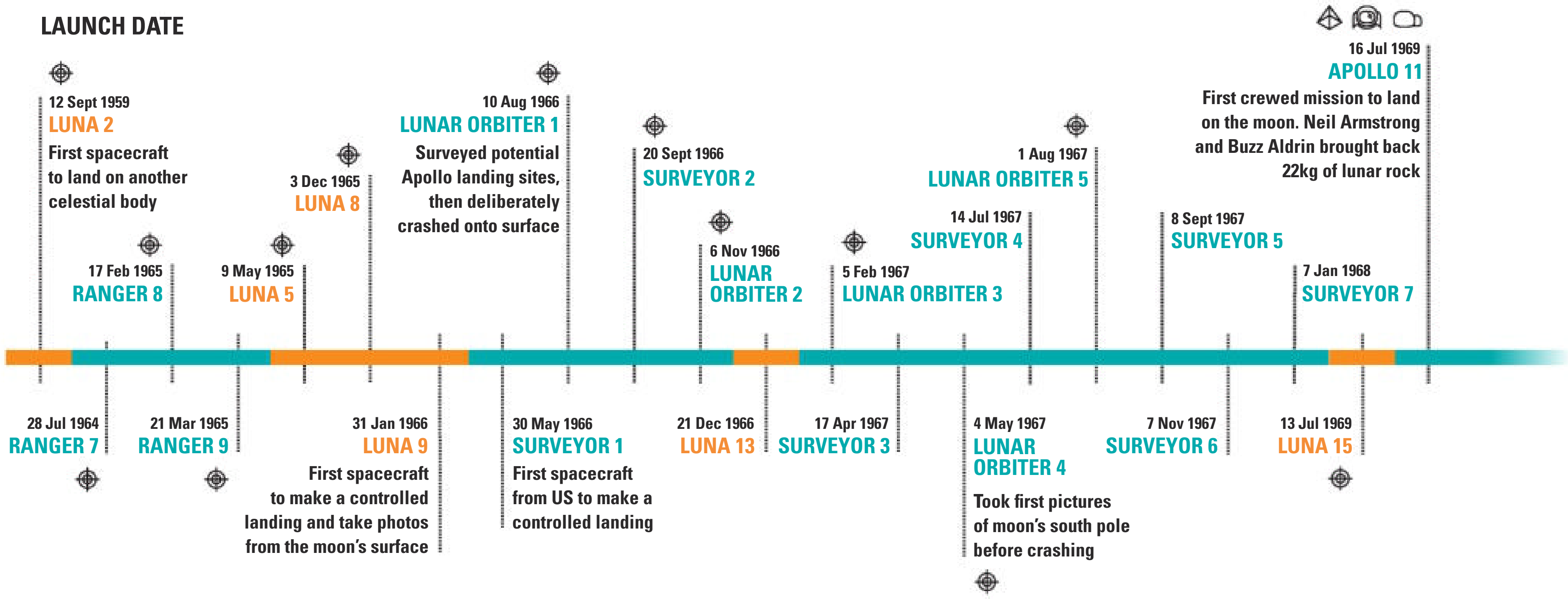
Of course, that does nothing to diminish the potentially catastrophic impacts of climate change on human society in the coming decades and centuries. And given our uncertainties about how climates work – and about Earth's precise position in the Goldilocks zone – Goldblatt says it is probably unwise to take too much for granted. "It's like playing tag on top of a cliff on a foggy day. No one's fallen off yet, but you don't know how close the edge is." ▮

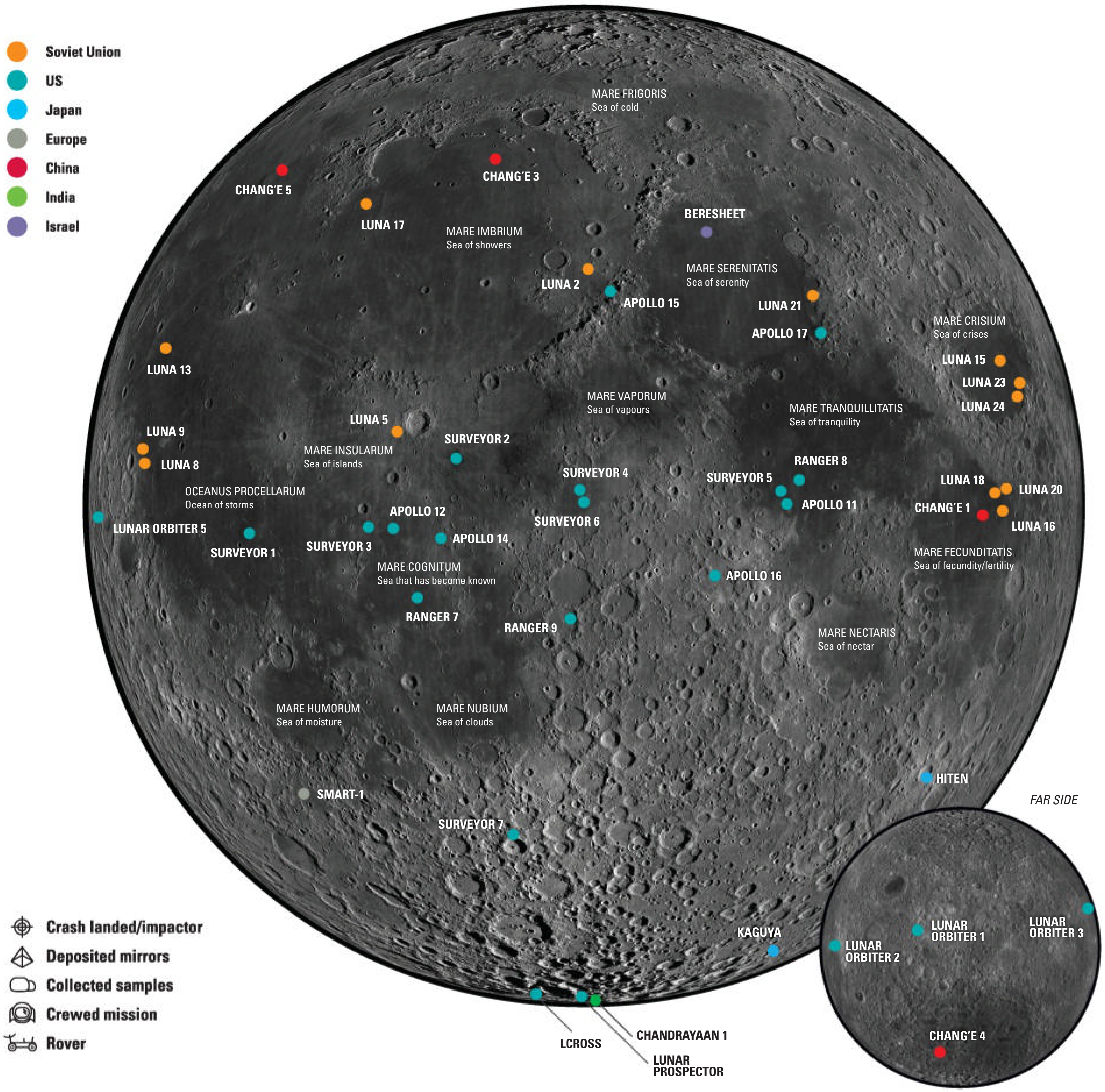
WHY THE MOON MATTERS

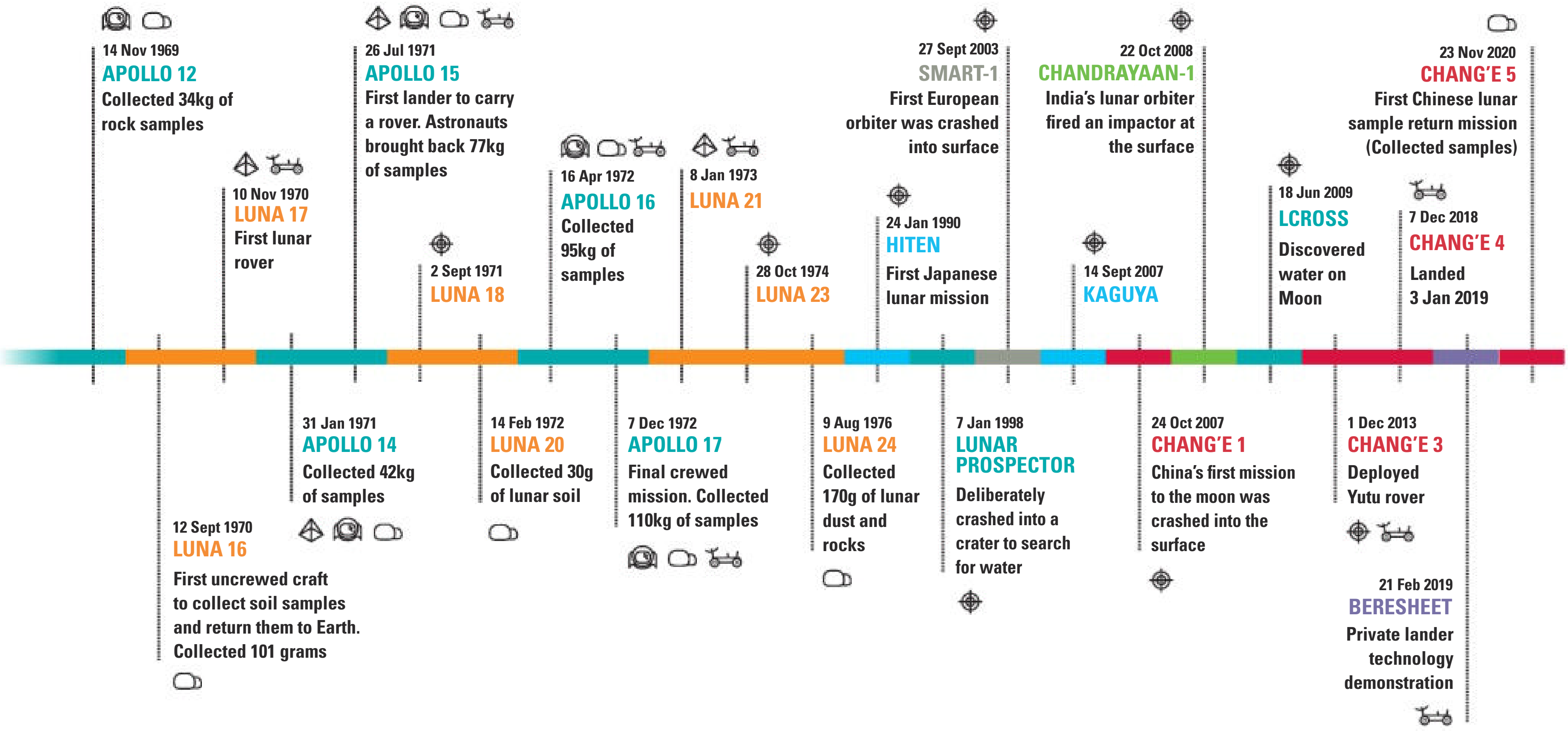
The moon's gravity gently tugs on Earth, creating its tides and keeping its rotation fairly stable. Without it, our planet could topple over from time to time, causing climate chaos. Having such a uniquely large companion may have helped life to emerge and survive on Earth – just one reason the moon is a worthy source of fascination.

AFTER Earth, the moon is the most studied object in our solar system. More than 70 successful missions have unlocked its geological history, determined its internal structure and measured its surface composition. The conclusions of those explorations stretch well beyond the barren lunar surface.

The same astronomical processes that have influenced Earth have also been felt by the moon. Yet while weathering and the restless shifting of the continents on our planet have largely erased the most ancient events from our geological record, that isn't true of moon rocks. Decoding the lunar record began in earnest 50 years ago, when the first moon rocks were collected by Apollo 11's Neil Armstrong and Buzz Aldrin. During a 2-hour-and-36-minute moonwalk, they pocketed 22 kilograms of the lunar surface, then brought it back to Earth for analysis. ›


LAUNCH DATE
12 Sept 1959
LUNA 2
First spacecraft to land on another celestial body
17 Feb 1965
RANGER 8
9 May 1965
LUNA 5
3 Dec 1965
LUNA 8
10 Aug 1966
LUNAR ORBITER 1
Surveyed potential Apollo landing sites, then deliberately crashed onto surface
20 Sept 1966
SURVEYOR 2
6 Nov 1966
LUNAR ORBITER 2
5 Feb 1967
LUNAR ORBITER 3
14 Jul 1967
SURVEYOR 4
1 Aug 1967
LUNAR ORBITER 5
8 Sept 1967
SURVEYOR 5
7 Jan 1968
SURVEYOR 7
16 Jul 1969
APOLLO 11
First crewed mission to land on the moon. Neil Armstrong and Buzz Aldrin brought back 22kg of lunar rock
28 Jul 1964
RANGER 7
21 Mar 1965
RANGER 9
31 Jan 1966
LUNA 9
First spacecraft to make a controlled landing and take photos from the moon's surface
30 May 1966
SURVEYOR 1
First spacecraft from US to make a controlled landing
21 Dec 1966
LUNA 13
17 Apr 1967
SURVEYOR 3
4 May 1967
LUNAR ORBITER 4
Took first pictures of moon's south pole before crashing
7 Nov 1967
SURVEYOR 6
13 Jul 1969
LUNA 15


Soviet Union
US
Japan
Europe
China
India
Israel
MARE FRIGORIS
Sea of cold
CHANG'E 5
CHANG'E 3
LUNA 17
MARE IMBRIUM
Sea of showers
BERESHEET
LUNA 2
APOLLO 15
MARE SERENITATIS
Sea of serenity
LUNA 21
APOLLO 17
MARE CRISIUM
Sea of crises
LUNA 15
LUNA 23
LUNA 24
LUNA 13
MARE VAPORUM
Sea of vapours
MARE TRANQUILLITATIS
Sea of tranquility
LUNA 5
LUNA 9
LUNA 8
MARE INSULARUM
Sea of islands
SURVEYOR 2
SURVEYOR 4
SURVEYOR 5
RANGER 8
LUNA 18
LUNA 20
OCEANUS PROCELLARUM
Ocean of storms
APOLLO 11
CHANG'E 1
LUNA 16
LUNAR ORBITER 5
APOLLO 12
SURVEYOR 6
SURVEYOR 1
SURVEYOR 3
APOLLO 14
MARE COGNITUM
Sea that has become known
MARE FECUNDITATIS
Sea of fecundity/fertility
APOLLO 16
RANGER 7
RANGER 9
MARE NECTARIS
Sea of nectar
MARE HUMORUM
Sea of moisture
MARE NUBIUM
Sea of clouds
HITEN
FAR SIDE
SMART-1
SURVEYOR 7
LUNAR ORBITER 3
LUNAR ORBITER 1
LUNAR ORBITER 2
KAGUYA
CHANG'E 4
LCROSS
CHANDRAYAAN 1
LUNAR PROSPECTOR
Crash landed/impactor
Deposited mirrors
Collected samples
Crewed mission
Rover



Another five Apollo missions added to the tally, returning a total of 2200 samples.

The dust and rocks kept at the Johnson Space Center in Houston, Texas, are treated as a priceless scientific and cultural resource. Over the years, improved instrumentation has allowed us to make ever more sensitive measurements and re-examine old questions

The biggest of these is how the moon formed. Astronomers have toyed with many ideas. Perhaps Earth was spinning very fast and a piece broke off? Or maybe the moon was wandering through space and was captured by our gravity?

In 1946, Canadian geologist Reginald Aldworth Daly proposed what we now think is the right idea: that a smaller planet hit Earth, kicking out a ring of debris from which the moon formed. In their first investigations of the Apollo samples, geologists found good evidence that this was the case. The moon rocks looked sufficiently similar to Earth rocks to suggest that the pulverised impactor had been mixed with a large portion of Earth debris.

Modern reanalysis shows that the moon rocks are in fact almost identical to Earth's, meaning our rocks were thoroughly mixed in with those of the impactor (a planet now named Theia). Simulations show how a particularly violent impact could have melted Earth and surrounded it with a doughnut-shaped cloud of vaporised rock, called a synestia. The moon could have condensed from that doughnut. Another possibility is that our planet was already covered by an ocean of magma at the time of the collision, which could have made it easier to mix the matter of Theia and Earth.

What happened to the moon after it formed has got researchers itching for a return mission.

A casual glance at the moon reveals dark markings across its surface, thought to have formed during a relatively short period called the late heavy bombardment.

↓ Page 28 later in this chapter has more on the late heavy bombardment

Evidence came from the Apollo samples, many of which are about 3.9 billion years old, which suggest that the moon was heavily pummelled by asteroids, creating large impact basins we see on the moon's surface, over about 20 million to 100 million years.

But none of the Apollo samples were bedrock – rocks sampled in the place where they formed – which has robbed geologists of the context needed to fully interpret their results. If we can go back and sample true bedrock, that should show the true ages of other basins, and tell us whether there really was a short, sharp late heavy bombardment or a continual rain over a longer period. This is just one of the reasons that people now want to return to the moon, more than 50 years after the last human left it. ▮

NASA/GSFC/ASU

GOING BACK TO THE MOON

Science, mineral wealth and deep-space wanderlust are all driving plans to revisit the moon. Before we go back, we should think about what kind of place we want it to become.

A GENERATION after the Apollo missions and Neil Armstrong's famous "one small step for a man" onto the lunar surface on 20 July 1969, the people preparing to revisit the moon look different from their forebears. They aren't all white men from the US, or specially trained astronauts. They include artists and billionaires. There are people from China, Japan and Europe. Many will launch far from Cape Canaveral in Florida. Once they arrive, they might live in inflatable shelters, single-occupancy domes connected like Lego bricks and larger 3D-printed habitats. And they will change the moon and our relationship with it for good.

Will the moon become gold-rush territory, a place where people extract resources for profit? Or a bastion of research for its own sake, much like Antarctica? A way station to other planets? Or even an environmental reserve, where mining is banned but tourists can enjoy extreme hiking trips, and artists can seek new inspiration?

NASA's Artemis programme aims to return humans to the moon by 2025. The mission will include an orbiting lunar space station enabling trips to the surface, and its crew should include the first woman to walk on the moon.

China is also developing the hardware it will need to land taikonauts on the moon. In 2018, the country accelerated development of its Long March 9 rocket, similar in size to the Saturn V that launched the Apollo missions. Chinese officials have said the rocket will power its first lunar surface missions in the 2030s. China's plans may be one reason for the sudden US interest in returning to the moon within the next five years, instead of NASA's original plan for a 2028 time frame.

If the next moonwalkers aren't Chinese taikonauts or female NASA crew members searching for water, maybe they will be space miners sent by Jeff Bezos. In May 2019, the Amazon founder, also owner of rocket company Blue Origin, unveiled a new lunar lander design called Blue Moon.

Most of the countries and companies vying to go back to the moon will want to claw back some of their huge investments, so mining is likely to be high on the agenda. Water will probably be the most valuable resource on Earth's satellite, at least to begin with. It could be split into hydrogen and oxygen to make rocket fuel for return trips to Earth and other planets or to be burned to generate power. Water prospecting is likely to draw people to the moon's shadowed craters, especially at the south pole, where spacecraft have sniffed its presence for the past decade.

And setting up a moon base could enable humans to travel to Mars and beyond, because the moon's lower gravity could make it easier and cheaper to fuel a long-range spacecraft.

→ Page 46 has more what it will take to go to Mars

By contrast with these expansionist and material ideas, Japanese billionaire Yusaku Maezawa made headlines in 2018 when he bought all the seats on a SpaceX capsule that the company's CEO Elon Musk wants to send around the moon. Maezawa said he planned to bring artists and performers, who would be commissioned to create new works inspired by what they see.

The European Space Agency's director general, Jan Woerner, has espoused a plan for an international moon village, built by an alliance of countries and companies, where future moon citizens mix jobs and objectives. For instance, taikonauts exploring at the south pole may cross paths with radio astronomers erecting an observatory on the moon's far side. From that vantage point, the moon blocks radio transmissions and noise leaking from Earth. This is potentially so valuable that Claudio Maccone at the National Institute for Astrophysics in Italy recently called for a radio-free zone on the far side. If that is to be realised, governments and private entities may need to establish firmer rules for how the moon should be used.

Others argue that the moon should be treated like a national park, with rules designed to keep it pristine. But the legal framework for doing this is unclear. Recognising the intrinsic value of the environment on the moon may be harder than it is on Earth.

Today, the laws of space are governed by the Outer Space Treaty of 1967, which rules that celestial bodies, including the moon, can't be claimed by any country or enterprise. But the treaty doesn't prohibit mining or other activities. The 108 nations that are parties to the treaty, as well as private companies, all operate as though the moon is similar to international waters. Two-hundred nautical miles from a coastline, the oceans belong to everyone and no one. The countries that can access that territory will be the first to access its contents, and possibly get rich from it.

Perhaps the next wave of lunar missions can do better if we think ahead, and bear in mind the need for human inclusivity and respect for the lunar environment. ▮

WHEN PLANETS MIGRATE

Mineral traces in the rocks of Earth are calling our solar-system creation stories into doubt. That gives hope for a universe full of life.

WE THOUGHT we had the origins of the solar system more or less worked out. Some 4.6 billion years ago, a vast cloud of dust and gas in some corner of an unremarkable galaxy began to collapse into a dense ball of matter. As more and more surrounding material was pulled towards it, the temperature and pressure at its core increased, to the point where nuclear fusion kicked in. This released vast quantities of energy and marked the moment our sun became a star.

←
Turn back to page 6 for more on how the sun works

As the newborn star slowly began to spin, smaller bodies started to coalesce in orbit around it. Close in, vast quantities of water ice were boiled away, leaving metallic and silicate compounds behind to form the smaller rocky planets. Further out, cooler temperatures allowed giant worlds of ice and gas to form. All orbited in a single plane along smooth, near-circular tracks.

The first chapter of this story, about the sun, has held up well – but a few decades ago, scientists realised that there are serious holes in the planet-formation plotline. For one thing, it struggles to explain the quantity and distribution of the Trojan asteroids, thousands of tiny bodies that chase after Jupiter in its orbit. Nor does it square with the shape of the Kuiper belt, the icy band beyond Neptune that holds Pluto.

→
Chapter 5 has more on the outermost solar system

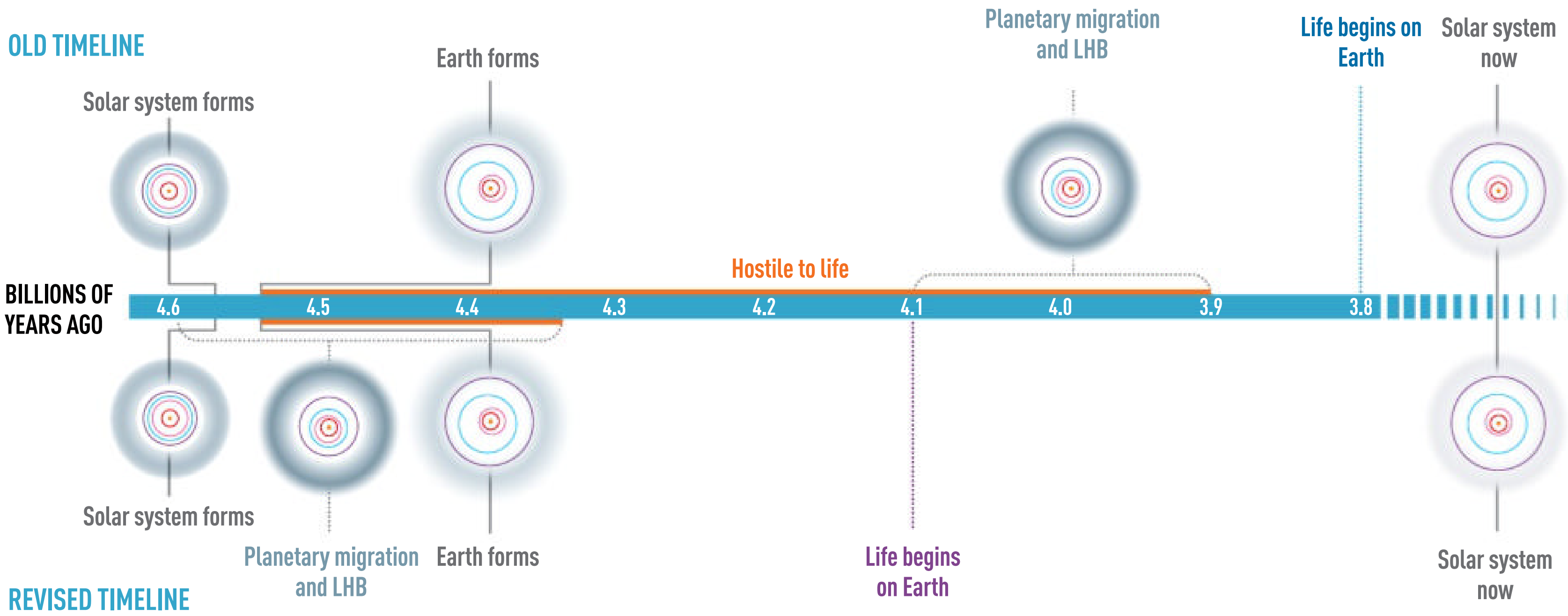
Many Kuiper bodies orbit at far greater angles to the planetary plane than the conventional picture would allow. Perhaps most perplexing of all, however, was the evidence our cosmic neighbourhood had once been under heavy bombardment. Rocks returned to Earth by the Apollo astronauts suggested the widespread cratering on our own moon was the result of a great assault 3.9 billion years ago – a ruction the conventional model found hard to explain. The solution, named after the city in France where it was devised in 2005, was the Nice model.

In this refinement of the traditional story, our solar system's four giant planets started out much closer together than they are today. This configuration was unstable, leading to hundreds of millions of years of gravitational tussling, during which the giant planets migrated into their current positions, disturbing the millions of tiny bodies littering the ancient solar system. Many fell under Jupiter's gravitational influence, becoming its Trojan followers, while others settled in the solar system's outer regions as highly angled denizens of the Kuiper belt.

Meanwhile, asteroids in the band between Mars and Jupiter were dislodged from orbit, many going on to collide with the innermost planets. This period of intense activity, known as the late heavy bombardment (LHB), would have left deep craters on the moon and given our fledgling planet a serious knock during the turbulent early stages of its development.

The small number of surviving solid rocks from this period have led us to picture early Earth as a fiery world covered in volcanoes bursting through a molten crust. The LHB's few hundred million years of constant collisions contributed to a nightmarish landscape so extreme that the geological period is known as the Hadean, after the Greek god of the underworld. The existence of life in such a hellscape was considered preposterous. Instead, the first traces of biogenic

To explain fossils 4.1 billion years old, we need to rewrite the solar system's history along with one of its most cataclysmic events, the late heavy bombardment (LHB)



carbon, dated at 3.8 billion years old, neatly coincide with the time Earth was finally at peace and the bombardment from outer space had slowed.

Nice and neat… but again, this story might need a rather different ending to fit recent discoveries on Earth.

Among the 200,000 shards of rock that Mark Harrison has retrieved from Australia since the mid-1980s, one contained two flecks of graphite, each barely the size of a red blood cell. The ratio of carbon isotopes within them implies they were created by biological processes – and yet they were found in a zircon crystal that had lain trapped deep in the Jack Hills in Western Australia for 4.1 billion years. That would imply our planet was inhabited at least 300 million years earlier than anyone had previously imagined, at a time when the Nice model says our Earth was a molten hellhole. If Harrison's fossils are all they seem, they wouldn't only rewrite the history of life and Earth, but the entire solar system's as well.

As far back as 1999, geologists uncovered other zircons in the Jack Hills that indicated part of Earth's surface had cooled and solidified 4.4 billion years ago. What's more, measurements of how much oxygen the rocks contain suggest that Earth was mild enough to support liquid water.

In 2013, Judith Coggon, then at the University of Bonn, Germany, was analysing another contender for the planet's oldest rock – on the other side of the world in Greenland. There, she found evidence that Earth contained significant quantities of gold and platinum as far back as 4.1 billion years ago – even though these metals were thought to have been delivered only later by the LHB.

Then, in 2015, Nathan Kaib at the University of Oklahoma, along with John Chambers at the Carnegie Institution for Science in Washington DC, published the results of their latest simulations of solar system formation. In 85 per cent of cases, the inner solar system ended up with fewer than the four rocky worlds it has today. Only 1 per cent of the time could they create a solar system that looked like the one we recognise.

Kaib has a simple solution. The giant planets still migrated, producing the Jovian Trojans and the Kuiper belt, but they did so much earlier – while the innermost planets were still forming. By turning up to the party fashionably late, Earth dodged a bullet. The early migration of the giant planets would have scattered most of the larger impactors by the time Earth's formation was complete.

But if the giant planet migration happened before Earth and the moon had formed, then what cratered the lunar surface 3.9 billion years ago? One suggestion is that a giant impact on Mars could have created that planet's northern lowlands, throwing up debris that later bombarded the moon. These Martian invaders could have been smaller than scattered asteroids, › and so less likely to scour all life from Earth.

Or maybe the bombardment wasn't so sudden after all. Even though the Apollo samples that led to the assumption were returned from several different sites on the moon, it has been suggested that they could all have come from the impact or impacts that formed the Imbrium basin – one of the large, dark patches that make up the man in the moon. Rocky shrapnel from this event could have contaminated disparate parts of the lunar surface, meaning that what at first looked like a host of simultaneous impacts might have only been a handful. If the impacts that caused the cratering on the moon were less of a spike and more of a steady drip, then the later migration of the original Nice model could have happened after all.

Whether the bombardment was early or more gradual, with relative calmness kicking in sooner in Earth's history, life could have emerged more quickly to leave its mark in the Jack Hills zircon. Then the life forms we had previously thought of as our earliest ancestors, dating from 3.8 billion years ago, weren't the beginning of the evolutionary tree at all. Instead, life on Earth began hundreds of millions of years earlier, almost as soon as the planet was ready. That would raise hopes for the speed and ease with which biology can take hold, and of its aptitude for sticking around in an unfriendly cosmos. Our revised history could point to a more interesting future. ∎

THE MEANING OF METEORITES

Meteorites that fall on Earth come mainly from the asteroid belt, a repository of material from the solar system's early days that sits between the orbits of Mars and Jupiter. But they come in a bewildering array of varieties, indicating they didn't all form there. Examining the chemical composition of any fragments that come our way, and comparing this with the results of computer simulations exploring how the gas giants might have moved around in the early solar system, can provide clues as to how that process unfolded.

In particular, an asteroid forming further from the sun would hold more deuterium, a heavy isotope of hydrogen. Analyse the ratio of ordinary hydrogen to deuterium in meteorites and you can tell roughly where their parent rock was born.

One of the best sources of meteorites is Antarctica. Rocks that fall on the continent's high interior get buried in the ice and carried towards the coast as the ice slowly slips towards the sea. Then they meet the rising underlying terrain of the Transantarctic mountains, where they can be forced upwards to the surface. For 40 years, researchers in the US Antarctic Search for Meteorites programme have combed the ice on snowmobiles, and have now found more than 21,000 objects, including meteorites from Mars and the moon.

By combing the ice, researchers have found meteorites from Mars and the moon

ANSMET/NASA

The next problem is pinpointing where the material came from. We need to know not just where a meteorite fell, but how it fell, in the hope of reconstructing its trajectory and so learning its parent asteroid's rejigged orbit. Fifteen years ago, Phil Bland at Curtin University in Perth, Australia, created the Desert Fireball Network, made up of 50 cameras spread across the desert of southern and western Australia. Each captures night-long exposures of the sky, including the luminous path of any meteors. A fireball's size reveals how large the rock is and whether it will burn up in the atmosphere. Bland's team measures its trajectory on multiple cameras and calculates where the meteorite landed.

Crucially, trajectory mapping from camera networks can point to where a meteorite came from. This way we can home in to plot a detailed chemical map of the entire asteroid belt, and perhaps unearth some answers as to what happened in the early solar system.

DEFENDING EARTH

Small space rocks can bring us fascinating information; big ones bring death. So how can we defend ourselves against catastrophic impacts?

THE risk of an asteroid collision is the price we pay for living in our crowded bit of space. There are millions of rocky and icy vagabonds jostling for room among the moons and planets of our solar system. So far, astronomers have spotted more than 21,000 asteroids with orbits that are set to bring them close to our world. Every day, another one of these near-Earth objects is discovered.

At the small end of the scale, they aren't worth worrying about. An asteroid the size of a car is likely to burn up in the atmosphere, putting on a light show but not causing any destruction on the ground. At the other extreme are giants such as the one that hit what is now Chicxulub in Mexico about 66 million years ago, probably wiping out or at least finishing off the non-avian dinosaurs. That one measured somewhere between 10 kilometres and 81 kilometres across, and would spell global doom if it hit today. Thankfully, such monsters are both incredibly rare and big enough to see coming (see diagram, overleaf).

Plenty of objects below the dinosaur-killing scale are still large enough to cause serious damage, but small enough to avoid detection. Asteroid surveys, mainly funded by NASA, are gradually finding these, but there are still large gaps. One way to tell how many we are missing is to count how often our asteroid surveys rediscover the same objects. The fewer new objects we spot, the more confident we can be that we have spotted most of the asteroids out there. So far, this suggests we have found less than half of the asteroids of city-killing scale, on the order of 100 metres across. None of the ones we have found has a significant chance of hitting Earth in the next 100 years, but those are worrying numbers.

Asteroid watchers make all their data public, so whenever a potentially dangerous object is spotted, astronomers in different countries simultaneously evaluate the risk. In 2013, the United Nations recommended that the global effort be more organised, so the International Asteroid Warning Network was formed, with astronomers and space agencies from Europe, Asia and North and South America. If they all agree that an impact really could be catastrophic, the network sends a message to the United Nations Office for Outer Space Affairs, which gathers member states together to discuss what they should do.

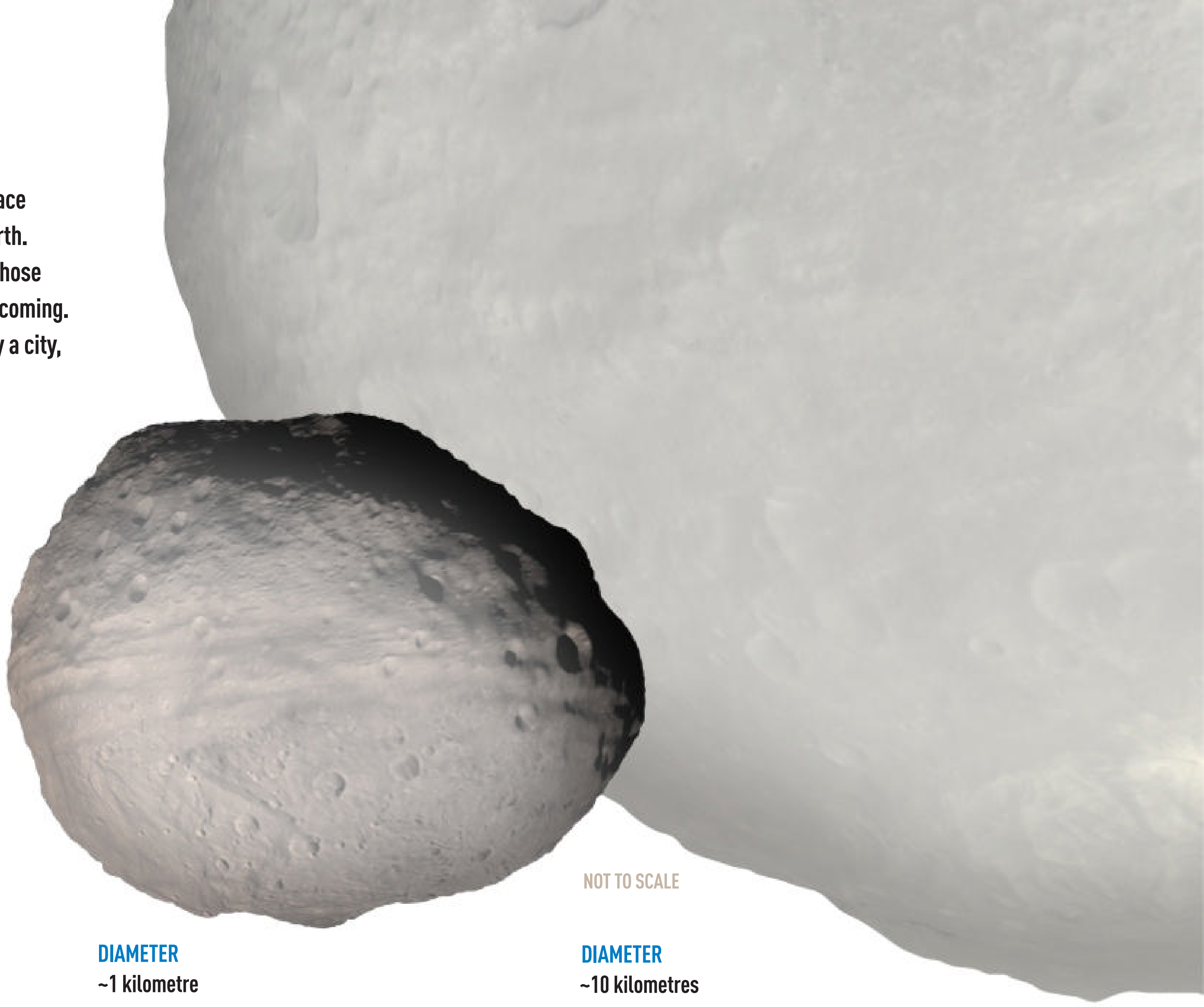
Ideally, we would detect the asteroid decades, or at least years, before it is projected to hit Earth. At that point, we won't know exactly where it is going to hit, but we will be able to say with some certainty that it is headed towards us. The moment we know that, it is time to start planning.

What are the options? Blowing the thing up with a nuclear bomb, the course favoured in disaster movies such as *Armageddon* and *Deep Impact*, may be a non-starter. There will be political objections to launching nuclear weapons into space, and practically speaking, it might make the situation worse. If we succeeded in blowing up an asteroid, it would turn into a cloud of shrapnel still headed towards Earth.

A better idea is to push it off course. For a long time, the most popular proposal was a gravity tractor, a large spacecraft that would fly close to an asteroid, slowly changing its trajectory via the craft's own gravitational attraction without ever actually touching it. This method would be slow, though, so most of the work in recent years has shifted to the use of kinetic impactors: spacecraft that slam into the approaching rock to change its course.

Before we can do anything like that, we have to learn more about asteroids. The physics of how to push ›

Our patch of the solar system is full of space rocks, many on a collision course with Earth. Most are too small to cause damage and those big enough to wipe us out are easy to see coming. Those in the middle, big enough to destroy a city, are the ones we need to watch out for



NOT TO SCALE

DIAMETER
<1 metre
DAMAGE
None
COLLISION FREQUENCY
Thousands per year. Too many to track

DIAMETER
~1 metre
DAMAGE
None
COLLISION FREQUENCY
30 per year. Too many to track

DIAMETER
~100 metres
DAMAGE
Could destroy a city
COLLISION FREQUENCY
One per 2000 years
MOST RECENT:
Tunguska event in Russia, 1908. We know of less than half of the objects this size that astronomers suspect are out there

DIAMETER
~1 kilometre
DAMAGE
Could affect an entire continent
COLLISION FREQUENCY
One per million years
MOST RECENT
About 900,000 years ago, Zhamanshin crater in Kazakhstan. We know of about 80 per cent of the estimated number of objects this size

DIAMETER
~10 kilometres
DAMAGE
Global
COLLISION FREQUENCY
One per 60 million years
MOST RECENT
66 million years ago, Chicxulub crater in Mexico. We have detected all the estimated objects of this size

SOURCE: NASA

something out of the way depends on its composition. We already know that some are porous bundles of rock called rubble piles, whereas others are solid iron. So immediately after detecting a dangerous asteroid, the race to characterise it will begin. Earth-based telescopes will tell us its size and shape, as well as its reflectivity. We expect less-reflective asteroids to have lower densities because they are a porous mixture of rock and ice, whereas brighter asteroids are likely to be more solid. Radar data could also let us define the orbit more precisely and reveal any moons that might be orbiting the asteroid, which would also need to be deflected.

There is a limit to how much we can find out about asteroids from the ground, though. That is why missions to bring back samples from potentially hazardous asteroids are so important. In 2018, NASA's OSIRIS-REx visited asteroid Bennu, and Japanese space agency JAXA's Hayabusa 2 visited Ryugu. Both bodies are more porous than we expected, with Bennu being 40 per cent pores and caves, and Ryugu as much as 50 per cent empty on the inside.

So we need to test what happens when a kinetic impactor hits such a rubble pile. NASA is on the job with the Double Asteroid Redirect Test (DART) probe. DART launched in late 2021, and is due to crash into 150-metre Dimorphos, a moon of the asteroid Didymos, around the end of September 2022. That is expected to change the orbit of Dimorphos enough to be visible from Earth.

Other ideas are also being considered. The simplest would be to paint one side of an asteroid white or silver. The painted part would then reflect more sunlight, and the momentum imparted by the extra light bouncing off that surface could change the asteroid's trajectory. Alternatively, we could attach engines to an asteroid and turn it into a spacecraft, or use high-powered lasers that could vaporise rock. The puff of dust jetting off the surface could act like a thruster, allowing us to push it off course. These options are untested and would probably take decades or require technology we don't yet have, so they aren't part of any official plan. ∎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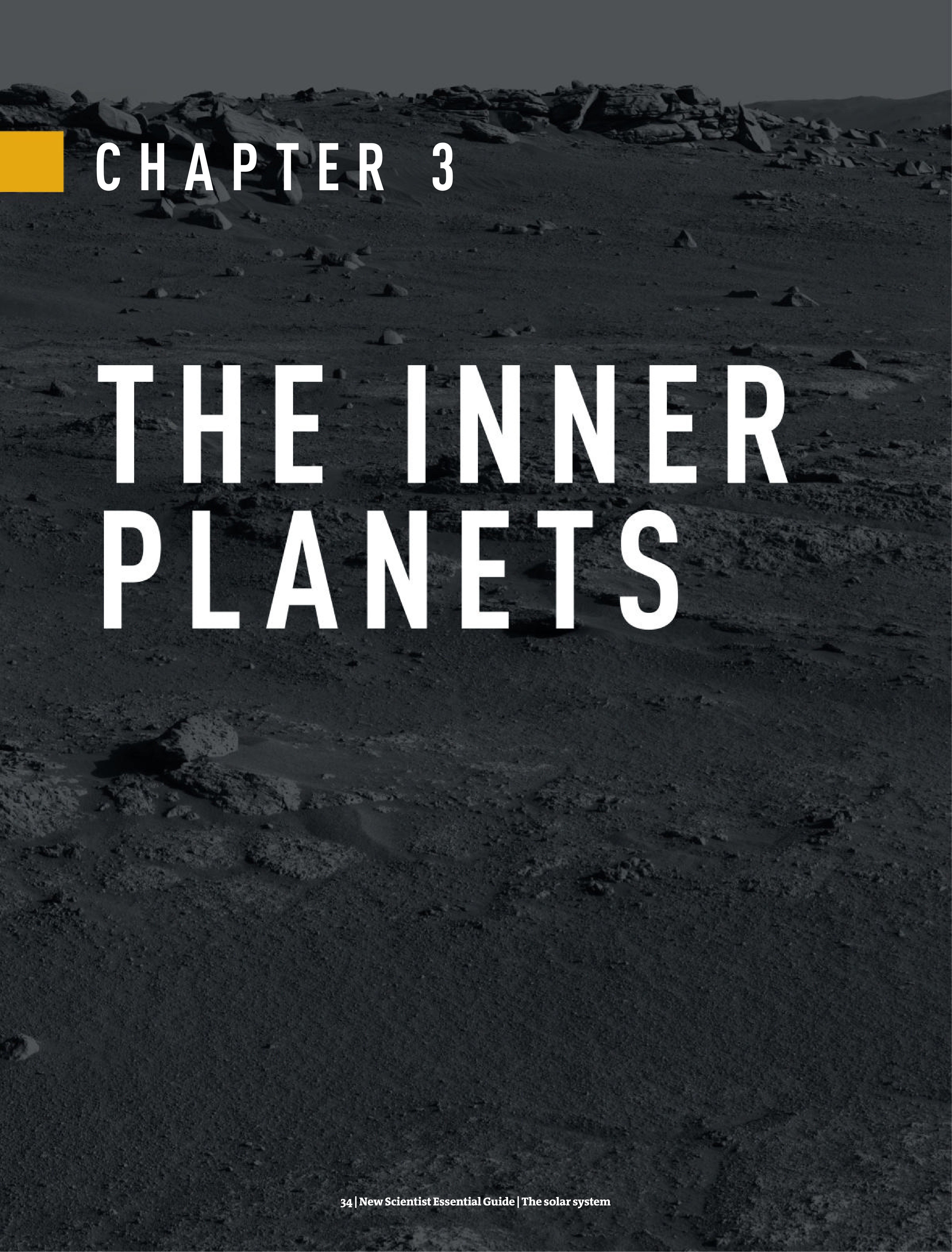

CHAPTER 3

THE INNER PLANETS

The three closest planets to Earth are all small, solid worlds. All of them have iron cores, bound with rock. Yet they are all spectacularly different from one another.

Mercury is a black and blasted plain. Venus is a sweltering world beset by rain of pure acid. Mars is cold and arid, with tantalising hints of alien life.

Understanding the origin of these differences could cast light on the nature of our own world and the diversity of rocky planets throughout the universe – and so prevent us from being too blinkered in our search for life.

MERCURY: THE IRON PLANET

The closest planet to the sun remains mysterious because we have hardly ever visited. It is hard to get to Mercury – but perhaps our third mission, now en route, will change our perceptions.

MERCURY is not a hospitable place. Its airless and lifeless surface is seared by the sun, reaching up to 430°C on the dayside equator. Because there is barely any atmosphere to hold and spread heat, the temperature drops to about -175°C under the blackness of night after the sun sets, in a daily cycle lasting twice as long as the planet's year (which itself lasts just 88 Earth days). The tortured landscape is raked with ionising radiation and scarred by billions of years of explosive impacts. Beneath it lies only a thin 500-kilometre mantle, just a thin rock shell around a huge iron core, reaching out 80 per cent of the whole planet's radius.

Why is Mercury so heavy in metal, unlike the other inner planets of the solar system? These planets, we believe, formed as a cloud of gas and dust surrounding the sun coalesced and condensed. Particles of metal and silicate minerals stuck together, gradually forming larger lumps of matter called planetesimals, which in turn collided and merged to form the planets. But most simulations of this process fail to produce an iron-rich planet like Mercury.

One idea is that the sun's magnetic field drew more iron into the innermost reaches of solar ›

NASA/JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY/CARNEGIE INSTITUTION OF WASHINGTON
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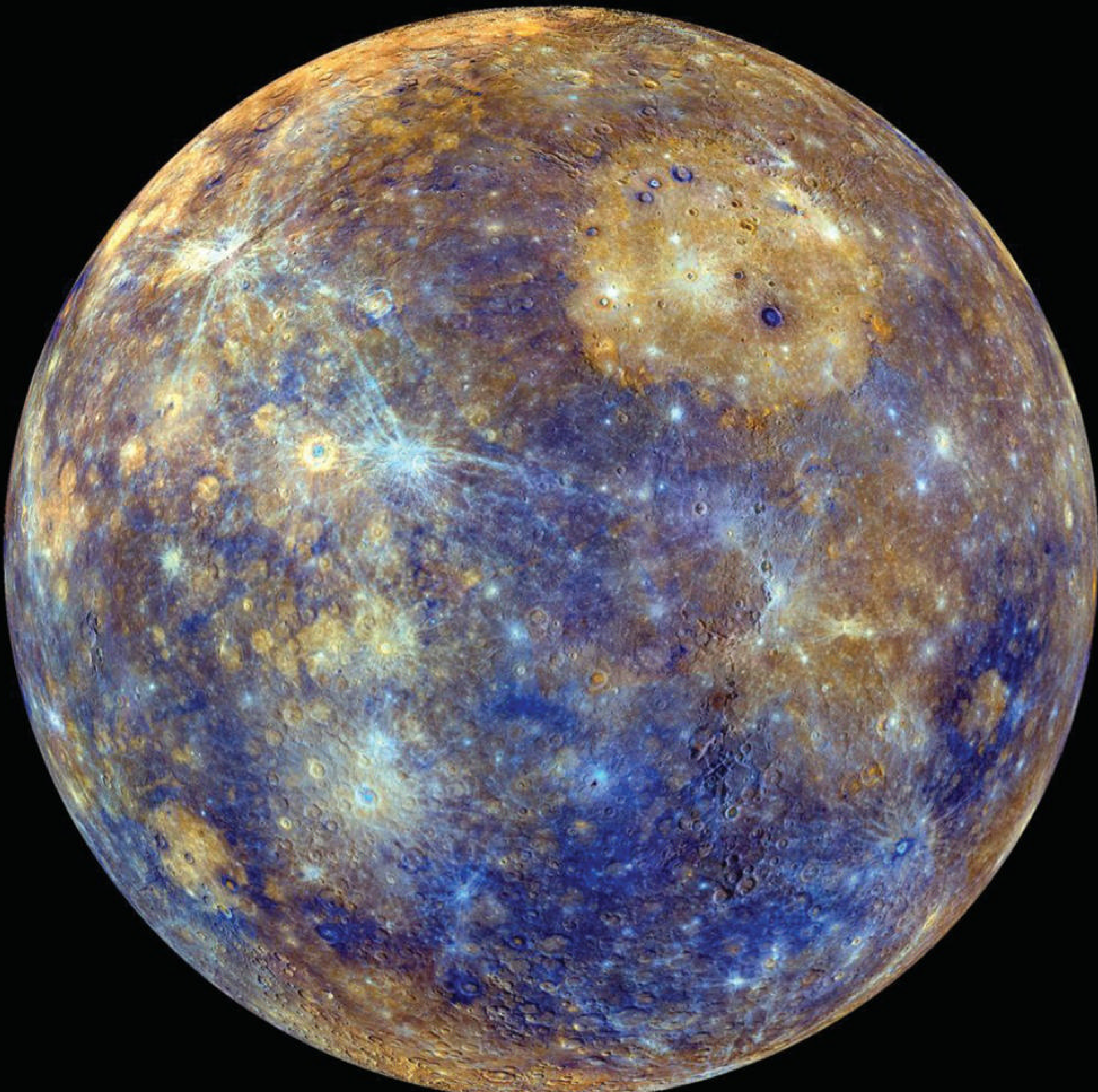


system, so Mercury would have started out rich in iron. Most other hypotheses focus on stripping away most of the original rock. Perhaps in Mercury's first 100 million years, a large object thousands of kilometres across hit the planet, blasting much of its silicate mantle into space. A snag was that this material should eventually fall back on Mercury.

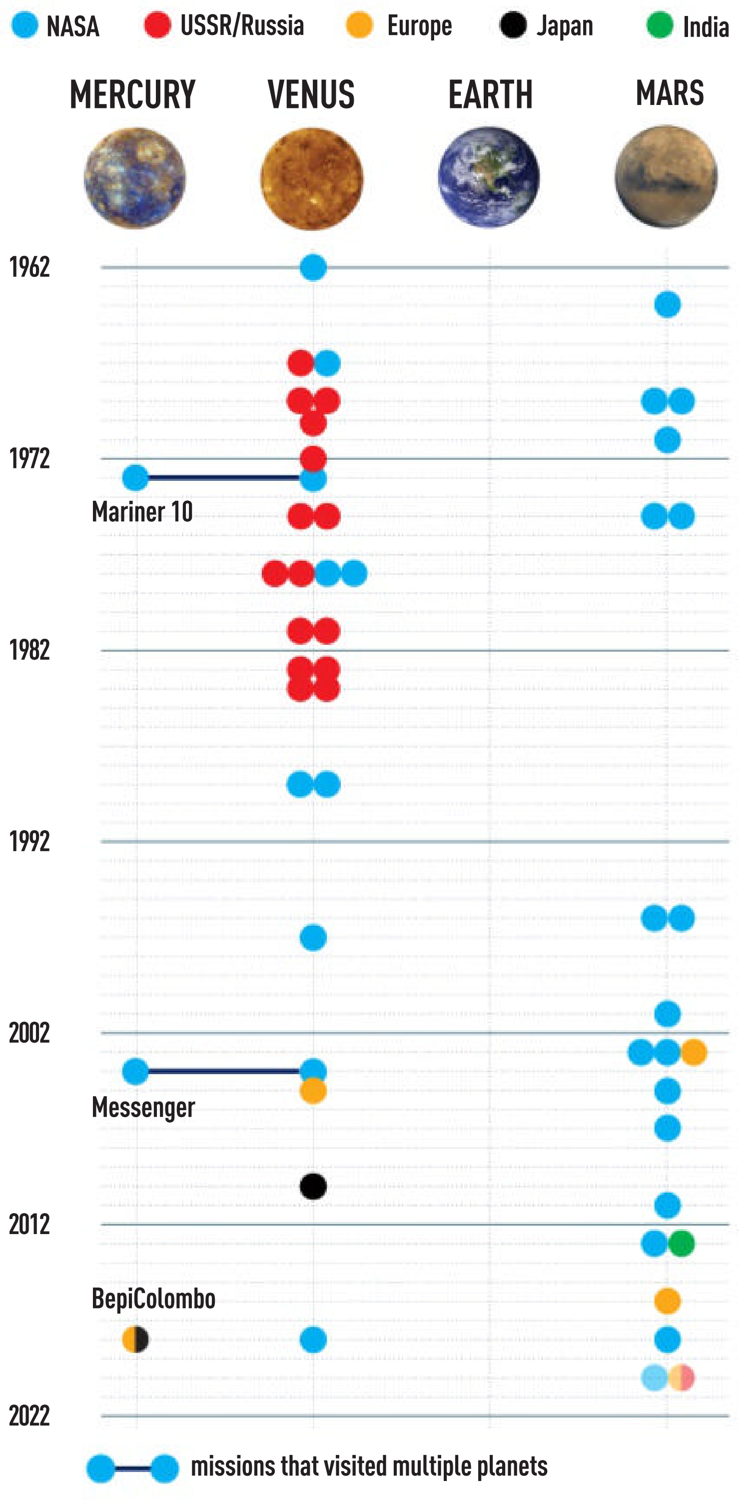
In 2020, Christopher Spalding at Yale University and Fred Adams at the University of Michigan proposed a solution. The ancient solar wind would have been 10 to 100 times stronger than it is today, so it could have blown the debris away from Mercury's orbit – potentially leaving some remnants of Mercury behind on Venus and even Earth.

But we have spotted signs of elements such as potassium that should have vaporised in the heat of a collision. So maybe a smash and grab robbery isn't the answer, and instead Mercury's silicates were stolen in a more subtle way, by its greedy neighbour. A series of close passes between Mercury and Venus when they were young could have stripped away Mercury's outer layers, leaving behind a world that is mostly dense core. "If you pass by without direct contact, there is much less heat generated. It just peels off the mantle," says Hongping Deng at the University of Cambridge, whose 2019 simulations showed this process in action.

The only way to find out more is to go back there, but that isn't as easy as it sounds. When your next-door neighbour is a star 6 million times heavier than you, visitors have a tendency to get redirected. Any spacecraft launched headlong towards Mercury would be accelerated by the sun's gravity and fly past so fast – at around 10 kilometres a second or more – that no feasible propulsion system could stop it. Instead, 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.

Only two spacecraft have ever made it there. The

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



first was Mariner 10, which flew past three times in 1974 and 1975. The second was Messenger, which orbited for four years from 2011.

Those two missions taught us a great deal about the planet, but they also uncovered mysteries and left many more questions unanswered. Mariner found that Mercury has a magnetic field, which was unexpected – Venus, Mars and the moon don't have them. Earth's field is generated by motions in our liquid outer core, a process similar to the sun's magnetic dynamo, but Mercury's core is thought to have solidified by now.

Messenger spotted those signs of potassium that cast doubt on the big collision theory. It saw what seem to be pools of ice at the centres of craters near Mercury's poles, which probably stay cool because sunlight never reaches the craters' bottoms – although we don't know how the ice got there in the first place. The spacecraft experienced directly just how hot the planet gets, as it had to periodically back away from Mercury just to keep its instruments cool. It also saw strange dips in the ground that don't look like impact craters and don't appear on any other planets we know. And in 2021, an analysis of Messenger images revealed a strange lack of boulders. Rocks more than 5 metres across are about 30 times less abundant on Mercury than on the moon. Perhaps they have been buried by a thicker layer of dust, or broken up by heat or micrometeorites?

Aiming to answer some of these questions and paint a more detailed picture is BepiColombo, a mission by the European Space Agency and Japan Aerospace Exploration Agency. BepiColombo has already made its first fly-bys and will go into orbit in December 2025. The spacecraft will split into two. One orbiter is dedicated to studying the solid planet and its ultra-tenuous atmosphere. The other will study the magnetosphere, the larger area of space within mercury's magnetic field, hopefully helping us work out how Mercury manages to be magnetic at all. ▮

VENUS: THE VEILED ONE

The solar system's second planet is Earth's twisted twin, conducting a masterclass in how not to be habitable.

BY CONTRAST to the paucity of our missions to Mercury, we have visited Venus dozens of times.

Many Venus missions have even put landers onto the planet's surface – although no lander has survived longer than 90 minutes. Venus is even more of a hellhole than Mercury, with surface temperatures averaging more than 460 °C.

It is so hot because of a runaway greenhouse effect. Its thick carbon-dioxide atmosphere traps heat near the surface, and also 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. For some unknown reason, one layer of the atmosphere whips around the planet in only about four days, rotating 60 times faster than the solid planet.

As well as holding its own mysteries, the atmosphere draws a veil over Venus. A thick cloud layer hides the surface, so we have very limited data on what lies below. We don't know whether the planet is still tectonically active, for example. From radar data, we can see that it has what appear to be volcanic landforms: channels carved by lava, plains of volcanic rock and more than 1600 large volcanoes – more than anywhere else in the solar system, although 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 ›

NASA/JPL-CALTECH

Venus is very similar to Earth in size and in basic ingredients, but has a very different environment

knows where the lava came from or where it went after creating the channel. "We don't see a big pile of lava at the end of these channels. We don't see a volcanic mountain or a volcanic crater at the beginning of these channels," says Tracy Gregg at the University at Buffalo in New York. "These channels on Venus have no source, no sink, and yet there they are."

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. Lander findings have hinted that these areas may be rich in silica, like continental crust on Earth. That would imply some complicated geology and chemistry in the past, yet another similarity to Earth.

Venus is Earth's near twin in size and basic ingredients. Early in its history, Venus may even have been pleasant for life, with surface water. Then why is it so different today?

Part of the reason is that the sun has gradually become brighter over the past 4.5 billion years. But the main problem with Venus today is its chokingly dense carbon dioxide atmosphere.

In 2021, Dennis Höning at Free University of Amsterdam in the Netherlands and his colleagues modelled how that atmosphere may have been created. They show that water would have reacted with the CO_2 released into the atmosphere by volcanic eruptions. This would have produced carbonic acid, which would have dissolved silicate rock, helping to capture CO_2 in rocks as carbonates.

On Earth, the process of plate tectonics carries these carbonates back into the planet's mantle, but because Venus lacks plate tectonics, they would have instead continued to build up, getting hotter as they were buried deeper by successive volcanic flows, eventually becoming unstable and releasing CO_2 through cracks in the surface. This would have set off a runaway greenhouse effect, releasing even more CO_2 and resulting in the environment we see on Venus today.

The team's calculations suggest that Venus may have been habitable for about 900 million years, which is much less than some earlier estimates. It could still be long enough for life to evolve, although probably not for complex life to develop.

Could life somehow cling on today, perhaps in the cooler clouds high in the atmosphere? In 2020, astronomers detected phosphine gas, which on Earth is a sign of life. The detection is disputed, and there may well be non-biological chemical processes in the planet's alien atmosphere that we don't yet understand, but the possibility of floating Venusians remains. Future missions, such as NASA's planned DAVINCI+, should provide clearer evidence one way or the other. ∎

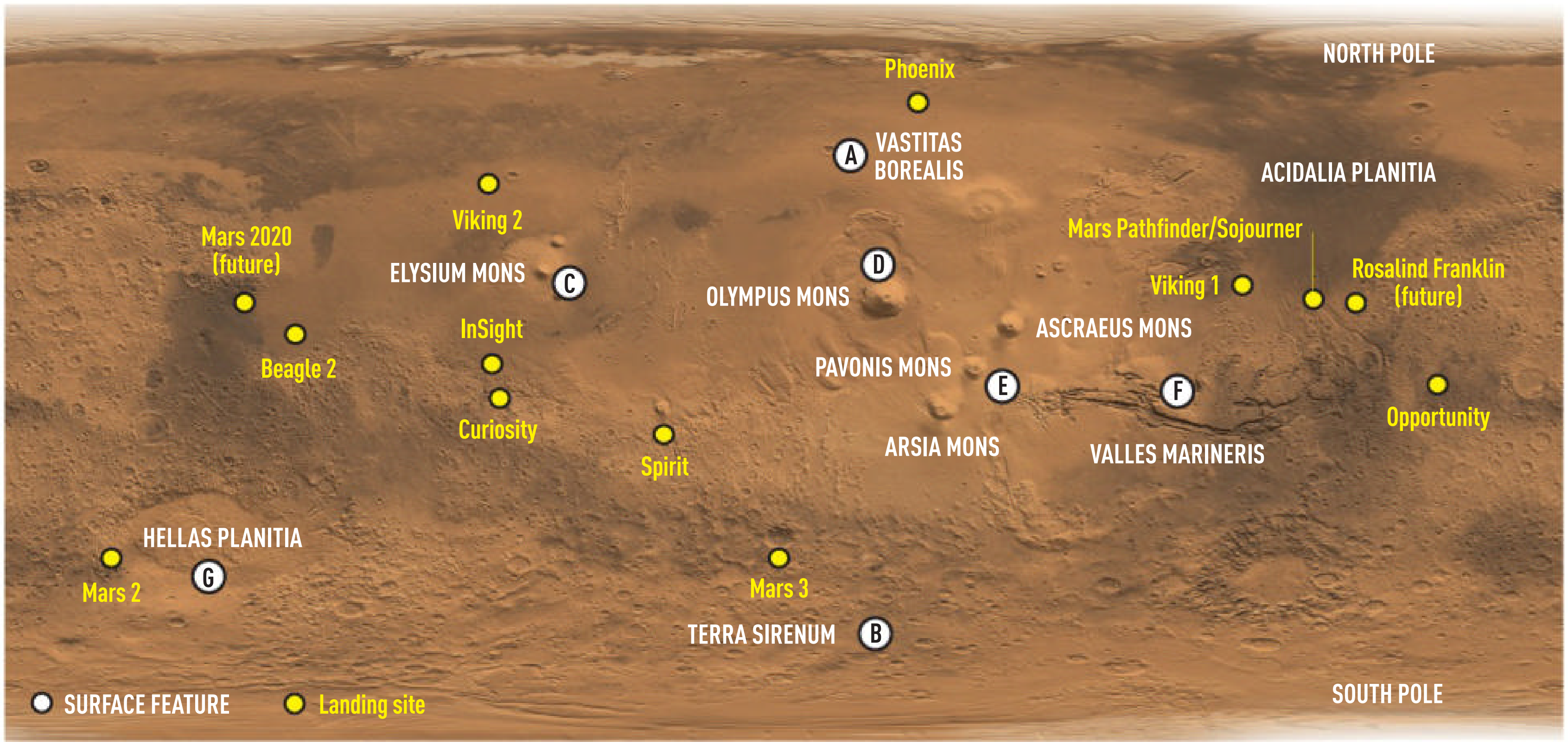
NASA/JPL-CALTECH/MSSS

MARS: HOME FROM HOME?

The Red Planet looms large in our imaginations, a perennial setting for science fiction and the target of media-friendly space missions. Despite its thin atmosphere, sterile soil and icy temperatures, Mars is a relatively hospitable destination. Of all our neighbours, it is the one we can most imagine visiting in person, and perhaps one day even colonising.

QUESTIONS about Mars start with why it is so small. Models of the solar system's formation suggest that it should be between 1.5 and 2 times Earth's mass. Instead, it weighs in at a mere one-tenth the mass of our world. The reason why still isn't understood, but may well be connected with the antics of Jupiter, whose gravity could have scattered much of the material available for planet-building where Mars formed.

Whatever the reason, the diminutive size of Mars gives it its character. Its gravity is too weak to hold onto a thick atmosphere that might have kept the surface cosy and damp. It lacks Earth's big, hot, liquid core, which here generates a magnetic field that shields us from space radiation. There is still plenty of ground to explore, including the highest mountain and the biggest canyon in the solar system. There is even a chance that life clings on today, but perhaps the true fascination of Mars lies in its distant past and near



SOURCE: NASA

A WALK ON MARS

A The northern hemisphere of Mars is dominated by vast and largely featureless plains, such as the Vastitas Borealis. This huge flat area around its north pole is about 4 or 5 kilometres lower than the planet's average elevation.

B Mars's southern hemisphere contains heavily cratered areas like Terra Sirenum. It is a mystery why the northern and southern hemispheres are so starkly different, a characteristic not seen on any other planet.

C Standing almost 13 kilometres high, Elysium Mons is the fourth highest mountain on Mars.

D Olympus Mons is the tallest known mountain in the solar system. Standing nearly 22 kilometres high, it is about two and a half times the height of Mount Everest.

E To the south-east of Olympus Mons are three vast, extinct volcanoes, including Pavonis Mons. Hundreds of kilometres wide, the tallest of them peaks at more than 18 kilometres.

F The Valles Marineris is a huge and intricate system of canyons that is more than 4000 kilometres long and up to 7 kilometres deep. Most scientists think this feature is essentially a crack in the planet's crust, which may have formed through plate tectonics.

G Hellas Planitia is an impact basin 3 kilometres deep. It is thought to have formed about 4 billion years ago when a huge asteroid struck Mars.

future, as a home for ancient aliens, and perhaps for us.

A lot of evidence points towards Mars being wet early in its history. Features that look like rivers and coastlines have been spotted from orbit and by rovers, and many of the planet's minerals contain water. Explaining the presence of this water has been difficult, given that the sun was 30 per cent less luminous at the time – coupled with Mars losing its magnetic field early in its life, leaving the solar wind free to strip away the planet's protective atmosphere.

In 2020, Lujendra Ojha at Rutgers University in New Jersey and his colleagues suggested that water could have been produced and kept as a liquid beneath Mars's surface thanks to geothermal heat, perhaps for hundreds of millions or even billions of years. According to their modelling work, the decay of radioactive elements like uranium, thorium and potassium in the crust and mantle would have generated enough heat to melt the base of some Martian ice sheets. Some of that water may have made its way to the surface.

It may not have been a tropical paradise, though. Frédéric Schmidt at the University of Paris-Saclay in France and his colleagues showed in 2022 that a liquid ocean could have existed with an average water temperature of just below freezing.

Schmidt and his team used a model that simulates how Earth's oceans and atmosphere interact, but changed the parameters to match Mars's ancient environment, such as its atmospheric gas make-up and a lower sun power. As well as a liquid ocean, the model suggests there may have been moderate rainfall along the ocean shores and a largely frozen southern region.

The ancient climate features that the model produced were similar to Earth's billions of years ago, and would have contained some of the key ingredients for microbial life. "If we could travel in time to 3 billion years ago, we could live on this ancient Mars with just a spacesuit for oxygen," says Schmidt. "Pressure, clouds, liquid water, ocean, rain, snow and glaciers: all of them were very similar to Earth today. Only oxygen was missing."

So where did all this water go? The Mars Atmosphere and Volatile Evolution (MAVEN) spacecraft was sent to find the answer. Since its arrival at Mars in 2014, it has been measuring how much atmosphere Mars is losing to space. From that, we can work out how much it had in the past.

The orbiter keeps track of both the activity of the sun and the ions streaming away from the planet's atmosphere to build up an inventory of everything that enters and leaves over time. It also estimates the total loss by measuring the fraction of heavier isotopes of certain atoms versus their lighter counterparts. As the lighter versions are easier to knock out into space with a stray cosmic ray or extra energy from solar photons, a higher fraction of heavy isotopes remaining in Mars's present-day atmosphere means much of the original atmosphere has been lost.

MAVEN focuses on hydrogen and oxygen as ways to trace water and carbon dioxide, and neutral argon as a way to measure the sheer volume of atmosphere loss. Based on measurements of these taken over a full Martian year, the team concludes that about 4 billion years ago, the Red Planet's atmospheric pressure – currently less than 1 per cent of Earth's – was up to 1.5 times what Earth's is today. They also found that it could have had the equivalent of a global ocean between 2 metres and 40 metres deep in its distant past.

The trouble is, that is less water than expected. In 2015, James Head at Brown University, Rhode Island, and Michael Carr at the US Geological Survey estimated that the equivalent of a global ocean a few hundred metres deep was needed to explain all the geological features that look like they were formed by water.

One possible reason for the discrepancy is that the long-held notion of Mars being like Earth in the past is wrong. One theory has it that the planet was actually cold and dry, and that streams and rivers formed underneath the ice pack instead of via water flowing on the surface. The other option is that the water is hidden away somewhere, maybe underground. Dark streaks recently spotted on crater rims that look like they could be liquid water may be fed by underground aquifers, for instance. Such ancient water reserves might be great news for future human exploration. ▮

LIFE ON THE RED PLANET

Samples collected by the recently landed Perseverance rover could bring us clues about life on Mars – and Earth, says Tanja Bosak.

PROFILE
TANJA BOSAK

Geobiologist Tanja Bosak studies the earliest evidence for life in Earth's geological record at the Massachusetts Institute of Technology, an expertise she is now bringing to bear on Mars thanks to the Perseverance rover.

PERSEVERANCE, lowered to the surface from a hovering sky crane in February 2021, is the fifth rover that humans have landed on Mars. It is exploring Jezero crater, once a Martian lake and a fantastic place to hunt for traces of life, with just the right kinds of rocks for preserving fossils. The rover carries 43 sample tubes, to be filled and left for a subsequent mission to collect and launch back into orbit around Mars. The plan is for these to be picked up and returned to Earth as early as 2031.

Why has there been so much excitement about the Perseverance rover?

This is the first opportunity for us to get samples from a really well-understood geologic context on Mars. We picked a site that once had water, and now we have a hope of getting samples that we can investigate in all sorts of ways once they are brought back to Earth.

What is Jezero crater like and why was it selected as the landing site?

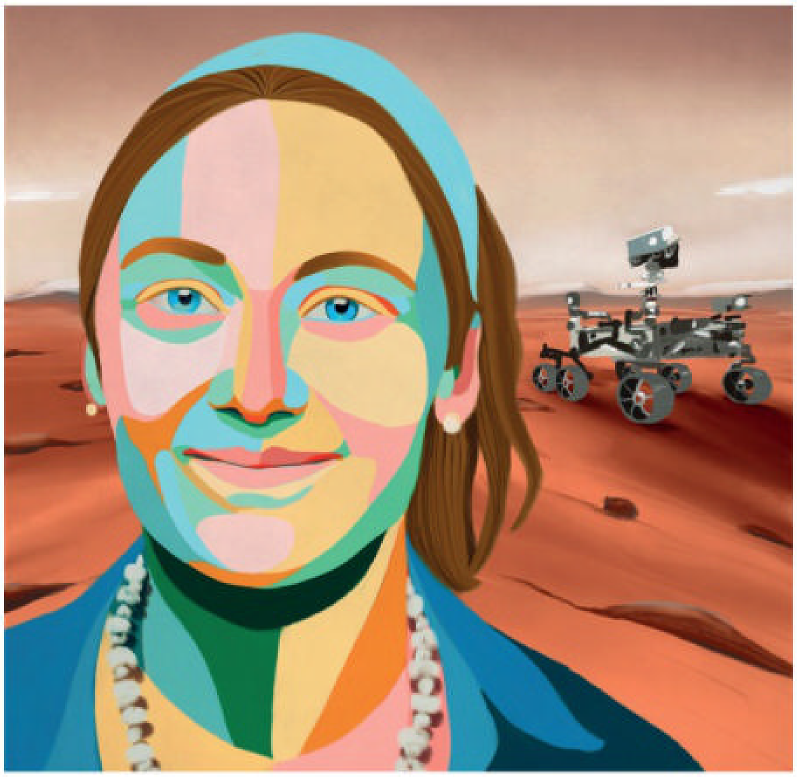
It is a fairly old crater that is heavily pockmarked and was filled with water at one point in Martian history. We know this because there's a surface feature that looks like a terrestrial river delta. Mars orbiters have shown us that there are various minerals present in the crater that could indicate conditions that were favourable for life.

It's these minerals that got people excited about Jezero. There are minerals called carbonates present that are similar to limestone. The stuff on Mars is magnesium carbonate instead of calcium carbonate. If these minerals were once colonised by microbes, they would have assumed certain telltale shapes that we can look for. There are also fine-grained sediments called mudstones that contain a lot of clay minerals. Microbial fossils or traces of organic matter could be buried and preserved in these sorts of sediments over billions of years.

Your job is to select some of these rocks that will be returned to Earth. Tell us about that.

There is a team of 15. Everyone has expertise in different types of samples. Some people date rocks for a living, others look at the records of ancient magnetic fields, some people have experience with meteorites. We need all that expertise to select a set of samples that can address a lot of questions.

The rover has all sorts of instruments we can use to



ROCIO MONTOYA

analyse the composition of the rocks. For example, we can measure the elements that are present, which tells us more about what kinds of rocks we're dealing with. Different rocks serve different purposes – you won't look for life in basalt, because it's an igneous rock and the heat and pressure it has experienced would have eradicated any traces of life. On the other hand, basalts may be an important tool to date the surface.

If we can recognise those telltale shapes related to life left in the carbonate rocks that I mentioned, then those would be great samples to acquire.

If we do find evidence of past life, what would it look like?

Nothing too obvious like a dried-up bone or a bird feather. It would be microscopic. Given that this terrain is so old, we can't hope for anything non-microbial. And if there was life on Mars, it could not have been huge. We don't have microscopes on the rover, so what we do is look for the best types of rocks and environments that could preserve something interesting. Liquid water is necessary for life – that's condition number one – so this is partly why Jezero was selected as the landing site. Then we have to go to the types of minerals that are the best at preserving potential evidence.

What would gold-standard evidence for life look like?

The best-case scenario is that we find a sample of a mudstone, analyse it on Earth and find specific types of organic molecules. Or maybe we hit a patch of clay where a fossil is preserved that looks like an organism we would find on Earth. That would tell us that when there was water on Mars, there was life that looked very similar to life on Earth.

Finding something like this could tell us a lot about the parallel evolution of life. Mars is so close to us, so this would address how different life could be on a nearby planet.

Are you expecting to get a conclusive answer on whether life existed on Mars as a result of Perseverance?

No. Anyone who has looked at fossils on Earth knows that the preservation of fossils or biosignatures is patchy. If we had infinite time and rovers on Mars, we could do a more comprehensive study.

But it's also really exciting to think: what if there was no life? If we see in every single analysis that there's no hint of life on Mars, I think that would be fascinating. I don't expect that to be the case.

Another possibility is that we get some very old samples and see some prebiotic molecules – chemistry that's still learning to become life. To me, that would be even more exciting, because we have no idea of when these sets of molecules learned to be life as we know it, either on Earth or Mars.

Why would finding no evidence of life on Mars be exciting?

It's hard, of course, to demonstrate complete absence of life; you could always argue that maybe we just didn't hit the right outcrop.

But let's say we find nothing even remotely hinting at life. Here we have this lake on Mars, early in its history when we think life was already present on Earth. There was water. There were minerals. If you see absolutely nothing in these conditions even though they are what we think of as habitable, I think that tells us that life needs something more to become widespread.

Beyond Perseverance and its samples, is there more to be done to keep learning about the potential for life on Mars?

There's always another location to go to on Mars. Jezero crater is not the only crater lake on the planet that existed during this time. There are other habitable environments. I think scientists studying Mars after the Perseverance mission will have plenty of choices in the years to come. ∎

HOW TO GET TO MARS

Putting people on Mars is a major goal for NASA – and China, Russia, India and private companies all have their sights set on the planet too. The most important driver for the Mars rush may be prestige, but there also are good scientific motivations. While rovers can do marvellous things, they don't have the dexterity, knowledge or intuition that a human would bring to understanding our nearest neighbour.

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.

The good news is that we don't need to dream up new types of engine or worry about things like sunlight-powered solar sails, which accelerate very slowly. All we need is a big rocket pointed in the right direction. With existing rocket technology, the most plausible trajectory would take about nine months, a little longer than an astronaut's standard six-month stint on the International Space Station (ISS).

Seven types of rocket in operation 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.

Two rockets in development, NASA's Space Launch System (SLS) and SpaceX's Big Falcon Rocket (BFR), are planned to be 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.

And we could always lighten the load by sending some equipment ahead of the humans.

Then comes the hard part. 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. Part of the solution will be to take 3D printers that can produce parts on demand.

Stocking the medicine cabinet is more tricky. Germs can thrive in spacecraft, and bacteria growing in simulated microgravity can develop resistance to

EUROPEAN SPACE AGENCY/SPL

Astronauts on an excursion from their habitat during Mars500, a simulated mission to the Red Planet

a broad-spectrum antibiotic. There are projects in the works to mitigate this, including antibacterial coatings for surfaces that might get dirty, like toilet doors. 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.

As well as missing Earth's gravity, astronauts won't be shielded by its magnetic field, which diverts harmful cosmic radiation. Astronauts on a Mars mission would hit 60 per cent of NASA's exposure limit on the shortest possible return journey, without taking into account time on the surface. And being so far from Earth – far enough that home becomes just another point of light in the sky – could be psychologically challenging.

On the way to Mars, nobody can quit the team and nobody can be added. The handful of people on board will need all the skills essential to keeping the mission alive – and they will have to get on. The crew will have to learn to deal with each other's personality quirks to defuse even small interpersonal conflicts.

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 so thin, with less than 1 per cent of the pressure on Earth. This means that parachutes don't create anything like as much drag. We could use boosters to slow down, like the Apollo astronauts on the moon. But because gravity on Mars is stronger than that on the moon, we would need a lot more boosters. Some combination of drag and boosters is probably the answer. NASA is testing Hypersonic Inflatable Aerodynamic Decelerators, a series of landing devices that use fabric to form a blow-up structure that is more rigid than a parachute and so creates more drag.

When we have worked out how to land, the question is where. A site near either of the poles would seem the obvious choice, with underground water ice and possibly liquid water, a crucial resource. Humans use a lot of water, and many proposed missions involve using water to make rocket fuel to get the explorers home. But the poles get as cold as -195°C and are prone to storms that make landing even harder.
The equatorial region mostly stays above -100°C and can reach 20°C. It has more sunlight that astronauts

Frigid temperatures and low pressures make life on Mars incredibly challenging. Plus, the years really drag

	EARTH	MARS
Average surface temperature	13°C	-62°C
Year length	365 Earth days	687 Earth days
Day length	23.56 hours	24.37 hours
Gravity	9.8 ms^{-2}	3.8 ms^{-2}
Atmospheric pressure	1 bar	0.006 bar
Solar flux	1000 W/m^2	593 W/m^2

3389 km radius

6371 km radius

could harvest for solar power, rarely gets storms and has all sorts of interesting terrain to explore, but doesn't seem to have much, if any, accessible water. The first missions may choose 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 gnawing cold, there is the constant risk of being hit by micrometeorites. Then there is the radiation from space. And with so little atmosphere, the pressure is incredibly low, almost akin to deep space (see diagram, above). NASA is running a competition to design 3D-printed habitats. Some entries use pieces of the landing craft in their design. Other building materials should ideally use stuff already on the surface, such as bricks of compressed soil for building igloo-like shelters.

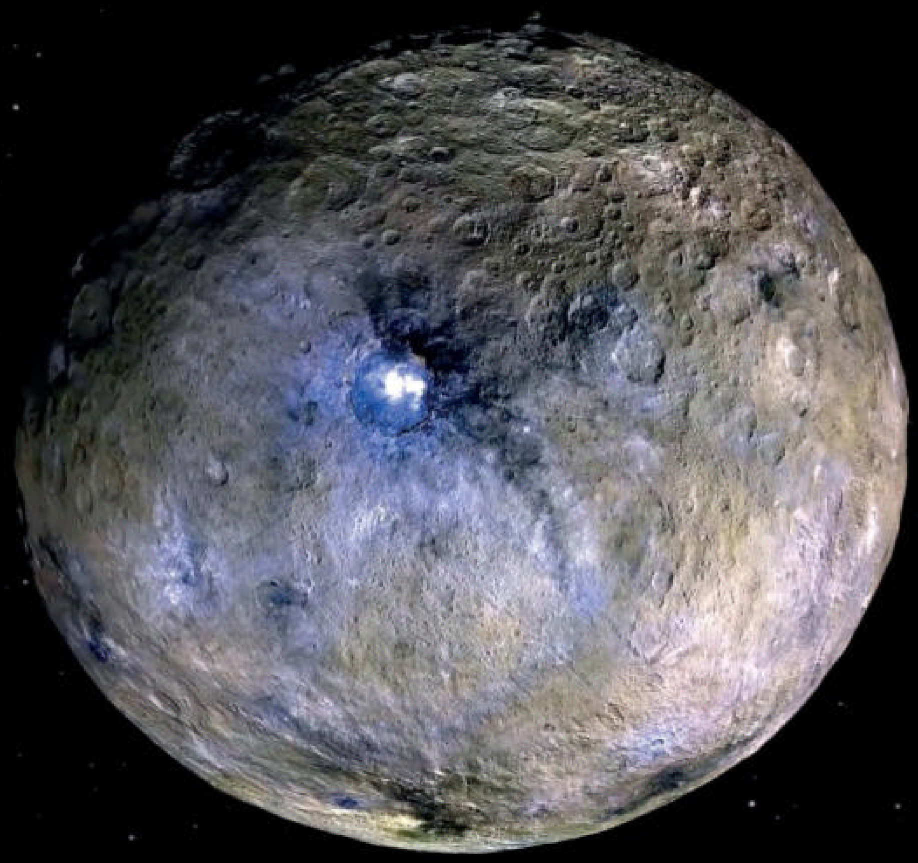
Martian rock could be a natural radiation shield. One proposal sees humans setting up their habitats in the cylindrical caves created by ancient lava flows. We have seen the entrances to such caves on Mars in satellite images and studied similar structures here. On Earth, these caves are generally about 30 metres wide, but 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. 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 isn't as 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 is no guarantee that it will be safe to drink. Even if it is, it will be full of fine dust. So the astronauts will have to bring sophisticated filtration systems.

Spacesuits, too, 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.

Some people may be hoping that we will settle permanently in the long term. But all serious existing mission plans involve bringing the explorers back. This means another launch, another nine-month journey, another landing. Luckily, it will be easier the second time. Mars's thin atmosphere and its weaker gravity mean getting into space won't be as tough. Then 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 poke 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. ∎



The large asteroid Ceres, measuring around 1000km wide, is much more than a lump of rock

CERES: QUEEN OF THE ASTEROIDS

Beyond Mars lie the asteroids – a huge diffuse belt of rocky material left over from the formation of the solar system. It is estimated that there are some 1.9 million asteroids in the asteroid belt larger than 1 kilometre across. Ceres, around 1000 kilometres across, is the greatest among them. Owing to the quirks of planetary classification, it also has the distinction (for now) of being the solar system's smallest recognised dwarf planet.

→ **See page 79 for more on the dwarf planet controversy**

Ceres was once thought to be a dead and static rock, but when NASA's Dawn spacecraft orbited it between 2015 and 2018, it found an active and curious little world. In 2015, it beamed back pictures of a mountain called Ahuna Mons, with bright streaks running down its sides that looked suspiciously like lava. Apparently even this mini world has a volcano.

We now know it has dozens of them. The lava coming out of these cryovolcanoes isn't molten rock, but muddy brine. When active, the cryovolcanoes of Ceres collectively splurge out an average of 10,000 cubic metres of the stuff a year. We don't yet have a clear idea what could be powering these eruptions, but according to a growing body of evidence, they may be fed by an underground ocean.

In its final phase, the spacecraft orbited just 35 kilometres above the surface of Ceres, focusing on the 20-million-year-old Occator crater. Earlier observations of bright deposits on the crater had hinted at the presence of salty water underneath. The new high-resolution images showed the spectral signature of hydrated sodium chloride, a salt that could lower the freezing point of water enough to allow it to remain liquid at the kind of temperatures within Ceres. Impact fractures on the surface of the Occator crater also suggest the presence of an ocean, some 40 kilometres below the surface.

Even the arctic surface of Ceres may have a water cycle. On the steep wall of Juling crater in Ceres's southern hemisphere, Dawn saw ice spreading in the height of summer. During summer days on Ceres, sunlight hits the bottom of the crater, but the wall remains mostly shrouded in cold shadows.

The spreading ice cover could be due to a combination of two effects: small landslides revealing ice from behind a layer of dust, and ice in areas that aren't usually sunlit getting heated up enough to sublimate into the air. The water vapour produced would then condense on the cool, shadowed wall.

NASA/JPL-CALTECH/UCLA/MPS/DLR/IDA


ARIZONA STATE UNIVERSITY

MISSION TO A METAL WORLD

Lindy Elkins-Tanton is leading a mission to the asteroid Psyche – a metal world that could reveal what lies at the core of our own.

PROFILE
LINDY ELKINS-TANTON

Planetary scientist Lindy Elkins-Tanton is the director of Arizona State University's School of Earth and Space Exploration, and only the second woman to lead a NASA deep-space mission.

Why go to Psyche?
We want to learn about how Earth formed, but we can't get to the core to test our ideas, so we are going to a metal world. It is the only place in the solar system where we can directly observe a planetary core.

How do you know Psyche is metal?
We're pretty darn sure from its radar albedo: a very high percentage of radar is reflected back by Psyche compared with other asteroids. We also know from how quickly it heats and cools – its thermal inertia is four times higher than any other asteroid. So it really seems to be largely metal, if not completely metal. We think it's the result of a planetesimal being hit over and over again as the solar system formed, leaving only its core.

When the Psyche spacecraft arrives there in 2026, how will you tell whether the asteroid is a core or something else?
We've got a lot of predictions for what it will look like if it's a core. To investigate, Psyche spacecraft will have an imager and a magnetometer, and we'll do an experiment to measure exactly how gravity varies around the asteroid's surface, which will reveal composition and structure. But the key instrument is the gamma ray and neutron spectrometer, which will tell us the elemental composition of the surface. Based on the metal meteorites that fall to Earth, we think it's mainly iron and nickel, and that's what we think Earth's core is too. But it has lots of goodies mixed in, which is what makes the asteroid miners excited.

The metal-rich asteroid Psyche could hold answers as to how Earth formed

The asteroid miners?

At this point, I have to say: "NASA reminds me this mission is about fundamental science and nothing to do with asteroid resources." That said, Psyche is mainly iron and nickel, but we also expect silver, gold, palladium, iridium and copper.

So the asteroid would be worth a lot?

I calculated it for fun, and in the metals market of January 2017, it would have been worth 10 quintillion dollars. That's a 1 followed by 19 zeros – a large multiple of Earth's gross domestic product, which is in the region of $100 trillion. But of course it's an irrelevant number because (a) if you brought it to Earth, it wouldn't be worth that any more, and (b) there's no way to bring it to Earth. It's complete fantasy.

Nevertheless, people want to exploit the resources in asteroids, right?

We don't have an Elon Musk for asteroid mining, and there is no significant technology for it yet, but there's a huge amount of interest and a number of companies working on it, so I'm sure it will happen.

How did you get into all this?

I actually wanted to be a veterinarian until I realised that animals hate veterinarians. Even at college I wasn't sure if I wanted to study biology or Earth science. And I didn't have the confidence to go for a PhD, so I went into business. Then I got married, had my son, then separated from my husband and became a math teacher. At 31, I decided to go back to get my PhD. I was a single mother and my son started kindergarten at the same time.

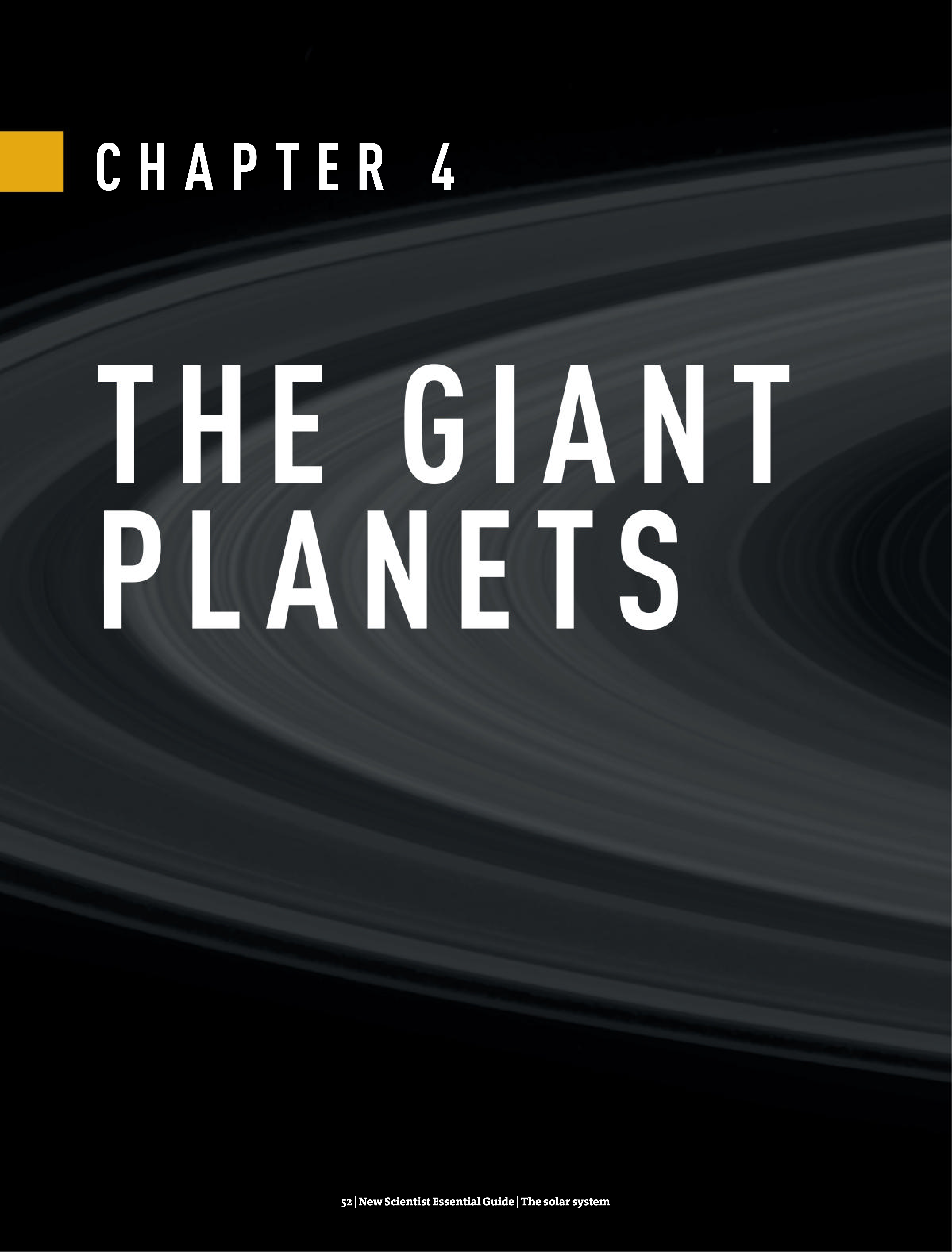
You are basically the J.K. Rowling of planetary science.

I guess! So in grad school, I studied half Earth and half the moon. I studied return samples from the Apollo missions, which I just adored. I made a model of how a magma ocean could freeze and that launched me into planetary science.

And, ultimately, planetary politics. Tell us about the Interplanetary Initiative that you started with Arizona State University president Michael Crow.

It's an effort to shape our future in space. I believe we're going to do a lot more space exploration, because it's human nature to explore and space is the place to go. The sheer fact that we can do it is miraculous. And the thing about space exploration is that it's almost uniquely inspiring to people – an illustration of an integrated society trying to do better. That was the great pull of *Star Trek*.

What happens when, on Mars, there's an Elon Musk settlement right next to a settlement from China? Do they become the best allies to help each other survive, or does their allegiance remain to entities back on Earth, at least 7 radio-minutes away? Can we figure out a better set of legal and social norms to go into the future with? I think we can. ∎



CHAPTER 4

THE GIANT PLANETS

Beyond the asteroid belt, four heavyweight planets reign. Unimaginably deep oceans of gas conceal their mysterious interiors, where strange states of matter may lurk.

Their powerful gravity has remodelled the solar system. Like the classical gods whose names they bear, they have both nurtured and toyed with life on Earth.

And the giants are surrounded by a panoply of fascinating moons. These solid, approachable little worlds have a remarkable diversity – and perhaps their own alien inhabitants.

JUPITER: THE RULER

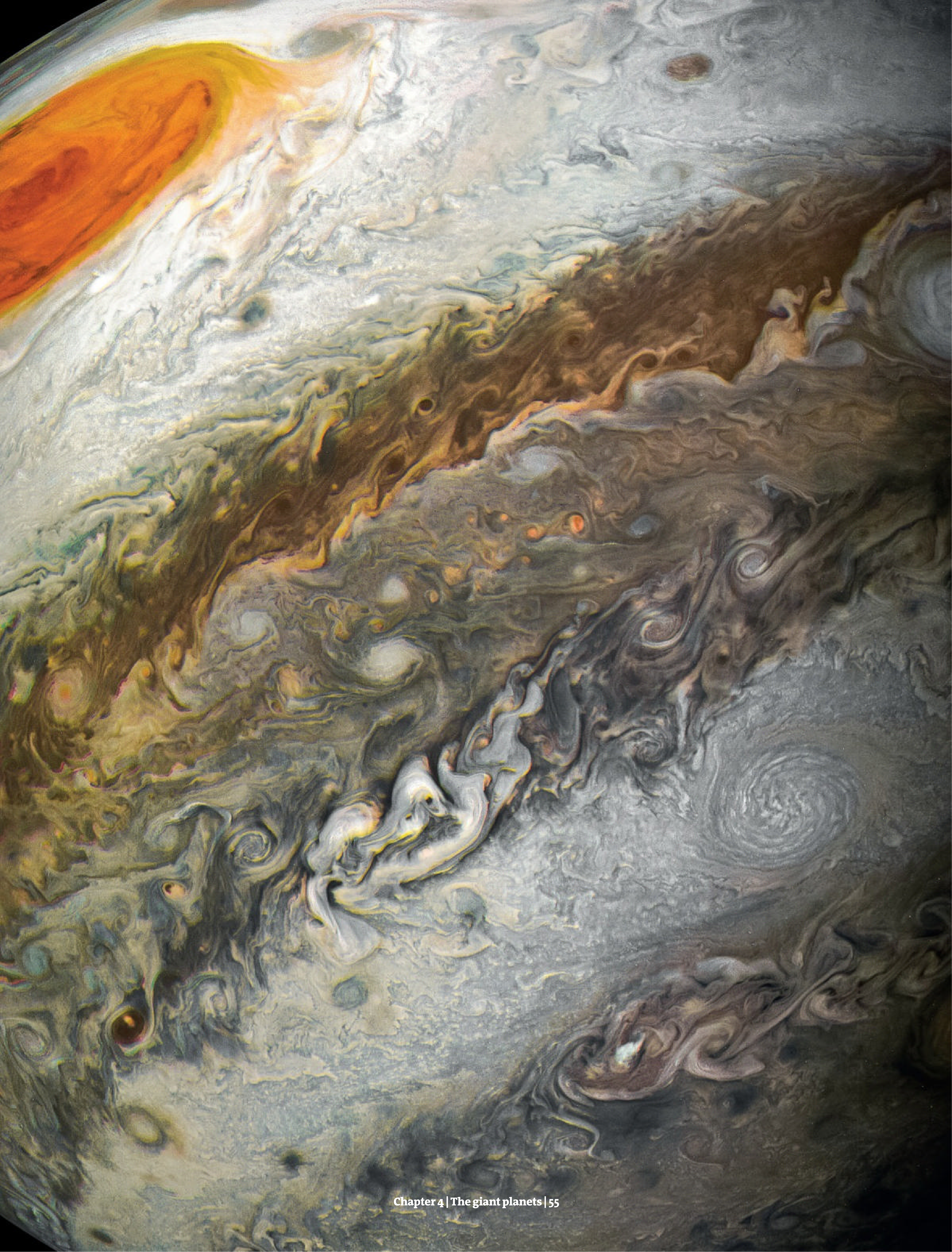
The biggest planet in the solar system, Jupiter's movements governed how our planetary neighbourhood formed, and might even be responsible for life on Earth. Its moons are worlds of superlatives, including the largest in the solar system, the most volcanically active and the one perhaps most likely to hold the solar system's second cradle of life.

NASA/JPL-CALTECH/SWRI/MSSS/KEVIN M. GILL

NEAR Jupiter's equator, a storm larger than all of Earth rages. Even the smaller hurricanes surrounding it are the size of planets. Dive into them and you will be bombarded with water and foul-smelling ammonia, and lower down frigid liquid hydrogen. Descend even further towards this planet's centre, and you may never find it. That isn't just because you will be dead from the heat or crushing pressure, but also because a distinct core might not exist at all.

Jupiter is named after the mightiest of the Roman gods for good reason. More than 140,000 kilometres across, it is about 11 times Earth's diameter and a tenth that of the sun. It seems unusual in comparison to planets orbiting other stars, too. Although we have found many bigger exoplanets, few are both this big and so far out from their stars.

But then Jupiter has always offended established norms. 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 hot water with the religious authorities of his day. They didn't know the half of it. At last count, Jupiter has 79 moons, more than any other planet. But the four original moons – Io, Europa, Ganymede and Callisto – remain the



> **"Jupiter's adventures are thought to explain a number of planetary mysteries"**

showstoppers (see "The Galilean moons", page 58).

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 distinctive feature: the Great Red Spot, a vast storm that has raged since at least 1830.

In 1995, NASA's Galileo mission 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 is concerned, the deepest insights came from a probe that the spacecraft dropped into Jupiter's atmosphere on 7 December 1995. Reaching an entry speed of more than 170,000 kilometres per hour, it sent data for 57 minutes, detecting winds of up to 500 km/h, a strange absence of lightning compared with similar storms on Earth and evidence that the energy driving the atmospheric convulsions was heat welling up from its interior. A big surprise was that Jupiter's atmosphere seemed to hold far less water than we expected for a body at this position in the solar system – although it might have been that the Galileo observations were just made at a particularly dry spot.

With its fuel running low, in 2003, the Galileo probe was sent to plunge into Jupiter's atmosphere and burn up. Since then, however, developments have only increased the planet's intrigue – leading us to the idea that its origin and early history are of huge significance not just for understanding it, but also the wider history of the solar system.

One thing we do think we know about Jupiter is it was the firstborn of the solar system planets. According to the leading theory, within a million years after the birth of the sun, dust and small rocks gathered to form a small rocky seed. Over the following few million years, it grew bigger and grabbed hold of surrounding gas to build the swirling giant that we know today, consisting mainly of hydrogen and helium.

But that isn't where the story ended. Jupiter's continuing adventures are thought to explain some planetary mysteries. 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 current size and distribution of the planets 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.

A scenario known as the grand tack postulates that once Jupiter had grown beyond a certain size, increased friction with surrounding dust and gas 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. This is our best guess for why Mars ended up so small. Jupiter itself was saved from crashing into the sun only by the slightly later formation of Saturn, the solar system's second, marginally smaller, giant: its increasing gravity steered Jupiter away from the brink.

To explain Uranus and Neptune, we need a second hypothesis. According to the Nice model, they probably formed closer to the sun than they are now, near Saturn's current orbit. Then, about 4 billion years ago, Jupiter and Saturn began a fateful dance known as an orbital resonance, as their orbital periods hit a 1:2 ratio. It meant that repeated small gravitational influences between the two could build up, rather than randomly cancelling out. This destabilised the orbits of all the giants, eventually pushing Neptune and Uranus outwards. 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 from which lonesome cometary travellers occasionally reach us.

→ See chapter 5 for more on the outer realms of the solar system

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 have Jupiter to thank for our own lives.

The latest mission to visit our giant benefactor is NASA's probe Juno – short for Jupiter Near-polar Orbiter, and also the name of Jupiter's wife in Roman mythology – which entered orbit around the planet in July 2016. Its instruments include cameras to take pictures of the planet at optical, infrared, ultraviolet and microwave wavelengths, and so better determine the composition of its atmosphere, plus devices to measure its magnetic and gravitational fields, providing insights into what is going on beneath the clouds. Passing over the Great Red Spot, for example, Juno's measurements have shown that the storm has roots extending around 500 kilometres down into the atmosphere.

Juno has been looping over the planet's poles on an orbit that lets it survey as much of the planet from as many angles as possible. It soon came up with surprises. The first ever pictures of Jupiter's poles revealed strange cyclones: nine in the north, with eight in a circle around one in the middle: and six in the south in a similar configuration. Why do these storms form in such odd, organised rings?

Galileo's measurements had led us to believe that Jupiter's innards were neatly arranged in layers. A shallow "crust" of liquid hydrogen lies above a much deeper layer of liquid metallic hydrogen, formed by pressures millions of times the atmospheric pressure at sea level on Earth coupled with temperatures of thousands of degrees. It is probably shiny like liquid metallic mercury, and heavier elements would dissolve into it. It was expected that below all this, about 70,000 kilometres down, would be a small solid core.

But not according to Juno. Scientists have been using the spacecraft to probe Jupiter's gravitational field by measuring its orbital motion very accurately. This now points to a large, ill-defined, fuzzy core where heavy elements mingle with the metallic hydrogen above. This could be due to a more gradual growth of the young planet, or a massive impact that disrupted the original compact core... or something completely different. ∎

THE GALILEAN MOONS

The four "Galilean" moons of Jupiter are among the largest non-planetary bodies in the solar system (figures in diagrams are diameters).

GANYMEDE

Diameter – 5268 km
Distance from Jupiter – 1,070,000 km

All four of Jupiter's Galilean moons are big and round enough that they would be at least dwarf planets if they were orbiting the sun. Ganymede is the biggest of all, outsizing even the planet Mercury.

As with Earth, but uniquely for a solar system moon, Ganymede has a strong field, generated by an internal dynamo in a liquid iron core. Its magnetism even creates a visible aurora. The Hubble Space Telescope has shown that Ganymede's aurora is modulated by yet another magnetic field, and the best guess is that this comes from a briny, electrically conducting subsurface ocean. Models suggest that there could be several such oceans in concentric layers sandwiched between shells of rock.

CALLISTO

Diameter – 4821 km
Distance from Jupiter – 1,880,000 km

At first glance, Ganymede and Callisto seem like twins transplanted to different neighbourhoods. They are around the same size and have a similar roughly cratered outward appearance, with prominent darker patches. Gravitational and magnetic measurements suggest that inside both is a roughly 50:50 mix of rock and ice.

But appearances deceive. While we reckon that Ganymede's interior is regularly layered, this doesn't seem to be the case for Callisto. Both moons probably formed when smaller bits of debris collided, but whether because of the circumstances of its formation or its subsequent history, Callisto, now in a frigid outer orbit, was just never warm enough for its ice to melt. Unlike Ganymede, then, its denser bits could never fall to its centre – and it remains a mixed-up body to this day.

Ganymede
5268 km

Titan
5150 km

Saturn's largest moon

Mercury
4879 km

Smallest planet

Callisto
4821 km

IO

Diameter – 3643 km
Distance from Jupiter – 421,700 km

Io might almost be a home from home. While most moons in the outer solar system consist principally of frozen ices, Io, like Earth, is mainly silicate rock, surrounding a molten core largely of iron. It is the densest moon in the solar system.

In stark contrast to our own dead moon, Io is volcanically the most busy world in the solar system. More than 400 active volcanoes dot a surface riven by earthquakes and lava flows. They create a strange, variegated face that looks rather like the top of a pizza.

Unlike Earth, Io has no internal heat source to drive it. Instead, it is engaged in a stately dance with Europa and Ganymede. The moon orbits Jupiter exactly twice as fast as Europa further out, while Europa travels twice as fast as the even more distant Ganymede. This orbital resonance teases Io's orbit into a slightly elliptical shape, resulting in huge tidal forces as Io approaches and recedes from Jupiter every 12 hours – forces that stretch and squeeze the moon's dense, molten core, heating it up.

On 21 December 2018, Juno saw a dramatic close-up confirmation of Io's activity. It captured pictures of the moon as it entered the shadow of Jupiter, but was softly illuminated by light reflecting off Europa. The images revealed a volcanic plume in action, shooting material off its surface.

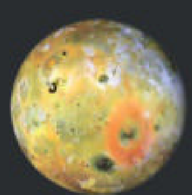
EUROPA

Diameter – 3122 km
Distance from Jupiter – 671,000 km

The passing glances that the Voyager probes cast at Jupiter and its moons in the late 1970s convinced us Europa was special. Its perfectly smooth surface, with no craters or mountains, is in stark contrast to the pitted visages of other moons. Complex, streaky patterns indicate a surface that is continually fractured and then filled with materials from inside.

Our best educated guess is that Europa has an outer crust of ice, with silicate rock beneath it and a possible iron core. The real excitement lies in the fact that – like Io, but to a lesser degree – Europa is warmed by its gravitational interaction with Jupiter and the other moons, probably enough to maintain a liquid water ocean beneath the icy crust. It is far from alone – we keep finding hidden oceans among the solar system's outer moons (see page 62 later in this chapter) – but it may be among the most hospitable for life.

Io
3643 km



Earth's moon
3474 km

Europa
3122 km

Pluto
2377 km

Largest
dwarf planet

SATURN: THE RINGMASTER

Saturn is perhaps the most glamorous of all the known planets, thanks to its spectacular ring system and its menagerie of extraordinary moons.

ALTHOUGH the other giant planets of the solar system also have rings, they are just faint traces of dust compared with Saturn's magnificent regalia. Pictures collected by the Voyager probes when they flew past in 1980 and 1981 revealed around 10,000 separate rings, each a cloud of particles confined to a narrow orbit. The Cassini probe, which orbited the Saturn system for 13 years until 2017, revealed the number of rings to be in the millions. And they are complex and dynamic – Cassini's images revealed clumps, holes, gaps and other structures.

The rings probably formed when a moon or comet came too close to Saturn and was ripped apart by gravitational forces. A long-running theory is that this was early in the solar system's history, and that the rings have gradually spread since then, perhaps forming moons in the process. But Cassini's measurements suggest otherwise. It found that Saturn's rings are lightweight, with a total mass of about 15 billion billion kilograms, only around 0.02 per cent that of Earth's moon. At the same time, the rings remain almost pure ice, despite a gentle rain of dust falling into them. This implies that they are relatively young, probably forming just 10 million to 100 million years ago. We may simply be very lucky to see Saturn with a temporary coronet. Or maybe the rings go through cycles: moons collide, forming new rings that coalesce into new moons, which eventually collide again.

Saturn itself is all the more enigmatic since Cassini. For example, the spacecraft tracked Saturn's giant hurricanes, 4000 kilometres across. While hurricanes on Earth are powered by heat released from warm ocean surfaces, there is nothing like that on Saturn, so what fuels its storms is unknown. At Saturn's north pole, one of these storms is surrounded by a striking hexagonal cloud pattern almost 25,000 kilometres wide, rotating once every 10 and a half hours. The hexagon was barely glimpsed by the Voyagers, but revealed in all its glory by Cassini – and it even changed colour from blue to golden while Cassini was orbiting. In 2019, Cassini's gravity measurements showed that the winds blowing around Saturn's equator extend much deeper into the planet's lower atmosphere than on Jupiter and far deeper than we thought, 9000 kilometres below the cloud tops.

Deeper still, something strange seems to be going on, according to research on the spiral-shaped waves that ruffle Saturn's rings. Some of these waves spiral inwards, and researchers think that they are the gravitational echo of vibrations inside the planet. But the pattern of these waves doesn't fit straightforward models of Saturn's interior, supposed to be a smooth mixture of hydrogen and helium. These anomalous waves may be pointing to an unexpected structure, possibly huge vortices deep inside the planet, or a layer where molecules of hydrogen and helium break up into separate atoms, which would make the mixture relatively transparent – a luminous sphere likely to vibrate differently.

But intriguing though it is, Saturn is overshadowed by its moons. These aren't the bland, cratered ice balls once imagined. The two stars among them are Titan and Enceladus, but even the supporting cast are multi-talented.

→ Pages 62 and 66 cover Enceladus and Titan in more detail

NASA/JPL-CALTECH/SPACE SCIENCE INSTITUTE

Saturn's moon Mimas appears near Saturn, dwarfed by its parent planet in this image

Take Hyperion, which tumbles chaotically in orbit. Subject of an early fly-by 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. Its dark zones look lower than its light-coloured ridges, perhaps because they absorb more sunlight, causing ice below them to evaporate and the dark layer to sink down.

At first glance, the equatorial ridge girdling Iapetus makes it look a bit like a walnut, or a badly moulded rubber ball. A Cassini fly-by 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, but how this happened is still unknown. Iapetus is oddly two-toned, with a darker leading edge. It is thought that this started out when Iapetus swept up some dark material in its orbit – one face always leading as the moon is tidally locked to Saturn. Since then, the dark face has absorbed more sunlight, warming it slightly, so ice tends to sublimate from that face and then freeze out on the bright, cold, trailing hemisphere.

At 396 kilometres in diameter, Mimas is the smallest known rounded body in the solar system. One side is dominated by the 130-kilometre Herschel crater with walls 5 kilometres high, which makes Mimas look eerily like the planet-destroying Death Star of *Star Wars*. It is, however, extremely vulnerable: cracks on its opposite side show that the impact that created Herschel nearly shattered the moon. And recent analysis even hints at an ocean within this little moon.

The innermost moons are especially small moons known as moonlets, and are again strange in different ways: super-smooth egg-shaped Methone, ravioli-shaped Pan and Atlas, cigar-shaped Prometheus.

Pan orbits in a gap in Saturn's A ring, the outermost of the large, bright rings. Loose material is piled up 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.

One theory is that the loose stuff is ring material that has piled up. The size of these skirts may be limited by a gravitational tug of war between them and Saturn: if ring particles pile too high on a moon's equator, the planet's gravity hauls them off again. Or Saturn's ridged moons may have got their weird shapes from a moonlet demolition derby. Simulations from 2018 show that when two moonlets hit each other head-on at low speeds, they form flattened ravioli shapes like Pan and Atlas. When they strike more of a glancing blow before merging, they end up elongated like Prometheus. About 20 to 50 per cent of the collisions resulted in ravioli or cigar shapes – which fits because about half of Saturn's moonlets have those shapes. ∎

HIDDEN OCEANS

Once we thought Earth was unique in bearing both life and liquid water. Now we find salty seas all over the outer solar system. These are the most promising places to look for alien life, and perhaps for our own origins.

THE importance of finding life beyond Earth cannot be overstated. To find it elsewhere in our solar system would surely mean it is widespread throughout the entire galaxy. It would allow us to study the chemical composition of life, and perhaps find out whether it must be based on DNA, or even on carbon chemistry.

→ Page 91 has more on the search for life beyond our solar system

Just 40 years ago, we never would have suspected that the secrets of how life formed on Earth, and whether it exists elsewhere, may lie in the icy moons of the outer solar system. Then came two seemingly unconnected events in 1977.

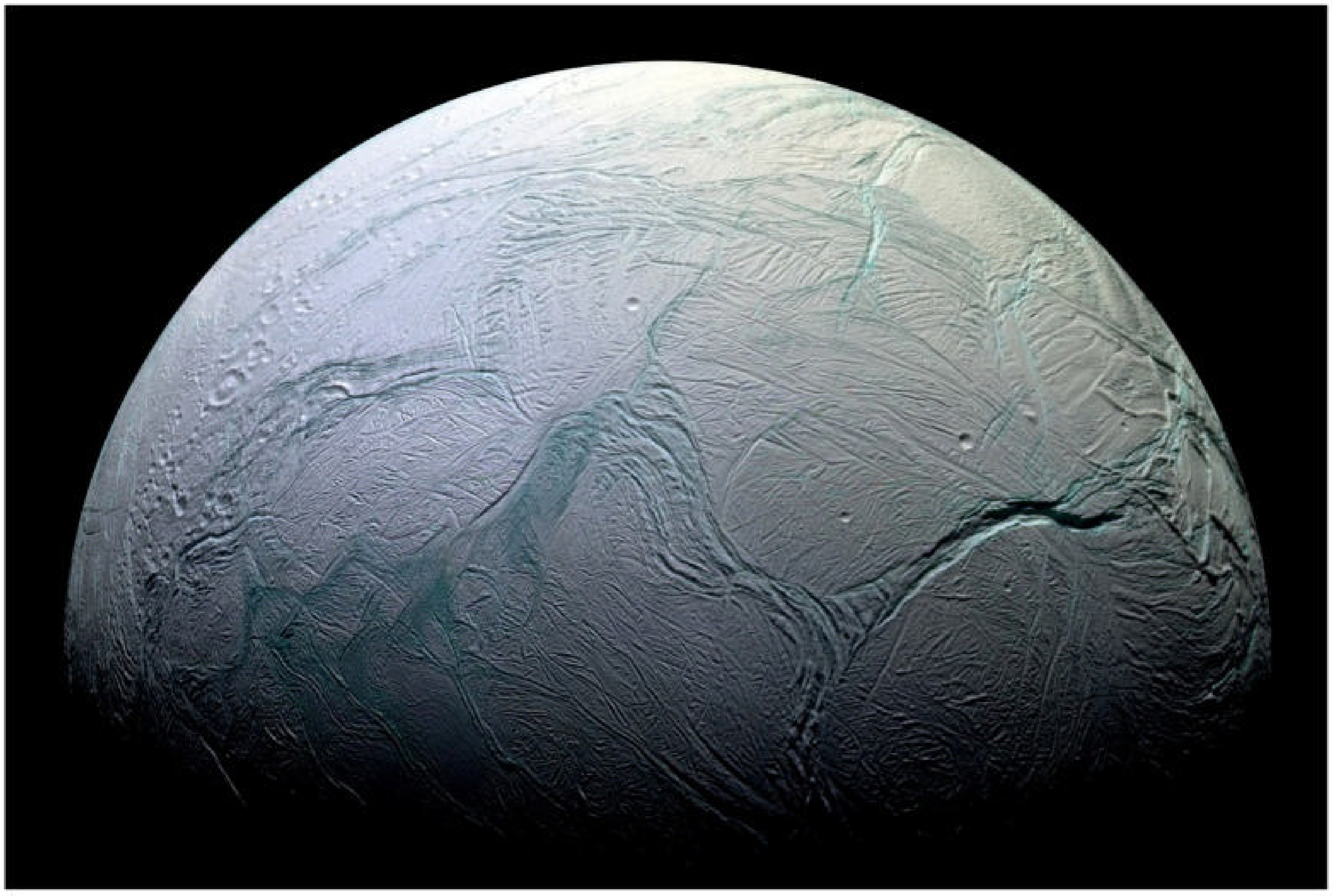
Off the Galapagos Islands, oceanographers Jack Corliss at Oregon State University and Tjeerd van Andel at Stanford University in California travelled to the sea floor in Alvin, the submersible best known for exploring the wreck of the Titanic. They were looking for hydrothermal vents, which jet warm water out from beneath the seabed into the cold ocean. They found these "black smokers" – so-called for the colour of the minerals that precipitate out of the hot water – and an extraordinary abundance of life around them. Corliss and others concluded that black smokers or other types of hydrothermal vents could have been the backdrop for the origin of life.

The same year, NASA launched Voyagers 1 and 2, our first multi-instrument, deep-space probes able to build a comprehensive picture of distant worlds. They gave us the first signs that some outer moons, such as Jupiter's Europa, hold both hidden oceans and organic molecules.

→ See page 72 for a graphical timeline of missions to the outer solar system

Excitement built further when the Galileo probe reached Jupiter late in 1995. It showed huge cracks in Europa's icy surface and areas where the ice blocks had moved, as if transported by currents in a subsurface ocean. Readings from Galileo's magnetometer revealed that a churning saltwater system encircled the whole moon. This ocean probably contains more water than Earth, and must be powered by a heat source at Europa's centre. That gives rise to the hope of hydrothermal vents on the seafloor, perhaps another site where life could have begun.

A new NASA mission, Europa Clipper, is due to be launched in 2024 and should start making a series of close fly-bys in 2030. It will aim to get a better idea of the key ingredients for life – water, chemistry and energy supply – for example measuring how deep



NASA/JPL/CALTECH

Molecules linked to life have been seen rising from Saturn's moon Enceladus

the ocean is and how far it is under the ice crust, what surface chemicals are generated by Jupiter's radiation and how those might be carried down to the ocean. A European Space Agency mission called s is due for launch in 2023. It will dive close to Europa and then enter orbit around Ganymede, which is also thought to have a hidden ocean or oceans.

A much smaller moon, twice as far from the sun, could be just as promising for life as Europa. Saturn's Enceladus is only 500 kilometres across and researchers had expected it to be frozen solid. But on an early fly-by in February 2005, Cassini's magnetometer saw something unusual in the magnetic field around Enceladus. A later pass showed that the south pole was much warmer than expected and was spouting plumes of salty water into space. These plumes had caused a telltale magnetic deflection.

The source of heat is tidal distortion, due to another orbital resonance. Enceladus circles Saturn twice for each orbit of the larger moon Dione, which allows Dione's gravity to stretch out the orbit of Enceladus so Saturn's gravity squeezes and stretches it. What surprised planetary scientists was just how much heat this generates – enough to melt ice and eject jets of water from large fracture zones near the moon's south pole. Some of this material ends up orbiting Saturn, forming its diffuse E ring.

Cassini measured the composition of these jets, detecting raw materials for life including salt, water, carbon dioxide and methane, as well as hydrogen, an ideal energy source for life. Silica found in the jets can be produced only in water close to boiling point, indicating that there are hydrothermal vents in the subsurface ocean.

Further analysis in 2018 found evidence for large, complex organic molecules made of carbon, hydrogen, and nitrogen, with masses more than 200 atomic mass units. The structures of these molecules – chains and rings of carbon atoms – indicate that they are actually fragments of even bigger compounds. Researchers suspect that after being produced at Enceladus's rocky core, the compounds hitch a ride on rising gas bubbles to form a rich organic film on the ocean's surface. Molecules this big and complicated could have been produced by life... or simply from rock interacting with hot water in Enceladus's core. Even then, they might be an important ingredient in the development of life.

Oceans are probably lurking beneath the shells of many more icy worlds, such as Titan, Triton, Mimas and Ceres. They, too, may foster life-friendly conditions. Perhaps oceans concealed by frozen crusts are the most common sites for life, while our blue planet, with its peculiar open oceans, is the outlier. ∎

LIFE ON ICE WORLDS

The icy moons of the outer solar system are our best bet for finding life, says Kevin Hand.

PROFILE KEVIN HAND

Kevin Hand is director of the ocean worlds lab at NASA's Jet Propulsion Laboratory in California, a leading expert on the potential habitability of these far-flung moons and a key player in the design of missions to explore them.

Icy moons such as Europa are as different from Earth as one could imagine. What makes you think they might harbour life?
The simplest answer is that they are where the liquid water is. And if we've learned anything about life on Earth, it is that where you find the liquid water, you find life. Combined with that, we also think that on Europa and Enceladus, the seafloors are probably rocky and could have hydrothermal activity. That's very important because when we think about what it takes for a world to be habitable, we know from our studies of life on Earth that it needs a couple of things as well as liquid water: the elements to build life and some source of energy to power it. On both Europa and Enceladus, we have good evidence for those two things.

What can missions look for?
The first thing will be chemical signatures of life. At the most basic level, you want to look for organic compounds. Then you might also look for molecules that have chirality, meaning they are not identical to their mirror images, which is another signature of life on Earth. You also look for inorganic indicators of life, not least cell-like structures. Life as we know it differentiates itself from its surroundings by making a compartment, the cell, and we predict that life elsewhere would form similar structures.

Do you think these places might harbour complex life?
For the most part, when I talk about the search for life elsewhere, I'm talking about the search for even the tiniest of microbes. A single-celled microbe, or the alien analogue, would revolutionise biology. But on Europa at least, I think there is a chance more complex life could have evolved.

The reason is that we've got this very intriguing relationship between Europa's surface and the magnetosphere of Jupiter, which bombards Europa with a rainstorm of charged particles. That, in turn, drives radiolysis, where water molecules are split apart and reform to make other things. We know from our observations with our telescopes and spacecraft that the surface ice on Europa contains hydrogen peroxide, sulphate and molecular oxygen. If these surface

ROCIO MONTOYA

oxidants are mixed into the ocean below, you may have a very chemically rich ocean. On Earth, it was the rise of oxygen that enabled the emergence of multicellular life. So it's not completely out of the question that Europa's oceanic oxygen perhaps drove evolution to more complex life there too.

You've followed those ideas about the origin of life to the very depths of Earth's oceans, including a visit to Lost City, a system of hydrothermal vents at the bottom of the Atlantic. What was that like?

It was a transformative experience. It was like a combination of being in a time machine, transporting me back to the origin of life on Earth, and a spacecraft taking me to the deep ocean of Europa. I'm in this tiny, pressurised glass sphere, just me and the pilot, and we're looking at these cathedrals of carbonate, these chimneys that could have been the site of the origin of life on Earth. Now, there's much debate about that, and it is possible life arose in a warm pond on an ancient seashore, or in some other locale that we have yet to understand. But hydrothermal vents like those at Lost City are a strong candidate. And at that moment, I did allow myself to imagine that this could be what we would find at the bottom of Europa's ocean.

What are the prospects for a mission that drills into the ice, or even gets samples from the oceans?

The dream of all dream missions is getting a submersible directly into these oceans. But scientifically and technologically, we need to follow a bit of a progression. We've got a commitment to a fly-by mission called Europa Clipper, scheduled to launch in the mid-2020s, and that mission will assess habitability. But it won't be able to search for biosignatures. I would hope that the follow-on mission would get to the surface with capabilities to directly search for signs of life, while also doing a lot of the measurements that we'd need to inform a mission that would drill or melt through the ice.

Keep in mind that, other than on the moon and Earth, we haven't drilled deeper than about 10 centimetres anywhere in the solar system. So going directly to a world like Europa and drilling through many kilometres of ice is an incredibly tall order.

If we were able to spot complex life in these oceans, what would it look like?

My experience at Lost City inspires my thinking on this. As I was collecting samples, I saw this undulating, shimmering, glass-like sheet of a creature just a couple of metres away. It looked kind of like a very large, translucent umbrella, nearly 2 metres across, and it was presumably filter-feeding on the microbes and other organisms surviving from the chemistry of the hydrothermal vents. So when I think about the prospect for larger life within an alien ocean, it is these sorts of creatures that come to mind.

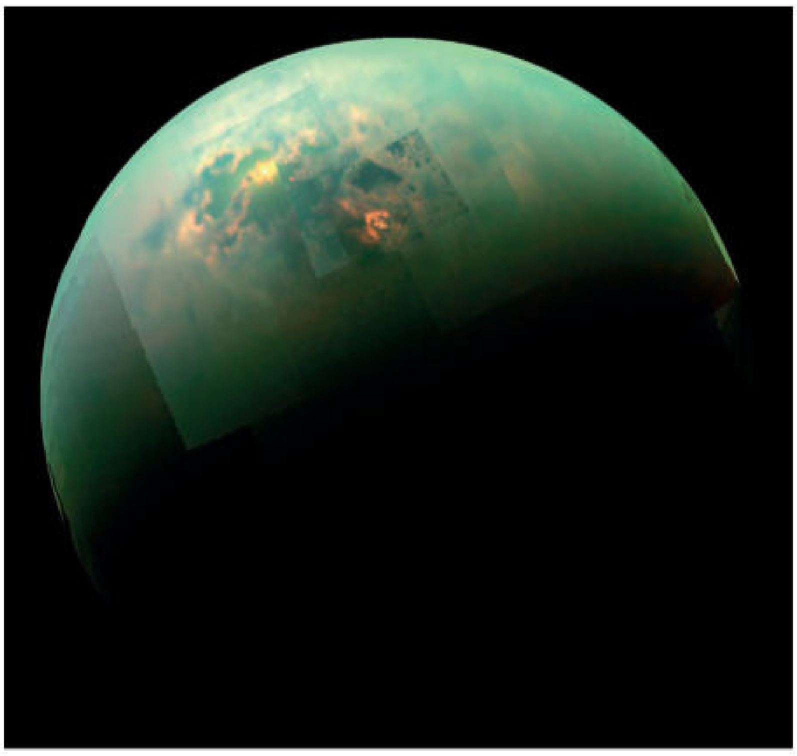
What would the discovery of life elsewhere tell us about the origins of life?

It would help answer a fundamental question, which is whether life arises wherever the conditions are right. That's something we address not by looking for life beyond Earth, but for a second origin of life. If we find it within these alien oceans in our own solar system, I think we can predict that we live in a biological universe.

Contrast that with finding life on Mars. I love Mars. But even if we find extant life beneath the surface of Mars, and that life is based on DNA, I would argue that you have to hedge towards conservativism and say that it would be indicative of life on Earth seeding Mars or vice versa. These alien oceans far out in the outer solar system, however, are much harder to cross-pollinate. ∎

It happens to be merely a moon, but Titan is one of the most extraordinary bodies in our solar system: Earth seen in a frosted fairground mirror. It has methane rain, rivers and seas, along with ice mountains and plastic dunes, all under a dense, smoggy atmosphere churning with complex chemistry. It could conceivably harbour life in both familiar and exotic forms.

TITAN: METHANE WORLD



NASA/JPL-CALTECH/UNIVERSITY OF ARIZONA/UNIVERSITY OF IDAHO

WE ONCE thought that Titan was the largest moon in the whole solar system, bigger even than Jupiter's mighty Ganymede. Astronomers at the time didn't realise that, alone among moons, it is shrouded in a thick atmosphere, which increases its apparent size. This rich atmosphere gives the moon many of its unique attributes, and also hides them from us.

Solar ultraviolet radiation drives reactions between nitrogen and methane molecules in the atmosphere that create an opaque orange-brown smog. Even when Voyager 1 passed Titan in 1980, it couldn't see the surface. The purpose of the Huygens lander, built by the European Space Agency and carried by the Cassini mission, was to find out what lay beneath.

Huygens descended to Titan's surface in 2005, giving us our first clear view. Photos taken during the lander's 150-minute descent showed networks of branching valleys, a landscape that looked strangely familiar, like hills on Earth sculpted by streams and rivers. The touchdown was hard, on a pebble-strewn flood plain near Titan's equator.

For the next 12 years, Cassini zipped around the Saturn system, relaying remarkable insights every time it passed Titan. Using radar to penetrate the smog, it saw seas and lakes. Titan is the only place in the solar system besides Earth known to have liquids on its

Titan is the only place other than Earth known to have liquid on its surface – but there are big differences that mean any life that may exist there would be truly alien

	EARTH	TITAN
		
ATMOSPHERE	Mostly nitrogen (77%) and oxygen (21%)	98% nitrogen, 2% methane and other hydrocarbons
ATMOSPHERE DEPTH	50 kilometres	600 kilometres
SURFACE TEMPERATURE	15°C	-180°C
SURFACE LAKES AND SEAS	Water	Methane and ethane

SOURCE: NASA/JPL/SSI

surface. But at around -180°C, this isn't water. The only H_2O on the surface is steel-hard ice, some of it forming mountain ranges that rise 3300 metres into the haze. Instead, Titan's rivers flow with methane and ethane, which are usually gases on Earth, but exist as dark, oily liquids in these frozen climes.

In radar observations a few weeks apart, Cassini found evidence that methane showers had soaked the soil, then evaporated – the first proof of precipitation beyond Earth. Clouds on Titan release seasonal downpours.

The methane rain replenishes Titan's hydrocarbon lakes and seas. The largest of these is Kraken Mare in the far north of Titan, more than 1000 kilometres long. These are more transparent than water lakes: a radar echo from Ligeia Mare was reflected from its bottom, 160 metres down. Bright "magic islands", which appear briefly in the dark lakes before disappearing, are now thought to be nitrogen bubbling out of solution.

Across many equatorial regions, Cassini revealed fields of dunes, up to 100 metres high. The local sand appears to be made from hydrocarbon polymers, something akin to plastic.

So Titan turns out to be like an alternate-universe version of home, with the same features, but very different chemistry. Could that chemistry lead to life? Liquid water is essential for life on Earth because it offers an ideal medium for chemical reactions and, as an effective solvent, an easy way to transport molecules within and between cells. But it might be possible to base life on other solvents, and Titan is seething with complex molecules that could be the basis for biochemistry.

In 2017, a cluster of telescopes in Chile called ALMA picked up a clear signature of a compound called vinyl cyanide. Here on Earth we synthesise this stuff, also known as acrylonitrile, to make acrylic fibres, synthetic rubber and plastics used in everything from cars to food packaging. In Titan's frigid hydrocarbon lakes, it could form structures similar to our cell membranes.

On Earth, living cells also require nucleic acids such as DNA to transfer genetic information from one generation to the next, and proteins for self-replication. Both of these components are built from large, complex molecules. In 2017, Ravi Desai at University College London and his colleagues reported the first evidence that Titan's atmosphere contains ingredients that can create all manner of these macromolecules. The discovery came from data gathered on one of Cassini's final sweeps through the upper atmosphere, where it identified molecules called carbon chain anions. These molecules act as catalysts for the formation of larger and more complicated organic molecules.

This leads to the tantalising possibility that a parallel kind of life has emerged in the hydrocarbon seas of Titan. And deep down under a shell of water ice lies another hidden ocean of salty liquid water – so it is just possible that there could be two separate realms of life on Titan with totally different biochemistry.

Of course, we don't even understand how chemical reactions gave rise to life on Earth, let alone how it ›

Uranus (top) is unusual in the axis of its spin, possibly the result of a large collision

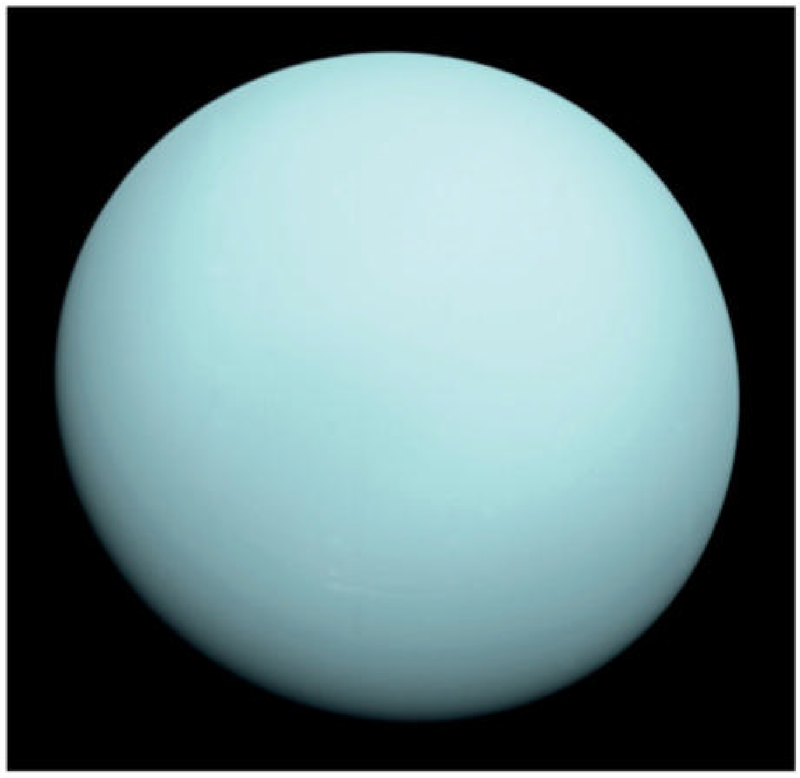
Neptune (bottom) experiences 2000kph winds, the fastest in the solar system

would happen in hydrocarbon seas. The only way to find out more is to go back and take a closer look.

In 2019, NASA gave the go-ahead for the Dragonfly mission, a daring plan to send a sophisticated drone to buzz around Titan, landing at key sites in search of signs of prebiotic chemistry. By flying from place to place, a drone can cover much more ground than a rover could, and thus gather more and better data. It can take full advantage of the unique atmospheric conditions on the moon. The density of the atmosphere is much greater than on Earth, and its gravity is only about 14 per cent of what we experience here – weaker even than that on our moon. What's more, there seems to be almost no wind at the surface: Cassini's observations suggest that if there are any ripples on Ligeia Mare, they are less than a millimetre tall. It might even be possible for a human to fly on Titan just by flapping their arms.

Titan is almost 10 times as far from the sun as Earth, and its smog blocks out a lot of light, so the quadcopter can't rely on solar power. Instead, Dragonfly will have to bring its own source of energy: a radioisotope thermoelectric generator, which uses the heat released by the decay of plutonium-238 atoms to generate electricity.

This far-away moon is the best laboratory we have to work out how chemical reactions led to life on Earth and under what conditions life can spark elsewhere in the universe. It is also one of the only places we can plausibly reach that could answer such profound questions. If Dragonfly's peregrinations ultimately reveal that water and other mundane, earthly ingredients aren't essential for chemistry to become biology, then we would look with fresh eyes at a vast swathe of worlds beyond our own solar system. Haze-shrouded exoplanets that once seemed barren would glow with the promise of exotic new forms of life. ∎



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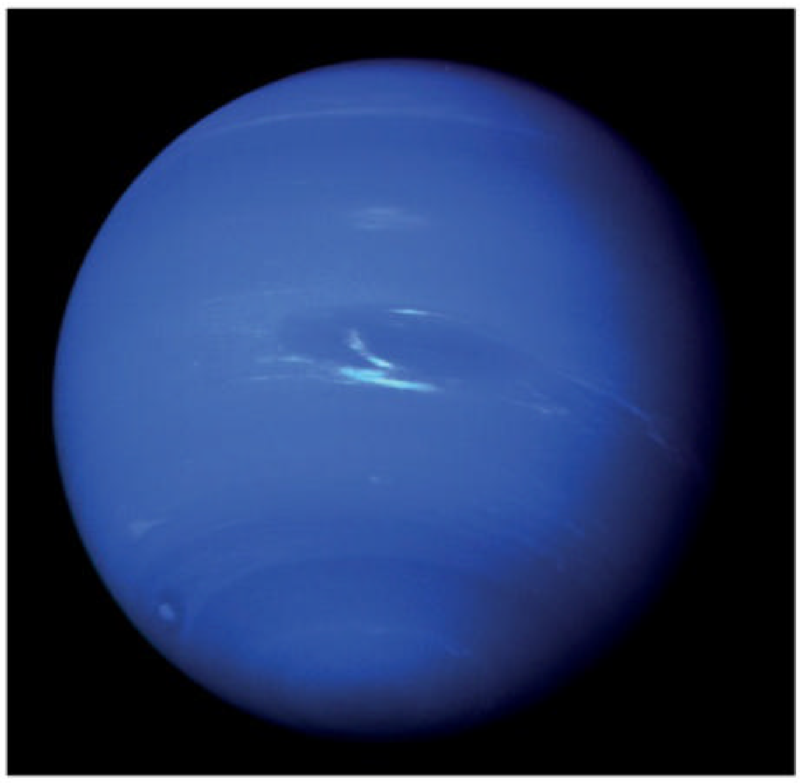


NASA/JPL

URANUS AND NEPTUNE: THE ICE GIANTS

A fleeting glimpse of the solar system's two outermost planets 30 years ago hinted at very weird science that could tell us a lot about exoplanets. Now we have a rare chance to go back.

THEY aren't the most distant objects in the solar system, or the biggest or the smallest or the most colourful, but Uranus and Neptune do hold some profound mysteries. We have roved across Mars, we have orbited Jupiter, we have even landed on Venus. But our only close look at these distant ice giants came more than 30 years ago when Voyager 2 hurtled past on its way out of the solar system. It snapped a few pictures, then the planets faded from view.

The little we do know about these frigid planets suggests they are extremely weird: they have crooked magnetic fields, they are colder than they should be and we don't know why they spin in odd ways. Understanding all this is important, because as we spot more and more planets around other stars, worlds about the size of Uranus and Neptune are the most common type. That tells us mid-sized gassy planets are a basic ingredient of the universe.

→ Chapter 6 has more on exoplanets

There is a small window of opportunity in the late 2020s and early 2030s when the planets will be arranged so that a slingshot around Jupiter would boost a probe to Neptune within six years. If we miss that slot, 2050 is the earliest we could be there.

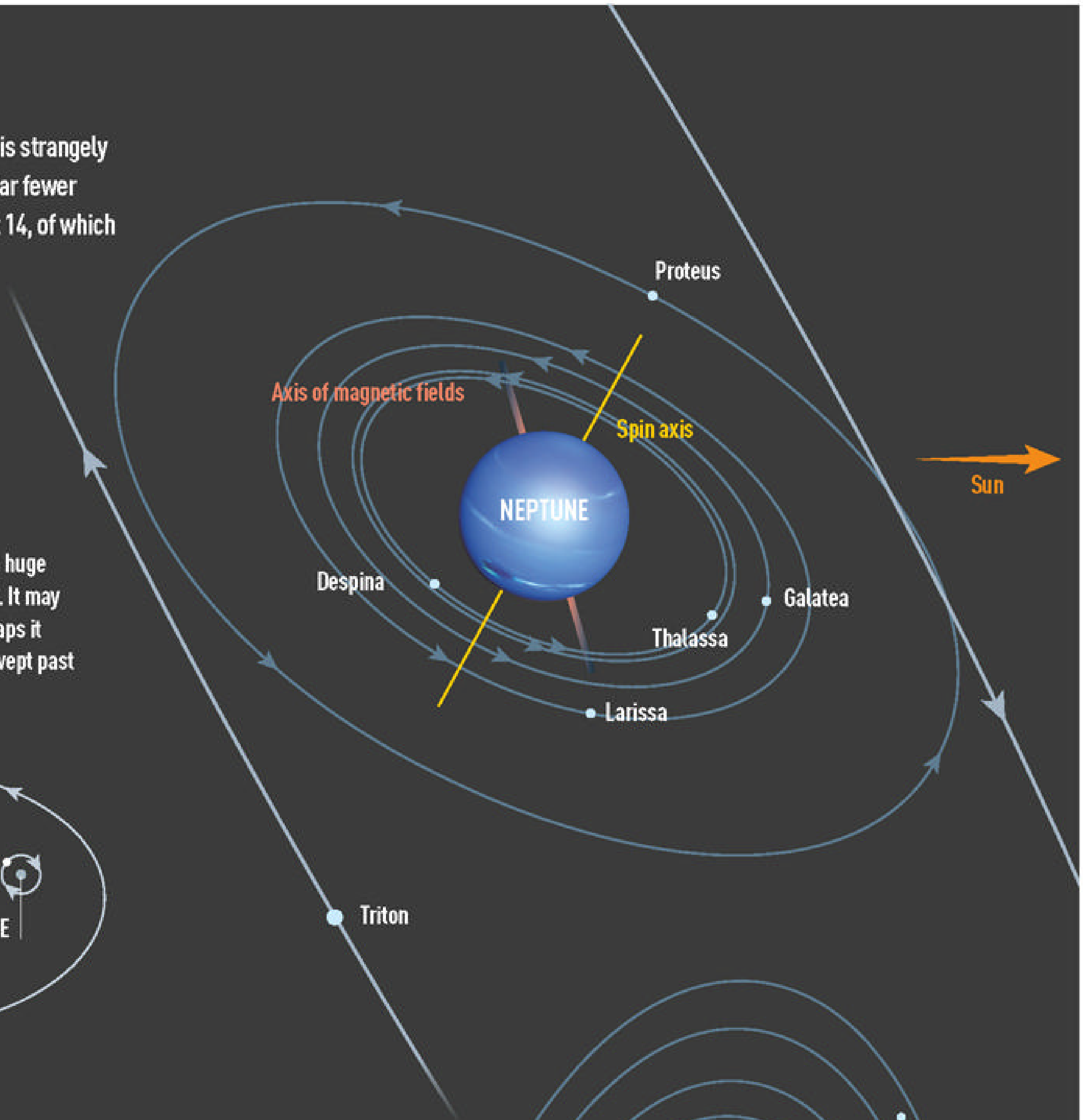
That is why NASA and the European Space Agency have been looking at missions to learn more about the ice giants. NASA's Decadal Survey for Planetary Science and Astrobiology, published in 2022 and covering missions for 2023 to 2032, gave the highest priority to a Uranus orbiter together with an atmospheric probe.

A trip to the ice giants could answer some big questions, such as: what made Uranus so crooked? Most of the planets in our solar system rotate on an axis 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 axis close to the plane of its orbit. Most of its moons orbit in the same direction that it rotates, at a right

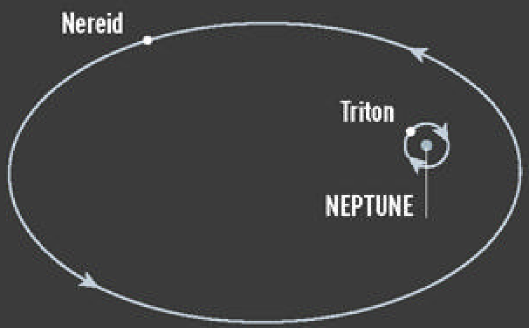
NEPTUNE

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



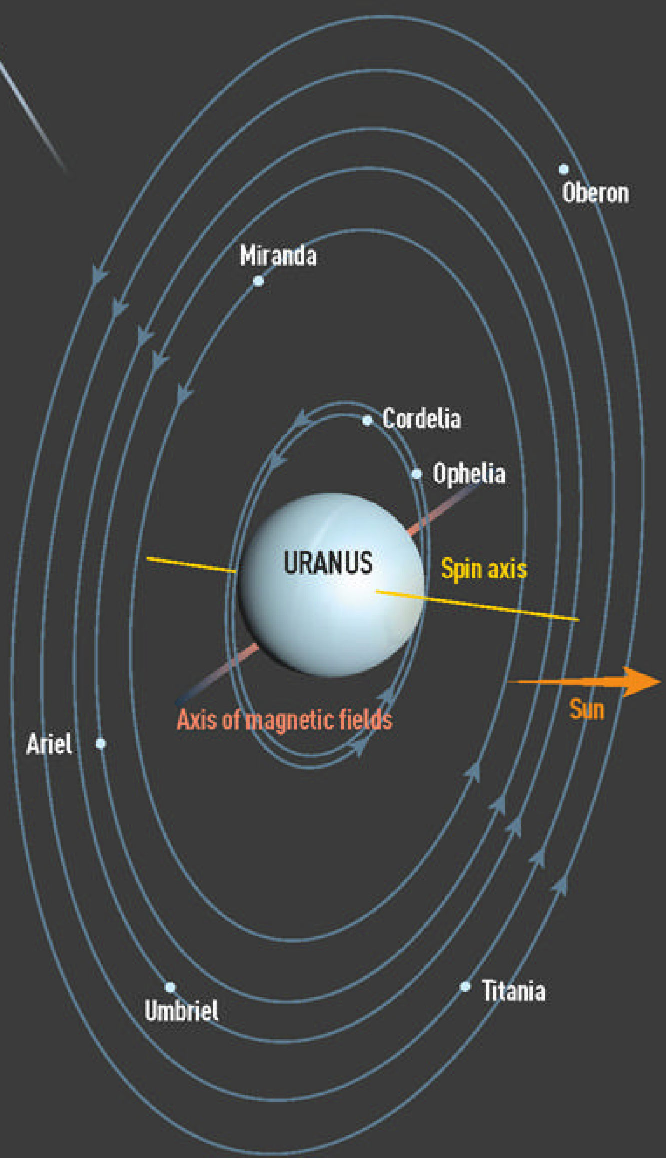
NEREID

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 angle to the plane of the solar system.

Most planetary scientists suspect that the cause 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. Maybe the moons grew out of the rubble tossed into space by the collision.

All this depends on Uranus having a solid core, otherwise it is hard to see how the collision narrative would work. 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.

As well as being off-kilter, Uranus is far too cold. When Voyager 2 buzzed past Uranus, its sensors picked up no heat signal at all. That doesn't make sense. As gas, dust and eventually rocks smash together during planet formation, they should generate heat, which will then radiate out over billions of years.

Models based on this basic idea, plus observations of Jupiter and Saturn, fit the heat output of Neptune neatly. Neptune's internal heat is though to drive its wild weather, including 2000-kilometre-per-hour winds, the fastest in the solar system.

Neptune and Uranus 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 should be similar. But Uranus is much colder than these models predict.

Perhaps Uranus's cold heart is related to its odd tilt, which may have sped up the planet's loss of heat. Or it could be that core is still warm, but there is something that stops the heat getting out.

We know so little about what is going on inside Uranus and Neptune. Voyager 2 managed a single measurement of each ice giant's magnetic field. 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. Uranus's field is more complex. It has lumps and bumps pointing in different directions, and its main axis sits at about 45 degrees to the spin axis. Neptune's is similar. And the centre of the magnetic field doesn't seem to sit in the middle of either planet.

Earth's magnetic field is generated by swirling molten iron in its outer core, driven by the core's heat and corralled by the planet's rotation. The ice giants' dynamos are probably very different. 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, so the dynamo isn't a single uniform sphere, but several interacting shells.

A more profound question is: why do the ice giants even exist? There wasn't enough material hanging around for them to form where they are today. The favoured explanation is the Nice model again: the ice giants were born closer to the sun, and grew quickly in the dense dust and gas there, before migrating to their current home.

← Turn back to page 28 for more on planetary migrations

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. That would help narrow down the possible ways in which Jupiter moved around too. So 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. ■

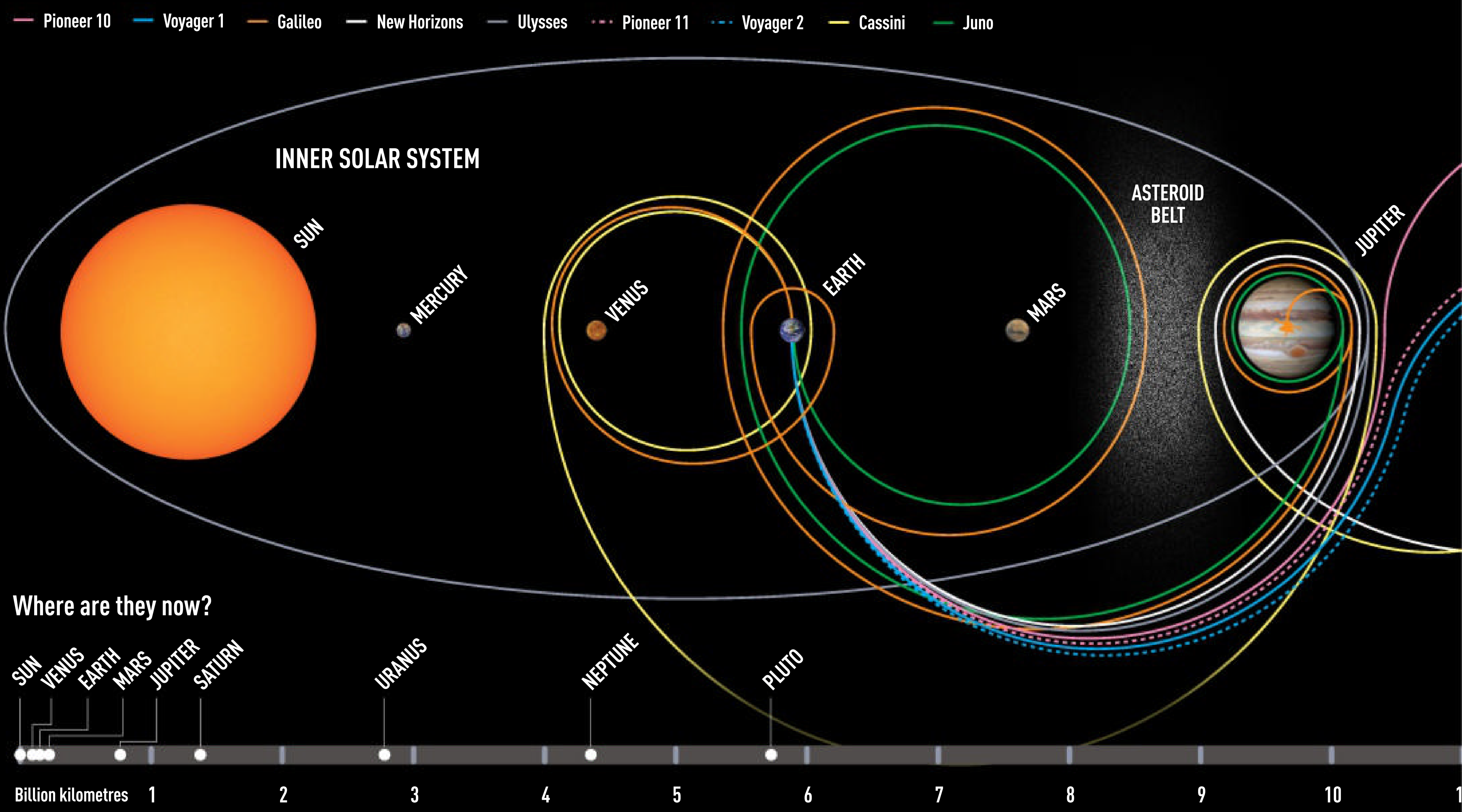
TRITON: THE CANTALOUPE MOON

We have a very fuzzy picture of Neptune's satellite Triton, the last giant moon of the solar system. We do know that part of its surface is textured like the skin of a cantaloupe melon, and that it has plumes of nitrogen gas and dust that spurt kilometres high. These plumes may come from areas where sunlight heats nitrogen ice, causing it to sublimate into the atmosphere. Or they could be caused by ice expanding underground and blasting holes in the moon's surface, like the plumes on Enceladus.

Triton orbits in the opposite direction to the planet's spin and the other moons. This indicates that it didn't form at the same time as Neptune, from the same cloud of material. Instead, it was probably captured later. Triton is a little bigger than Pluto, and its surface is made of similar materials, so it may well have come from Pluto's neighbourhood, the Kuiper belt. As it was captured, Triton's gravity may have knocked other moons out of orbit – explaining why Neptune has only 14 moons, far fewer than Jupiter, Saturn or Uranus.

PROBING THE OUTER SOLAR SYSTEM

Besides Cassini, eight missions have passed the asteroid belt – and several are still broadcasting from the furthest solar system and beyond.



PIONEER 10

LAUNCHED: 3 MARCH 1972

Pioneer 10 was the first probe to cross the asteroid belt, between July 1972 and February 1973. Arriving at Jupiter in December 1973, it passed some 132,000 kilometres from the planet's cloud tops and obtained fuzzy images of the four large Galilean moons, Ganymede, Europa, Callisto and Io. Out of contact since 2003, 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.

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 Saturn's clouds on 1 September 1979. It almost collided with a small moon and photographed Titan. An anomalous slowing of both the Pioneer probes brought long-lasting speculation that the established laws of gravity didn't work in space, but this "Pioneer anomaly" is now thought to be down to heat loss from the probes' thermoelectric generators. Last heard from in 1995, Pioneer 11 is now heading towards the constellation Scutum.

VOYAGER 2

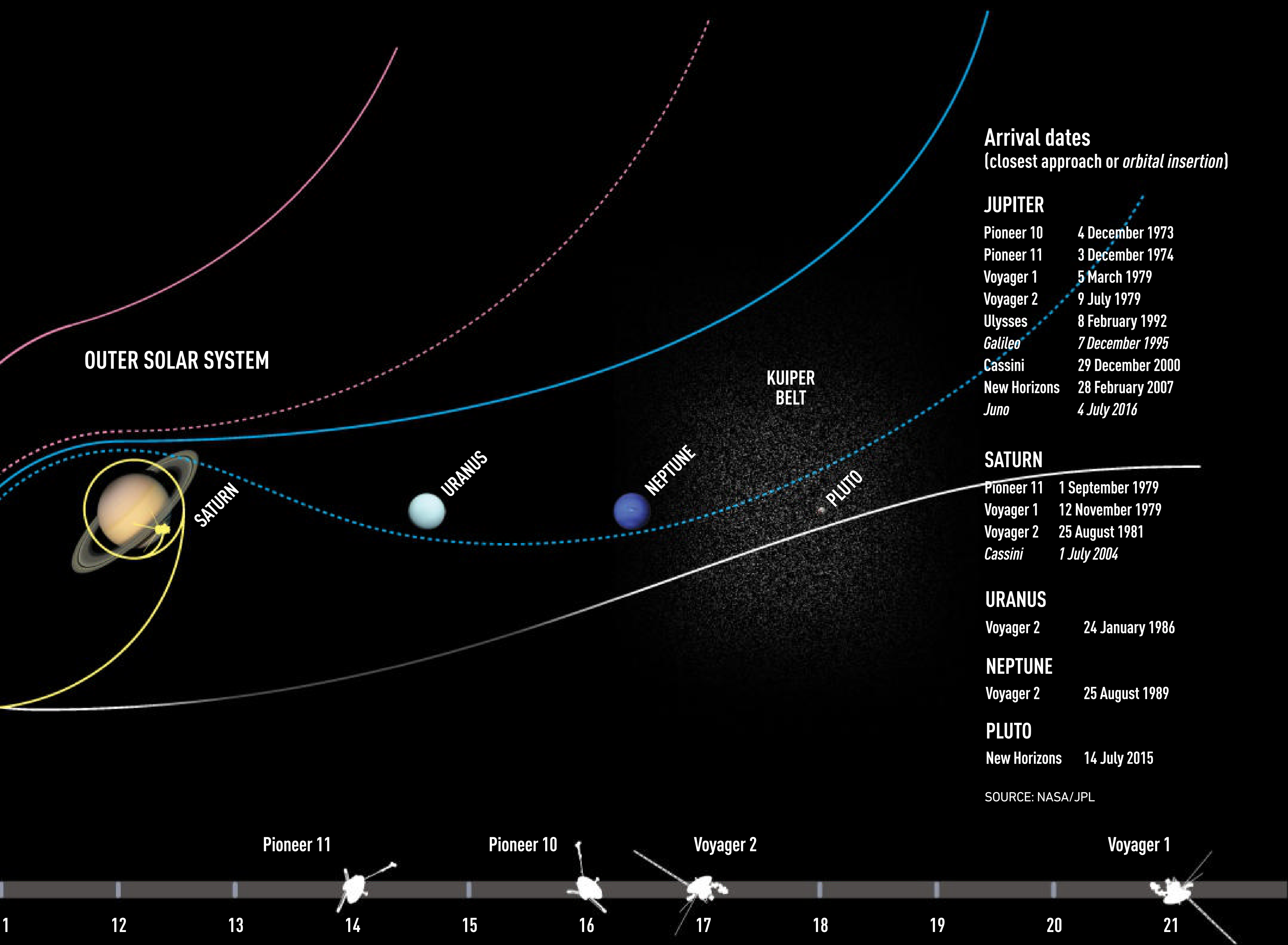
LAUNCHED: 20 AUGUST 1977

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 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, sampling interstellar plasma beyond the reach of the solar wind, as it heads towards the constellation Telescopium.

VOYAGER 1

LAUNCHED: 5 SEPTEMBER 1977

Voyager 1 launched after Voyager 2, but beat its sister probe to both planets by taking a faster trajectory. 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 interceptor.



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. Entering Jupiter's orbit on 7 December 1995, Galileo's activities included sending a probe into the giant planet's atmosphere. It also collected data supporting the idea that Jupiter's moon Europa has a subsurface liquid ocean. The 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. It was decommissioned in 2009.

CASSINI-HUYGENS

LAUNCHED: 15 OCTOBER 1997

One of the most successful planetary exploration missions of all time, the Cassini probe spent 13 years cruising Saturn's moons, and fulfilled the goal of sending a probe to the moon Titan, revealing its eerie landscapes reminiscent of a deep-frozen Earth. The mission's planned end came on 15 September 2017 when it burned up in Saturn's atmosphere.

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 also rendezvoused with the snappily titled space rock (486958) 2014 MU69 in the Kuiper belt on 1 January 2019.

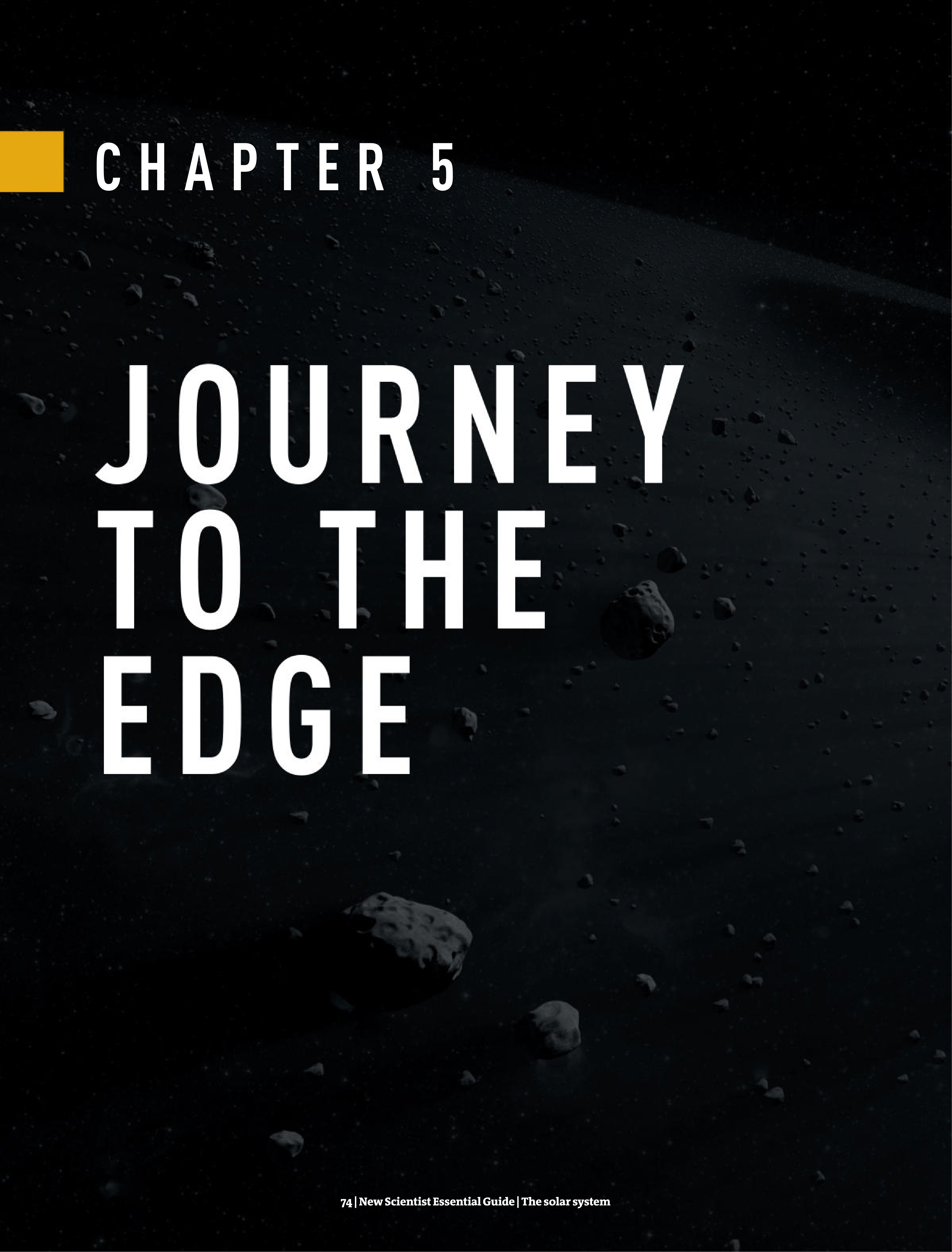
JUNO

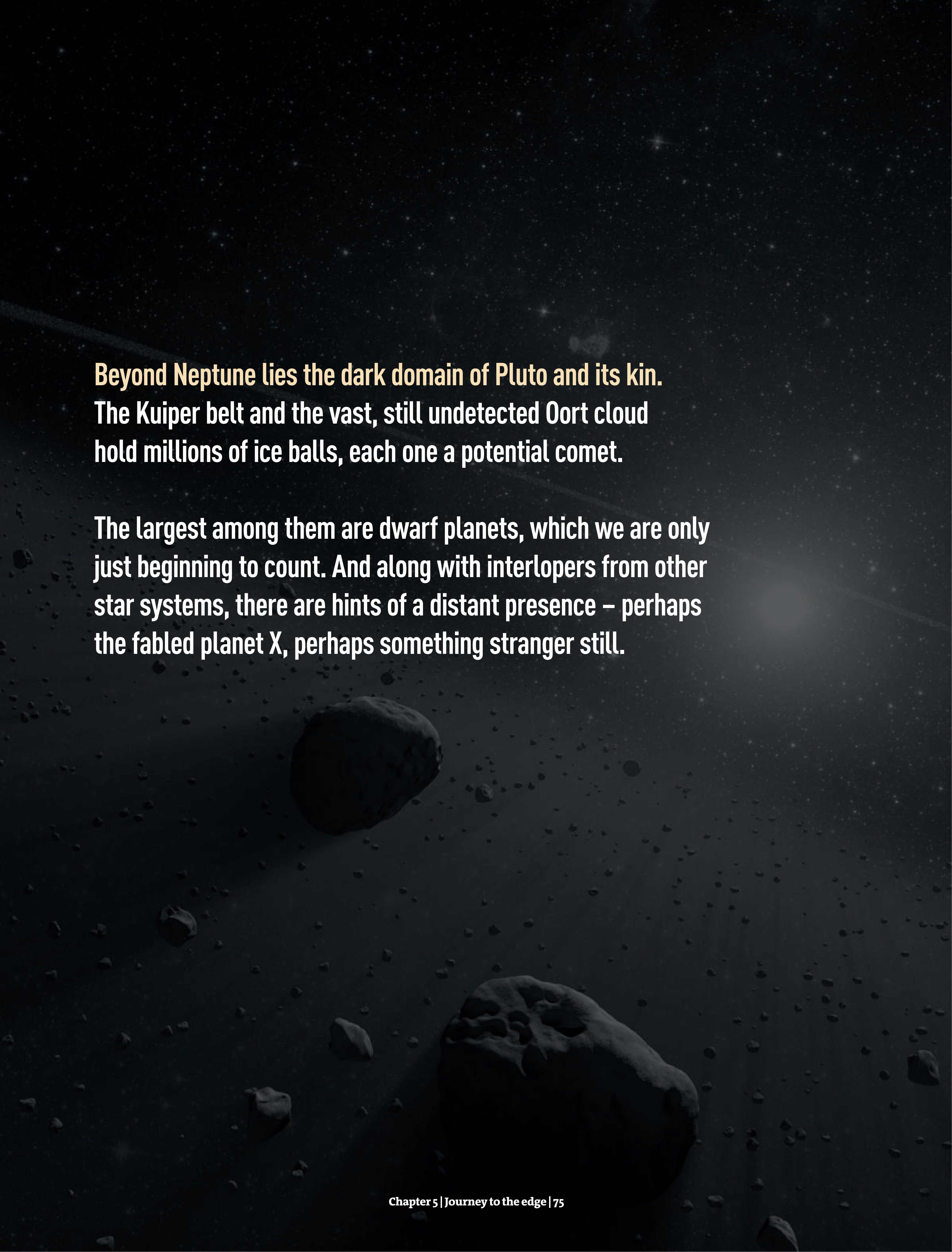
LAUNCHED: 5 AUGUST 2011

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.

CHAPTER 5

JOURNEY TO THE EDGE





Beyond Neptune lies the dark domain of Pluto and its kin. The Kuiper belt and the vast, still undetected Oort cloud hold millions of ice balls, each one a potential comet.

The largest among them are dwarf planets, which we are only just beginning to count. And along with interlopers from other star systems, there are hints of a distant presence – perhaps the fabled planet X, perhaps something stranger still.

PLUTO: HEAD OF THE KUIPER CLAN

With its floating mountains, ice volcanoes and a churning plain of nitrogen sludge, Pluto shows how complex a little world can be.

UNTIL a few decades ago, the frontier of the solar system seemed a lonely one, with Pluto its sole denizen. Pluto, discovered in 1930, was the epitome of dim and distant: a faint dot in even our most powerful telescopes, 4.5 light years from the cosy inner solar system, dawdling around the sun every 248 Earth years.

Then, in the 1990s, astronomers began finding more icy bodies out there, forming a swarm of debris stretching far out beyond the orbit of Neptune. This region is now known as the Kuiper belt. It starts at 30 AU out from the sun and extends to perhaps 40 AU (1 AU, or astronomical unit, is the distance from the sun to Earth).

These icy bodies, known as trans-Neptunian objects (TNOs), are thought to be leftovers from the birth of the eight major planets. Some are dwarf planets on Pluto's scale – a diverse bunch, with different colours and shapes and satellite systems. Rather than being a lone afterthought, Pluto has become the leader of a new class of small, icy worlds.

On 14 July 2015, New Horizons skimmed within just 13,000 kilometres of Pluto's surface, finally revealing just how complex this particular world is. Take Sputnik Planitia. Surely one of the strangest terrains anywhere in the solar system, this is a living, shifting landscape, a 1000-kilometre plain divided up into rough polygons a few tens of kilometres across, which are almost certainly the mark of convection. Similar patterns appear on the sun's surface and can sometimes be seen in a gently simmering saucepan.

Here, solid nitrogen is convecting very slowly. Nitrogen ice is soft, and an excellent thermal

NASA/JHUAPL/SWRI
PREVIOUS PAGE: MODE-LIST/ISTOCK

insulator, meaning even a feeble heat source from below can build up the temperature, kicking off convection. The heat left over from Pluto's turbulent formation, supplemented by more from the decay of radioactive trace elements, is expected to add up to about 4 milliwatts per square metre – enough to drive the churning of Sputnik Planitia.

Blocks gathered at the junctions of some convection cells are probably hills made of water ice, which is as hard as granite at Pluto's surface temperature of around -230°C. These hills are floating on the denser nitrogen. Even mountains would float here. On the north-western flank of Sputnik Planitia are the jumbled peaks of the al-Idrisi range, kilometre-high mountains that may be afloat today, or may once have drifted across Sputnik Planitia to become beached.

While most mountains that punctuate Pluto's surface are jagged, like the al-Idrisi range, Wright Mons bucks that trend. It is a broad mass, 150 kilometres across and 4 kilometres high, with a huge central pit. It looks suspiciously like a volcano – as does its taller neighbour Piccard Mons. They wouldn't have erupted molten rock, but instead some chillier fluid, probably water mixed with another substance that lowers its melting point. This betrays surprisingly recent heat and turmoil on Pluto, a tiny, cold world that, by rights, should have frozen solid long ago. Wright Mons is certainly no relic from the dwarf planet's early days. Its sides bear hardly any visible impact craters, so can't have been exposed to the rain of space debris for too long. It is probably much younger than a billion years, and perhaps only a few million.

A large area surrounding these two mountains – at least 180,000 square kilometres – is made up of undulating hummocks of ice that seem to be unique to Pluto. In 2022, Kelsi Singer at the Southwest Research Institute in Colorado and her colleagues examined New Horizons images, composition data and topographical maps of the area to determine how this unique terrain formed. They found that it was probably created via what is called effusive cryovolcanism, with liquid or relatively soft ice seeping out from underground to gradually create huge mountains and overlapping mounds. There is no evidence of explosive volcanic eruption, just slow, effusive seeping. The overlapping nature of the hummocks indicates that there were probably many episodes of volcanism over time, and the lack of impact craters hints that this happened within the last couple of hundred-million years. To form this vast landscape, cryovolcanoes had to spew out more than 1000 cubic kilometres of ice, requiring Pluto's insides to be hotter than researchers expected. Cryovolcanism could still be happening today.

There is plenty of action above ground too. Pluto's atmosphere is cold and thin, with surface pressure equal to that 80 kilometres above Earth, yet its weather seems to be surprisingly like ours. Nitrogen sublimates from the ices of Sputnik Planitia, rather like water evaporating from Earth's oceans (except that on Pluto, the sublimation process leaves pockmarks peppered across the landscape). It then falls as snow or freezes out as frost on the eastern highlands, finally flowing back down to the plain in glaciers. There are even signs of nitrogen fog in places.

But winter is coming. After reaching its closest point to the sun in 1989, Pluto's northern hemisphere gradually tilted towards the sun. This raised the temperature of Sputnik Planitia, increasing the atmospheric pressure from 0.4 to 1.2 pascals between 1988 and 2016. But Sputnik Planitia is now moving into a long period of twilight, suggesting the atmosphere will begin to condense and freeze on the surface of Pluto, almost vanishing over the next 100 years.

Today's atmosphere is streaked with hazy layers of aerosol particles, again like Earth. These layers stretch up to 200 kilometres above Pluto's surface, 10 times the height expected before the arrival of New Horizons. While the lower-level hazes may be photochemical smog caused by the action of sunlight on methane and other gases, the higher layers must be created by some other process, perhaps by free electrons in Pluto's ionosphere.

HOW TO BE A PLANET

When NASA's New Horizons craft was launched in January 2006, its destination was still the solar system's ninth planet. Later that year, Pluto was declassified. According to the International Astronomical Union's controversial definition, to be a full-blown planet, a solar-system body must now fulfil three criteria.

1. *IT MUST ORBIT THE SUN;*

2. *ITS MASS AND GRAVITY MUST BE LARGE ENOUGH TO MOULD IT INTO AN ALMOST ROUND SHAPE;*

3. *IT MUST HAVE CLEARED ITS SURROUNDS OF BODIES OTHER THAN THOSE BOUND TO IT BY DIRECT GRAVITATIONAL INFLUENCE (SUCH AS MOONS).*

Pluto fails only on the last criterion, because of the swarm of other objects orbiting in the Kuiper belt. Some of these, such as Eris, are classified as dwarf planets along with Pluto.

It isn't clear whether this smog is responsible for painting Pluto red. New Horizons found that huge swathes of the surface are covered in some kind of red material. Researchers assumed that these red patches were made of tholins – organic substances that form in the atmosphere and then drift down to the surface. Pluto's atmosphere clearly has the ingredients to produce this gunk. Then, in 2021, Marie Fayolle at the Delft University of Technology in the Netherlands and her colleagues made artificial Pluto tholins in the lab, taking a low-density mixture of carbon monoxide, nitrogen and methane and then exposing it to radiation similar to what would hit Pluto's atmosphere in space. This caused the molecules to react and condense into dust-like particles. The spectrum of light reflected by these artificial tholins doesn't match that from the red material on Pluto's surface, suggesting that some unknown material is painting Pluto red – although tholins can't be ruled out, as their colour might be modified by a fluffy surface texture on Pluto.

Maybe the most important discovery of all is an unexpected absence. Pluto and its large moon, Charon, both have a relative shortage of small craters. That may be telling us something profound about how planets form. According to the traditional picture, objects known as planetesimals grew as little rocks gradually came together to make bigger rocks. This process should produce a lot of objects a few kilometres in diameter, and far fewer objects tens or hundreds of kilometres across. Planetesimals of all available sizes should hit Pluto and Charon from time to time, forming craters – so the lack of smallish craters on Pluto seems puzzling.

It might fit an alternative model called pebble accretion, in which large planetesimals form almost instantly when swarms of little pebbles immersed in gas suddenly collapse. Pebble accretion wouldn't create so many small planetesimals. Perhaps this is a vital stage in building not just little icy worlds like Pluto, but also the cores of gas giants and warm, rocky planets such as Earth. ▮

COMETS: A TOP SIX

Occasionally, a bit of the Kuiper belt or the even more distant Oort cloud gets dislodged, entering a highly elliptical orbit that takes it far closer to the sun. We know these solar system wanderers as comets – balls of ice and dust with large comas of gas and long tails trailing behind. They can tell us much about the origins of our planetary neighbourhood.

1. HALLEY'S COMET

British astronomer Edmund Halley was the first to realise that comets are periodic, after observing the comet that now bears his name in 1682 and tallying it to records of two previous appearances. He correctly predicted it would return in 1757. The comet is also though to be depicted in the 1066 Bayeux Tapestry. The solid nucleus of Halley's Comet measures 16 kilometres by 8 kilometres, and travels around the sun every 75 to 76 years in an elongated orbit. It last passed close to Earth in February 1986, when the European Space Agency probe Giotto observed it from a distance of just 600 kilometres.

2. SHOEMAKER-LEVY-9

Comet Shoemaker Levy-9 distinguished itself by breaking into 21 pieces under the stresses of Jupiter's gravity in 1992, then slamming into the giant planet in 1994. The spectacular show was watched by telescopes across Earth, in orbit and aboard the space probe Galileo. The impact of one fragment – around 3 kilometres across – is said to have yielded an explosion equivalent to 6 million megatonnes of TNT, creating a plume that reached 22,000 kilometres above the cloud tops.

3. HYAKUTAKE

Hyakutake is an example of a long-period comet, thought to originate in the distant, mysterious Oort cloud. Appearing as an icy-blue blob with a faint gas tail, it was the most spectacular comet display for decades as it passed just 15 million kilometres from Earth in March 1996. This was the closest the comet had come to the sun in 9000 years. The spacecraft Ulysses happened to pass through Hyakutake's tail later that year, showing that the tail was at least 570 million kilometres long.

4. HALE-BOPP

The long-period comet Hale-Bopp made its closest approach to Earth for 4000 years in January 1997. With a nucleus up to 40 kilometres across, it could be viewed from Earth with the naked eye and was visible from Earth when it was still outside the orbit of Jupiter.

5. TEMPEL-TUTTLE

Tempel-Tuttle is the progenitor of the annual Leonid meteor shower. Shooting stars streak across the night sky every November, as Earth passes through the dust and rocks shed by the comet. Particularly bright meteor showers known as storms occur roughly every 33 years, with observers dazzled by hundred or even thousands of meteors per minute.

6. CHURYUMOV-GERASIMENKO

Launched in 2004, the European Space Agency's Rosetta space probe touched down on comet 67P/Churyumov-Gerasimenko in 2014 and released a small cube-shaped lander called Philae onto the comet's icy nucleus. The result was a new stream of scientific findings, among them that the water on Earth probably wasn't delivered by comets, as many had assumed – or at least not from ones like Churyumov-Gerasimenko. Rosetta's ROSINA spectrometer also detected oxygen and a zoo of complex molecules, including one amino acid on the comet's surface. ▮

PLANET X?

Some of the most distant known denizens of the solar system seem to show puzzling alignments, pointing perhaps to an ancient close encounter, an undetected planet or some more shadowy influence.

OUT in the solar system's liminal zone, there may be more bodies than there are stars in the entire Milky Way. Bit by bit, we are building up a picture of what is out there. The first object discovered here – besides Pluto and its moon Charon – showed up in 1992, and is still known only as (15760) 1992 QB1. Since then, we have charted the orbits of more than 1000 Kuiper belt objects. They include several confirmed dwarf planets, including Eris, Makemake and Haumea, along with their tiny moons.

But at some point, the Kuiper belt just... stops. This "Kuiper cliff" occurs some 40 astronomical units (AU) out, and from there on, it is, as far as we can make out, a whole load of nothing until you encounter the far more distant – and still hypothetical – Oort cloud encircling the solar system (see "The Oort cloud", page 83). This is a mystery. Simulations based on the conventional story of solar system formation don't produce this cut-off. The Kuiper belt should extend far further.

In fact, it turns out this region isn't completely empty. Only patient observation with telescopes can reveal anything in it, and we saw nothing until November 2003 when Mike Brown at the California Institute of Technology in Pasadena and his team discovered the dwarf planet Sedna. Sedna is considerably smaller than our moon, but hugely more reflective: it would be almost as bright as the full moon if it were the moon's distance away. Being 30,000 times further away at present, it is very hard to spot, and it moves so slowly that it hardly stands out among the fixed stars. In a sense, finding Sedna was a lucky shot: if its surface were as dark as that of a normal asteroid, it probably would have remained invisible.

Sedna's orbit is very elongated, getting as close as 76 AU from the sun but extending out to 940 AU at its furthest. We can see it only when it is close, and recent estimates have suggested that there could be some 500 Sedna-like objects hiding further away.

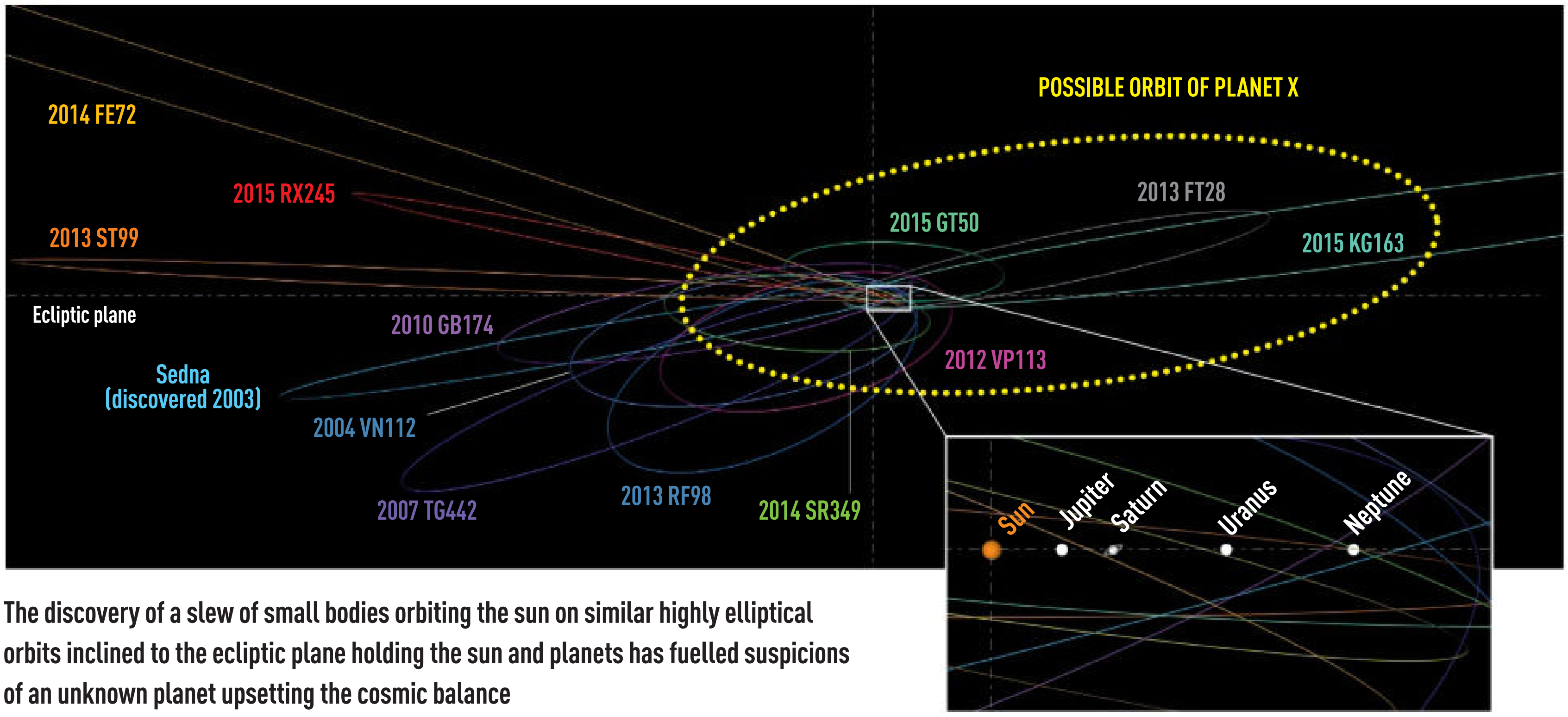
We have since found more trans-Neptunian objects (TNOs) similar to Sedna – and they present the second big puzzle. Several of them orbit in practically the same plane, but this isn't the same as the plane occupied by the solar system's major planets. What's more, viewed from the sun, their points of closest approach all lie in roughly the same direction.

One idea to explain this alignment is that Sedna and its family didn't originally belong to this solar system at all. Stars aren't born in isolation, but in litters of perhaps thousands, where the shock wave of a supernova shakes up interstellar gas. The sun would have had many nearby siblings when it was born, and their gravitational jostling would have left its mark on the early solar system.

In 2015, Simon Portegies Zwart at Leiden University in the Netherlands and his colleagues published simulations showing how a close brush with a bigger sibling could produce the Kuiper cliff, by ripping out any planetesimals beyond about 40 AU. At the same time, more than 2000 planetesimals orbiting the other star would have become bound to the young sun, about half ending up in orbits similar to that of Sedna. Some of these foreign bodies would have been thrown our way, and perhaps a few fragments of them are among our meteorite collections.

If this idea is right, Sedna's name would be strangely appropriate. The Inuit woman after whom it was named was supposedly abducted by a gull-like bird god after her husband abandoned her on a cold, deserted beach – perhaps not so different from the solar ›

The discovery of a slew of small bodies orbiting the sun on similar highly elliptical orbits inclined to the ecliptic plane holding the sun and planets has fuelled suspicions of an unknown planet upsetting the cosmic balance



The discovery of a slew of small bodies orbiting the sun on similar highly elliptical orbits inclined to the ecliptic plane holding the sun and planets has fuelled suspicions of an unknown planet upsetting the cosmic balance

system's frozen outer reaches where the celestial Sedna was found. But there is another way to explain the alignment of Sedna and its siblings. In 2012, Rodney Gomes at the National Observatory in Rio de Janeiro proposed that they might be influenced by an as-yet undiscovered planet hundreds of AU out. Each time one of these objects comes close to this hypothetical planet, its orbit would be altered, eventually causing them all to skew in a similar way.

In January 2016, Brown and his Caltech colleague Konstantin Batygin used the orbits of six extreme TNOs to calculate how big this thing should be and what its orbit should look like. They came up with a Neptune-mass world in a highly elliptical orbit at an average of 400 to 500 AU from the sun, tilted from the plane of the major planets by about 18 to 25 degrees. If this planet exists, it probably hasn't yet completed a single revolution of the sun since woolly mammoths and sabre-toothed cats roamed Earth 10,000 years ago.

Planet X could explain another long-standing mystery, that of the sun's misaligned spin axis. Since the 1850s, we have known that our star rotates on an axis tilted six degrees from the average plane of its retinue of planets. Over the years, astronomers have proposed explanations ranging from magnetic interactions with the primordial disc from which the sun and planets formed to the disruptive influence of an ancient stellar companion that somehow got lost to interstellar space. The presence of planet X could also explain the elongated trajectories of a class of outer solar system bodies called the centaurs, whose orbits cross those of the giant planets. The fact that no one has been able to see this planet yet isn't surprising – it would be far from the sun, so only dimly illuminated.

Then again, it could be something invisible to ordinary telescopes. Jakub Scholtz, a theorist at Durham University in the UK, suggested in 2019 that perhaps we should be looking for a black hole.

One motivation for this extraordinary idea is that there is no easy way to explain how a large planet could have got out there. At the distance it sits today, there wouldn't have been enough raw material to build something that large. It could have formed much closer, then been hurled into the darkness by the gravity of Jupiter or Saturn, but a single interaction can't do the job. Instead, a string of interactions is needed to make sure planet X stays far away.

A second hint came in from much further afield. The Optical Gravitational Lensing Experiment (OGLE) watches stars in the centre of the Milky Way for unexpected increases in brightness caused by gravitational lensing (when light from background sources is bent and magnified by the passage of intervening objects that would otherwise be too small or too faint to be seen). Out of 2600 lensing events that OGLE detected between 2010 and 2015, six turned out to be ultrashort, lasting less than half a day. These signals could be produced by planets – or, as Hiroko Niikura at the University of Tokyo in Japan and his colleagues pointed out in 2019, they could be made

THE OORT CLOUD

You will find it in every astronomy textbook: the spherical cloud of a trillion lumps of rock and ice that forms the outermost boundary of our solar system. Starting at perhaps a few thousand astronomical units from the sun, the Oort cloud's distant edge could lie some 100,000 times further out from the sun than Earth, more than a third of the way to its nearest stellar neighbour, Proxima Centauri.

At least, we think so. The Oort cloud's existence was hypothesised in 1950 by Jan Oort, with the justification that long-period comets, swinging by the sun on orbits that take hundreds or thousands of years, must come from somewhere. The idea is that the gravity of nearby stars and the galaxy as a whole can disturb objects in the Oort cloud, occasionally slingshotting them towards the inner solar system.

We have never seen the cloud directly, as denizens exist in almost total darkness and would be far too faint for us to spot. In June 2021, however, we spotted its biggest present to us yet, when astronomers announced the discovery of comet C/2014 UN271 (Bernardinelli-Bernstein) beyond the orbit of Uranus. The solid nucleus inside the coma of dust and gas that surrounds it was subsequently measured to be about 137 kilometres across – more than half the length of Wales.

This makes it twice the size of its closest known competitor, comet Hale-Bopp, discovered in 1995. There is another non-Oort cloud comet that is technically larger – 95P/Chiron, which orbits between Saturn and Uranus and is thought to have a diameter of around 210 kilometres – but its status as a comet or minor planet is debated.

Comet Bernardinelli-Bernstein will make its closest approach to the sun in 2031 at 10 times the Earth-sun distance, and will be closely watched by telescopes – including the James Webb Space Telescope – before flying out into the solar system again on an orbital path that may last millions of years.

by black holes of a few Earth masses.

Scholtz noted that the alignment of mini-worlds in the outer solar system indicated an object of similar mass. Could it be a black hole too? If so, this would be one of the smaller significant bodies in our solar system. A hole of around 10 Earth masses, big enough to stand in for planet X, would have a diameter of about 18 centimetres. It could even be a clue to the origins of the universe, because the only way such small black holes might be formed, as far as anyone knows, is by the ultradense maelstrom existing in the very early moments of the big bang. And it could be evidence that such primordial black holes comprise dark matter, the mysterious substance that holds galaxies together.

Finding out whether there really is a black hole in our solar system won't be easy. Optical telescopes would never see it. X-ray telescopes stand a chance, because material falling into this little black hole would heat up and give off a burst of X-rays. The catch is that these flashes would be fleeting, so we would have to be looking in exactly the right direction at exactly the right time.

Perhaps the best way to catch a primordial black hole is to look for the thing it has in abundance: gravity. Slava Turyshev at NASA's Jet Propulsion Laboratory in California has suggested using a fleet of miniature spacecraft powered by solar sails. Deviations in their expected trajectories could reveal any massive object lurking out there – be it a planet or a black hole.

In the past few years, the evidence for a hidden presence at the edge of the solar system has been questioned. In 2020, Kevin Napier at the University of Michigan and his colleagues analysed the orbits of 14 TNOs from three different sky surveys. They found no sign of an orbital alignment that would point to an extra planet in the solar system. But other astronomers still suspect something is out there.

The Vera C. Rubin Observatory in Chile should settle the question. Due to start observing in 2023, it is expected to find tens of thousands more mini-worlds in the remote reaches of the solar system. Their orbits should prove once and for all whether there really is a massive object out there, and even allow astronomers to precisely predict its location – at which point the telescope can take a closer look. If it sees a planet, that will be a huge deal. If it doesn't see anything, and yet the anomalous alignment remains, that might be time to launch the solar sails. ▮

'Ouamuamua is a Hawaiian phrase meaning "a messenger from afar arriving first"

'OUAMUAMUA: AN INTERSTELLAR INTERLOPER

An unexpected arrival five years ago made plain that travellers from far-off star systems are among us. They raise fundamental questions about how planetary systems are made.

THE twin detectors of the Panoramic Survey Telescope and Rapid Response System, Pan-STARRS, sit atop a 3000-metre peak in Hawaii, constantly scanning the sky for space rocks straying too close. On the night of 19 October 2017, they spotted a dim trail of light, fast moving against the starry backdrop. This object wasn't orbiting the sun, it was paying us a visit from far outside our solar system.

Asteroids or comets orbiting the sun generally follow closed, elliptical paths. This object's trajectory was an open curve, a hyperbola, meaning it couldn't be orbiting the sun. It had already made its closest approach, and was racing away at 38 kilometres per second, fast enough to escape back into interstellar space.

There are plenty of things that could throw debris out of other solar systems: violent impacts, the gravity of migrating planets, a nudge from a passing star. The objects most likely to be ejected are icy bodies on the periphery of their planetary systems, much like those in our Kuiper belt and Oort cloud. Although on the small side for a comet, with a length around a few hundred metres, the object at first seemed unexceptional. It was spinning head over heels through space, much as comets do, with a rotation period between 7 and 8 hours. Its colour was a dull red hue familiar from the comet 67P/Churyumov-Gerasimenko, investigated by the Rosetta spacecraft from 2014 to 2016 – a shade shared by around 15 per cent of objects in the Kuiper belt. In the solar system, this colour is produced by 4.6 billion years' worth of solar ultraviolet light reacting with simple carbon-based molecules such as methane to produce the complex, ruddy-coloured organic compounds called tholins.

But that was it for similarities. When comets from our solar system's recesses approach the sun, some of their ice turns to gas, forming a visible atmosphere called a coma, and often a tail. Here, there was no evidence of such activity. The object seemed inert, an asteroid-like rock. Its official designation was changed to A/2017 U1 (A for asteroid), and then to 1I/2017 U1 'Ouamuamua, the "I" referring to its interstellar origin, and "'Ouamuamua" to a Hawaiian phrase meaning "a messenger from afar arriving first".

'Ouamuamua's lack of cometary characteristics could point to an origin closer to the centre of the planetary system it formed in. Or perhaps during the object's long journey through interstellar space, bombardment by cosmic rays removed its ice, or drove chemical reactions that formed a thick crust of tholins encasing the object, preventing 'Ouamuamua from outgassing and growing a dust tail as it passed the sun.

EUROPEAN SOUTHERN OBSERVATORY / M. KORNMESSER

The shape was a bigger surprise. As ‘Ouamuamua receded, spinning head over heels, its brightness changed as light reflected from sides of different sizes. The light varies by a factor of 10:1, suggesting that it is 10 times longer than it is wide. There is nothing native to our solar system with dimensions like that. Because we are seeing the object at an angle relative to the sun, light may only be reflecting off part of it, and this could exaggerate its length. Another estimate puts the ratio at a more conservative 6:1. It could be a long cigar shape, or more like a disc.

It is certainly unlike most objects in our neighbourhood, which tend to be rounded or lumpy – a natural consequence, we think, of the accretion processes that formed them. ‘Ouamuamua could simply be a statistical outlier. Or perhaps objects often form with elongated shapes, which are ground down over the aeons by collisions – and ‘Ouamuamua happened to be ejected from its home system before it could be eroded. It could be a shard of a planet that got too close to its star and was ripped apart. Or maybe there is something more fundamental amiss, and we need to revisit our accretion models to explain how planetary building blocks can adopt such a strange shape.

As ‘Ouamuamua moved past the sun, it started to speed up, more than could be accounted for by gravitational forces alone. The simplest explanation was that, like a comet, it was releasing dust and gas as the sun heated it, which would act as a sort of thruster to push it forward. But observations showed that there was no small-grained dust coming off ‘Ouamuamua, and none of the gases that we looked for showed up. That led some researchers to speculate that it might be large and flat, like a solar sail, and the sun’s light alone was pushing it to speed up. A few even pondered whether it could actually be a solar sail constructed and sent here by aliens – but others have pointed out this doesn’t fit the tumbling rotation, as a solar sail would have to stay aligned with the sun to give it the observed acceleration. Instead, ‘Ouamuamua could be getting a push from outgassing water vapour, just at a lower level than we were able to detect.

Finding the home system of ‘Ouamuamua would provide a great deal of context about it. While we can’t say anything for definite, by tracking its trajectory back and simulating the motions of stars to see which ones it might have passed close to, we can make some educated guesses. Two suggestions are the Local Association, a group of stars associated with the Pleiades star cluster some 440 light years away, and the young stellar clusters found in the constellations of Carina and Columba. If either proposition is correct, then ‘Ouamuamua would be relatively young: the stars of the Local Association are no more than 150 million years old, and the young clusters in Carina and Columba are just 45 million years old.

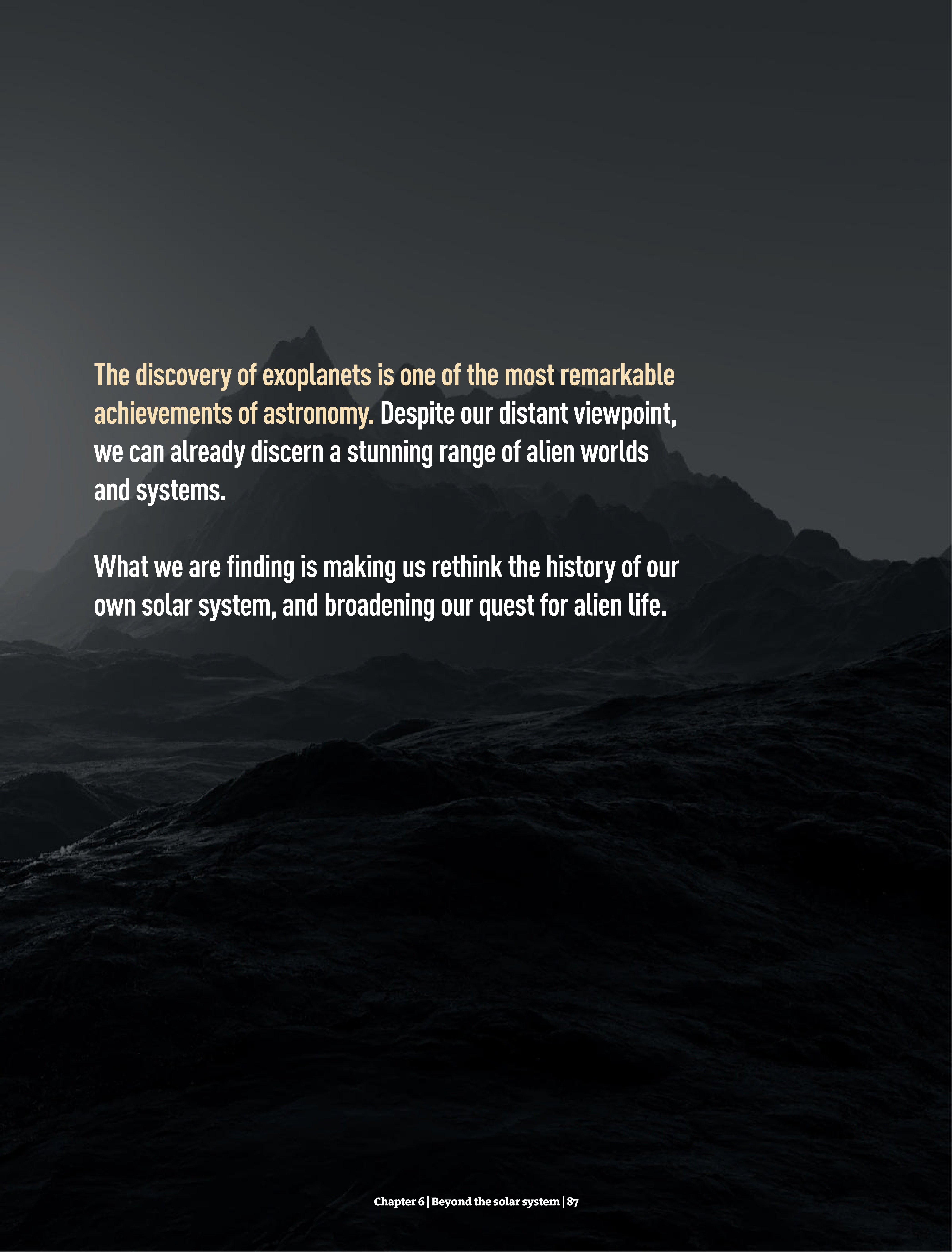
In August 2019, we saw a second interstellar object, comet Borisov. Because it was spotted earlier in its journey through the solar system, we were able to observe it in more detail. Borisov has far more carbon monoxide than comets in our solar system usually do, but the amount isn’t consistent across the entire object. That probably means it started forming relatively close to its home star before moving outwards. The light reflecting off Borisov’s coma was highly polarised and the coma was also remarkably smooth, both of which imply that the comet was in a pristine state, essentially unchanged since its formation.

The detection of ‘Ouamuamua and Borisov suggests that there are many interstellar objects travelling around our galaxy at any given moment. Indeed, there may be many going undetected within the solar system. By one estimate, 10,000 interstellar objects of a similar size to ‘Ouamuamua are passing through the solar system within the orbit of Neptune at any one time.

Such objects could play a role during the birth of solar systems. How you grow from dust in a disc to larger objects is an unsolved problem, known as the metre-size barrier. Interstellar objects could be the answer. The low speed of young stars relative to their neighbours, coupled with the braking effect of the dust and gas that surround them, could cause these objects to enter orbit around a star rather than simply passing through. Then they could act as seeds to help the dust to condense into planetesimals. ∎

CHAPTER 6

BEYOND THE SOLAR SYSTEM



The discovery of exoplanets is one of the most remarkable achievements of astronomy. Despite our distant viewpoint, we can already discern a stunning range of alien worlds and systems.

What we are finding is making us rethink the history of our own solar system, and broadening our quest for alien life.

WORLDS BEYOND

In retrospect, the discovery of the first planet orbiting another sun-like star shouldn't have been such a surprise.

BACK in the early 1990s, most astronomers suspected that other planets were out there somewhere, but they thought these objects would be too small and dark to be detectable, lost in the glare of the stars they orbit. Few tried to hunt for exoplanets. "It would have been considered a really silly topic for my thesis," says Didier Queloz, who was a PhD student at the University of Geneva at the time.

His PhD advisor, Michel Mayor, was an authority on analysing the spectrum of light coming from stars. Two decades earlier, he had developed a spectrograph that could detect the Doppler shifts in a star's light caused by a massive object nearby. For example, in a binary star system, in which two stars orbit around their common centre of gravity, the gravitational pull of one star affects the radial velocity of its partner star, causing it to wobble slightly in its orbit.

Between them, Queloz and Mayor improved the sensitivity of the instrument so much that they realised it might allow for the detection of giant planets. So they decided to start looking. They picked 100 stars that no one had paid much attention to and settled in for what they thought would be a decade of data gathering, the kind of timescale that it takes for Jupiter to go around the sun. "Michel told me to start looking at the radial velocities, then he went on a sabbatical to Hawaii," says Queloz.

That was May 1994. In July, Queloz first looked at 51 Pegasi, a star 50 light years away, and by September, he was puzzled. The star's radial velocity

The HD 209458 b transit discovery was the first time an exoplanet was seen crossing its star

NASA, EUROPEAN SPACE AGENCY, ALFRED VIDAL-MADJAR (INSTITUT D'ASTROPHYSIQUE DE PARIS, CNRS)
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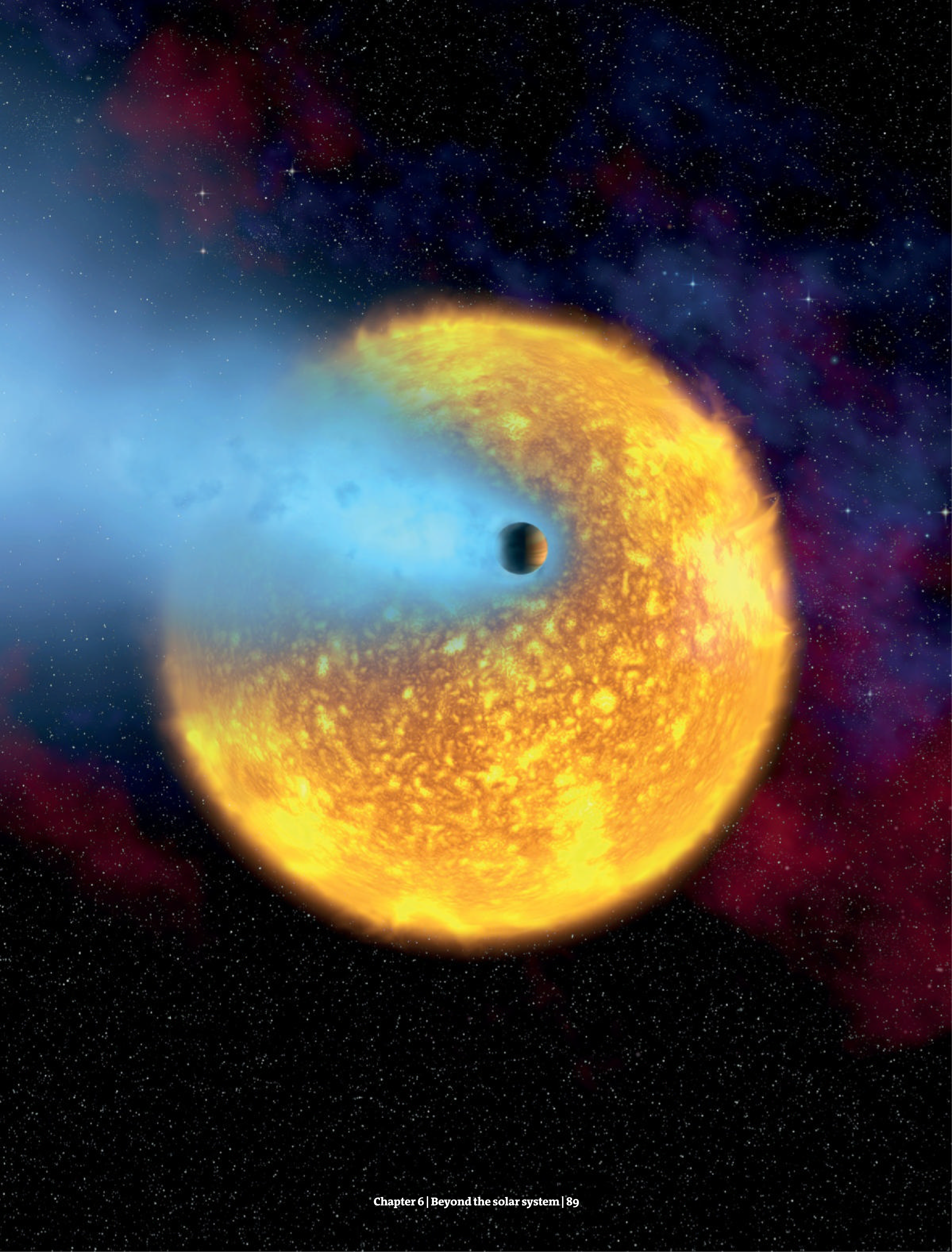


kept changing in ways Queloz didn't understand: the wobbles were too small for a binary star system, but the value was changing way too fast to be caused by a planet. He was initially convinced it was caused by a bug in the software, but he couldn't find one, and the wobbles didn't appear when he looked at other stars.

By March 1995, Queloz decided it must be a giant planet, whizzing around 51 Pegasi once every 4.2 Earth days, orbiting much more closely than Mercury orbits the sun. Nobody expected to see a gas giant in such a tight orbit. It was a conclusion bordering on scientific heresy.

51 Pegasi b it turned out to be the first of a new type of world, a hot Jupiter. And that was just the start.

In 1999, two PhD students, David Charbonneau and Timothy Brown, used a home-built telescope to observe a hot Jupiter known as HD 209458 b passing in front of its star and blocking out some of the starlight. This transit method revolutionised exoplanet-hunting: in the past 20 years, astronomers have used it to detect thousands of exoplanets.

We now know our galaxy contains a panoply of worlds and systems. As well as hot Jupiters, there are super-Earths (rocky planets larger than Earth) and mini-Neptunes (little ice giants, some of which might even host planet-wide liquid-water oceans). As we find more and more exoplanets, it seems that anything goes – with huge implications for our understanding of our own solar system.

↓
See later in this chapter for more on how our solar system fits in

The haul of confirmed worlds is more than 5000 and climbing. Some, such as the seven Earth-scale planets of the TRAPPIST-1 system, have truly captured the popular imagination. "We didn't realise that the discovery of other worlds would mean so much to the public," says Queloz. ∎

FIVE OFFBEAT EXOPLANETS

Among the 5000 or so known exoplanets, there are plenty of oddballs. These are just a few.

55 CANCRI E – SUPER-HOT SUPER-EARTH

A rocky world about twice the size of Earth and nine times as massive, 55 Cancri e orbits its sun-like star every 18 hours. That means it is 25 times closer to its star than Mercury is to the sun. The interior of this scorching hot, carbon-rich world may be made mostly of diamond and graphite.

ROSS 128 B – A HOME FROM HOME?

Tucked inside the habitable zone of a cool M dwarf star, this is one of the most Earth-like exoplanets ever discovered. It seems to be rocky and boasts a mild climate, with estimated temperatures ranging from -60°C to 20°C. What's more, its parent star isn't as active as most M dwarfs, raising the chance of it being habitable.

HAT-P-7B – CLOUDY WITH A CHANCE OF GEMSTONES

A gas giant some 40 per cent larger than Jupiter, HAT-P-7b is tidally locked, so one face has permanent day and is baked to a searing 1900°C. Early indications are that its night-side atmosphere harbours clouds of vaporised corundum, the mineral that makes up sapphires and rubies.

KEPLER-7B – THE POLYSTYRENE PLANET

Although much larger than Jupiter, this gas giant is only a tenth as dense – about the same as polystyrene – making it one of the most diffuse exoplanets ever discovered. Heat from the parent star must have something to do with it, though the mechanism behind it remains unclear.

KEPLER-16B – THE WORLD WITH A DOUBLE SUNSET

Just like Tatooine from the *Star Wars* movies, Kepler-16b orbits two stars. Unlike Luke Skywalker's home planet, however, it is cold, gaseous and not considered a candidate for extraterrestrial life.

HOW GREEN IS OUR GALAXY?

It is perhaps the biggest question in the universe: are we alone? The only answers so far have been educated guesswork at best – but among the throng of exoplanets, more and more look like they could support life.

TO SOME people, the sheer size of the universe makes it unlikely that life formed only once. To others, the remarkable complexity of life on Earth is testament to its uniqueness. The huge uncertainties in estimating the likelihood of life are encapsulated in a famous equation formulated by astronomer Frank Drake (see page 92).

But we may be in sight of a real answer, thanks to new telescopes that will let us study exoplanet atmospheres and surfaces – and, if we are lucky, reveal the first signs of life beyond Earth.

To work out what we should be looking for, it helps to reverse our point of view. If alien astronomers were observing Earth from a remote star system, would anything about it grab their attention? Compared with our rocky neighbours Mars, Venus and Mercury, the distinctive mix of oxygen and methane in Earth's atmosphere would be sure to trigger interest. Oxygen makes up 21 per cent of the atmosphere now and is entirely due to life, entering the atmosphere from photosynthetic bacteria and plants that convert sunlight into energy.

←
Turn page to page 18 for more on sensing life on Earth from space

A lifeless planet might hold either oxygen or methane, but not both together, because they react and destroy each other. Methane can be produced by volcanoes and hydrothermal vents, and oxygen could be formed when radiation from an active star splits molecules of water into hydrogen and oxygen, with the lighter hydrogen escaping from the planet's atmosphere. But such geological processes produce these gases at a relatively low rate – so finding oxygen and methane coexisting in appreciable quantities on a distant planet is a pretty good indicator that life is churning them out. ›

Frank Drake's 1961 equation remains the best method to get a rough sense of how many detectable alien civilisations should exist within our galaxy (N). According to the latest data, that number is somewhere between 1 – our lonely selves – and an impressive 4 billion

DRAKE EQUATION

$$N = R^{*} \times f_{p} \times n_{e} \times f_{l} \times f_{i} \times f_{c} \times L$$

- N: Communicative civilisations
- R^{*}: Rate of star formation
- f_p: Fraction of stars with planets
- n_e: Number of habitable planets per star
- f_l: Fraction of those planets that develop life
- f_i: Fraction of those planets with intelligent life
- f_c: Fraction of civilisations that release detectable, technological signals
- L: Lifetime of those civilisations

Life on Earth produces thousands of other promising biosignature molecules, including methyl chloride, dimethyl sulphide and nitrous oxide. Another promising target is phosphine, a gaseous compound of phosphorus and hydrogen that is produced on Earth by anaerobic microbes, which don't rely on oxygen to survive. Its discovery in the atmosphere of Venus in 2020 caused a brief flurry of interest in life existing there. The gas, the simplest that can't be produced by any natural processes as far as we know, should be relatively easy to detect in an exoplanet's atmosphere.

There are many other potential habitability signatures to be gleaned from exoplanet atmospheres, too. Astronomers can sense exoplanet chemistry using transits, the tell-tale dips in the brightness of stars as orbiting planets pass in front of them. As light from the host star passes through the planet's atmosphere, different colours are absorbed depending on which gases are present. The resulting gaps in the spectrum we see from Earth can tell us what the planet's atmosphere is made of.

This has already been achieved for gas giants, and soon several new missions and instruments will aim to identify molecules in the atmosphere of an Earth-like exoplanet. The first is NASA's James Webb Space Telescope, which launched in February 2022. ARIEL, a European Space Agency mission due to launch in 2029, will join in, along with large ground-based telescopes such as the European Southern Observatory's Extremely Large Telescope, due to start observing in 2027.

An even more ambitious aim is to analyse light reflected off the surface of an exoplanet, to look directly for living material. Light is an electromagnetic wave, made of vibrating electric and magnetic fields. Usually, the light we encounter from the sun or a light bulb is unpolarised, meaning that the electric field points in all directions. Polarised light, on the other hand, vibrates in particular directions. Starlight becomes partially polarised when it reflects off a planet's surface, and the way it is polarised should contain clues about what is there. Crucially, plants on Earth produce a distinctive kind of polarisation that no non-biological substance is known to mimic.

The catch is that polarised light reflecting off distant planets is extremely difficult to observe. It is dimmer than the light coming from a star via an atmosphere. And only 1 per cent of the reflected light is polarised, making the signal fainter still. Yet in January 2021, two separate teams announced they had detected polarised light from an exoplanet. Both are gas giants, so now astronomers have to refine the detection techniques so that they can repeat the feat for smaller, more Earth-like planets.

The next big question is where to point our telescopes. In the quest to find life beyond our solar system, we have long sought the familiar: an Earth-like planet orbiting a sun-like star in the habitable zone or at just the right distance to have liquid water. But that view is changing.

When NASA's Kepler space telescope launched in March 2009, ground-based telescopes had detected just 300 or so exoplanets. It found around 2600 more.

Nothing generated as much excitement as the 30 "Earth-like" exoplanets Kepler has turned up. These worlds qualify for that label by being less than twice Earth's size and orbiting within their star's habitable zone. Kepler-452b, announced in 2015, is one of the most Earth-like. At 1.6 times the size of our planet, it stands a good chance of being rocky. And its parent ›

SCIENCE HISTORY IMAGES / ALAMY STOCK PHOTO

MISSION TO PROXIMA CENTAURI

We have learned in the past few years that Proxima Centauri, the nearest star to the sun, has its own system of planets. The most exciting among them is Proxima b, which seems to be a little larger than Earth, and orbits in the habitable zone of its star – although that doesn't necessarily mean the planet really is habitable. Any life there would somehow have to cope with the nasty outbursts of X-rays and ultraviolet from the star.

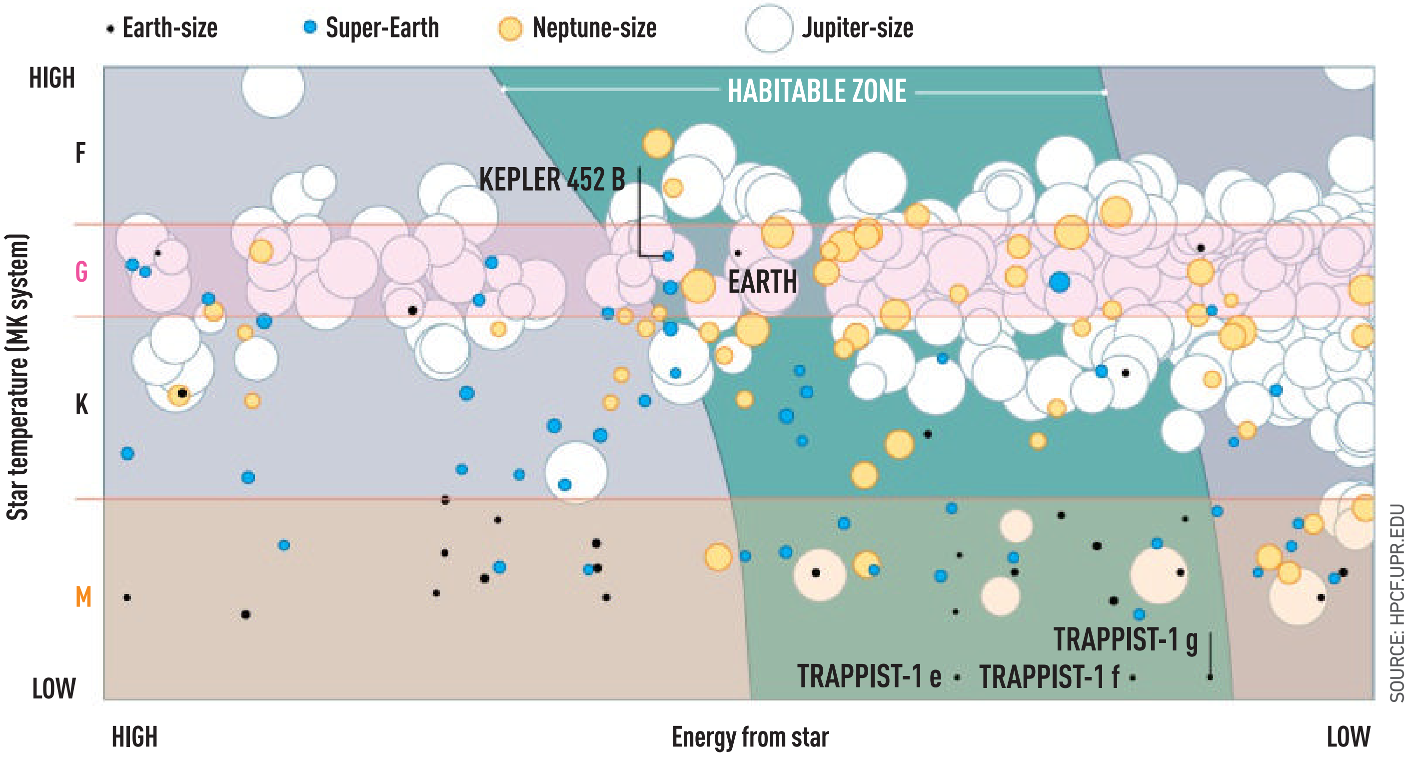
Then there is Proxima c, with a few times Earth's mass, probably a small gas giant. It is much brighter than expected, suggesting that it is surrounded by a huge disc of dust or a shining system of rings bigger than Saturn's. A third, tentatively detected, planet appears to have a mass one-quarter that of Earth, one of the lightest exoplanets ever found.

The Proxima system might be our neighbour in interstellar terms, but it is still 4.2 light years away, almost 2000 times as far off as the Voyager 1 spacecraft. Using conventional rockets, the journey would take tens of thousands of years, but one project aims to reach it within decades.

The Breakthrough Starshot project, announced in April 2016, envisages hundreds of tiny spacecraft, each equipped with a "light sail" and the minimum amount of hardware needed to record and transmit information. An enormous array of lasers on Earth's surface would shoot photons that would exert pressure on these light sails, just as the wind exerts pressure on a boat sail, and accelerate them to about a fifth of the speed of light – some 60,000 kilometres per second – within just 10 minutes. They would coast past the orbit of Mars 20 minutes later, go beyond Pluto within 7 hours and get to Proxima Centauri in 20 years.

There are lots of ifs to this idea. The initiative's researchers will have to build electronics and antennae that are sufficiently light, but also powerful and accurate enough to beam images back across 4 light years. They need to build the most powerful laser system ever seen, capable of generating around 60 gigawatts of light output, and persuade governments that it isn't a superweapon that could fall into the wrong hands. They also need to ensure that the lasers can hit the small light sails accelerating away from Earth at immense speeds, and steer them to the target – and develop an ultralight fabric that can be hit by gigawatts of laser light without being vaporised.

Most of the exoplanets we have found around sun-like or "G-type" stars are gas giants: too hot and gassy to host life. Rocky, Earth-sized planets in the habitable zone, where liquid water can exist, seem to be more common around cooler M dwarf stars



star is similar to our sun, albeit roughly 1.5 billion years older and thus slightly larger and brighter.

But Kepler observations suggest that there are far more potentially habitable planets orbiting M dwarfs, stars that are much smaller and cooler than our sun (see diagram, above). M dwarfs make up about two-thirds of all stars, including most of our nearest neighbours. Estimates based on Kepler data suggest that between a quarter and a third of them host rocky worlds in their habitable zone. An example of this abundance is an ultra-cool star called TRAPPIST-1. In 2017, astronomers found that it has no less than seven rocky planets. Surprisingly, three are squeezed into the habitable zone. Models had suggested that it shouldn't be possible for so many planets to orbit so close to one another.

Many astronomers now think M dwarfs are our best bet for finding signs of extraterrestrial life, in part because they orbit so rapidly that we can watch many transits one after another, building up data on their atmospheres. Others question how habitable M-dwarf planets might be. These planets are generally tidally locked, with one side constantly facing the star. The dayside would probably be too sun-baked to be hospitable, the nightside too cold. The best hope for life on these "eyeball worlds", assuming that bizarre weather patterns don't interfere, might lie in the razor-thin band where there is perpetual twilight.

To be warm enough for liquid water, they must orbit close to their star, and M-dwarfs tend to be volatile, both of which means planets are bathed in radiation and solar flares. But advocates for M dwarfs point to studies suggesting that dense atmospheres and planetary magnetic fields might offer some protection from solar winds and radiation.

All sorts of other unusual extraterrestrial havens have been suggested. There is no reason why a planet that orbits a binary star shouldn't be habitable, for example. And perhaps we should expand our idea of the habitable zone to include worlds closer to their stars. There is evidence that Venus may once have borne liquid water – and a climate model of the young Venus published in March 2020 showed a large cloud settled directly under the sun's glare, reflecting back much of its heat.

How about planets around white dwarfs – the little, hot cinders of sun-like stars? In April 2020, Thea Kozakis at Cornell University in New York published calculations implying that planets could exist in the habitable zone of a white dwarf for up to 8.5 billion years – longer than Earth's residence to date in the sun's habitable zone. One catch is that as white dwarfs kick out less heat than normal stars, the habitable zone would be much closer in, with years lasting a matter of days. Like the planets of M dwarfs, they would almost certainly be tidally locked.

Or why bother with a star at all? Models show that many solar systems lose a planet at some point. Deprived of sunlight, some form of life might be sustained by chemicals and heat from within the planet. We have already found Earth-mass rogue planets wandering between the stars, thanks to gravitational lensing. When one of these planets passes in front of a distant, unrelated star, its gravity acts as a lens that temporarily magnifies the star's light. Based on his detections so far, Przemek Mróz at the California Institute of Technology estimates that there are between one and three Earth-mass rogue planets for each of the 100 billion stars in the Milky Way. We could soon be finding a lot more of them thanks to the Nancy Grace Roman Space Telescope that will launch in 2026 and observe microlensing events.

Buried oceans on exomoons are also plausible habitats, as they are on Europa and Enceladus in our own solar system. The drawback, as with rogue planets, is that such life would be immensely difficult to detect from Earth.

←
Turn back to page 62 for more on prospects for life on Europa and Enceladus

Of course, life on a distant world may be totally different from that on Earth. It could be based on silicon rather than carbon, or run on unknown metabolisms that use a liquid other than water. That increases the possible range of inhabited worlds still further, as they could be far outside our narrow idea of a habitable zone where liquid water flows on the surface. For these types of weird life, synthetic biology and research into alternative biochemistries could help us understand what unique chemicals to look for. ∎

IS OUR SOLAR SYSTEM UNIQUE?

The discovery of the huge diversity of planetary systems out there has begun to revolutionise our view of home.

BEFORE the rush of exoplanet discoveries, astronomers tended to assume that our own solar system was the template for others. They were sure that we would soon find sister systems, with little rocky planets in the middle, a few gas giants further out, all following near-circular orbits – an orderly arrangement reflecting an orderly process of formation. Of course, it didn't quite work out like that.

Hot Jupiters were the first surprise. They seemed to be the wrong worlds in the wrong place. To make a gas giant planet like Jupiter, you first need to grow a solid core of material several times Earth's mass, a centre of gravity around which gas can accumulate. The torrent of radiation near a young star makes this impossible. And yet our exoplanetary observations reveal that these planets are startlingly common.

Hot Jupiters must have formed elsewhere and moved closer. The favoured theory is that this happens very early in planet formation, when there is still a lot of material in the disc of gas and dust surrounding a new star. As › a young giant grows, its gravity can create density differences across the gas disc, which, in turn, pull on the planet, causing it to spiral inwards or outwards.

This kind of migration turns planet formation into a dynamic process, and helps explain other exoplanet oddities. HD 37605 b is a gas giant that follows a highly elliptical orbit like a comet's. The Kepler-20 system has two Earth-sized planets slotted between three Neptune-sized worlds. In Kepler-90, eight planets from Earth-size to Jupiter-size are squeezed into orbits all closer to their star than we are to the sun. These all point to the idea that the solar systems today aren't in the shape in which they originally formed.

A different kind of migration has been used to help explain the shape of our own solar system. According to the Nice model, our giant planets moved around in a complex gravitational dance long after they were formed, giving Neptune and Uranus their distant orbits and scattering comets around.

←
Turn back to page 28 for more on planetary migrations

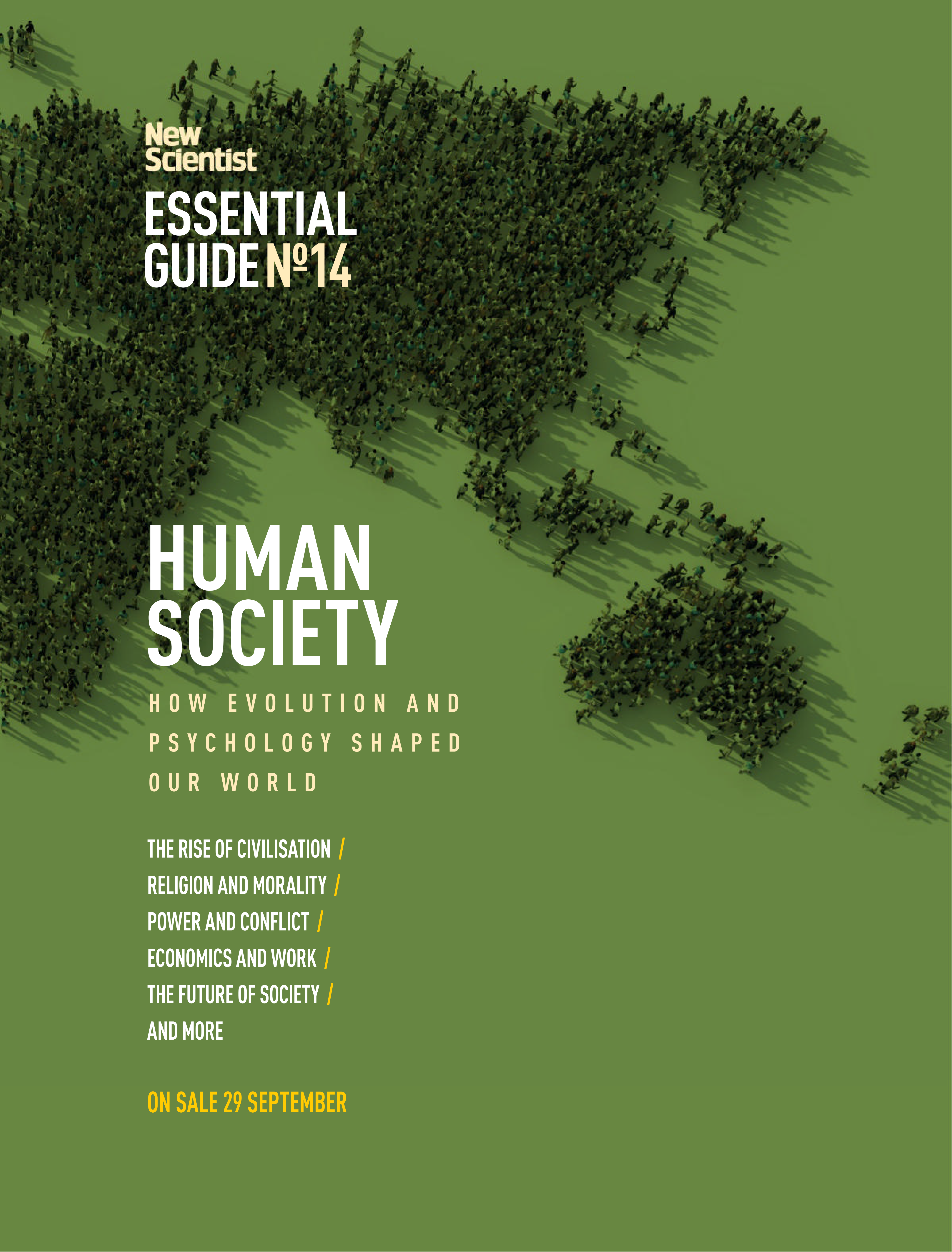
This could also account for why we don't have any worlds of medium size, between rocky planets like Earth and gas giants. When we look beyond the solar system, we find a lot of mid-range planets – the super-Earths and mini-Neptunes. They make up more than half the planets we know, implying that they are easy to make. Their absence here could be explained if Jupiter migrated inwards at some point, disrupting the space in which a super-Earth would have formed.

What is unclear is whether there are many planetary systems out there like ours. So far, few have been found with gas giants orbiting at Jupiter-type distances.

One reason may be how we find exoplanets. Every detection method has an inbuilt sensitivity towards detecting certain types of worlds. For example, the method originally used by astronomers Michel Mayor and Didier Queloz, a radial velocity survey, is most sensitive to large planets very close to their stars. The transit method, used so effectively by the Kepler space telescope, tends to find highly compact planetary systems. Such biases mean it is hard to make definitive statements yet about what is "normal". Solar systems like ours could be relatively common, but we just haven't seen them yet.

Or maybe chaos reigns. Thanks to the Nice model, we are realising just how sensitive planet formation is to the details of the process. While the model was designed to reproduce the solar system, tweak it slightly and you get a whole different planetary system. For example, Neptune could be flung right out of the system rather than shunted into a distant orbit, or Earth could be forced onto an elliptical orbit that would make it uninhabitable. In general, migration could randomise the shape of planetary systems, in which case we shouldn't expect to find many that look like ours.

New information is on the way. The European Space Agency (ESA)'s Gaia mission and the European Southern Observatory's Very Large Telescope Interferometer both look for exoplanets in a different way, watching for how stars change position in response to the gravity of planets. ESA's 2026 Plato mission, a souped-up successor to Kepler, has been optimised to search for Earth-sized planets in the habitable zones of sun-like stars. They could finally find twins of the solar system... or, by not finding them, provide a sobering new insight. Instead of being a typical planetary system, maybe our home is really quite freakish. ▮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