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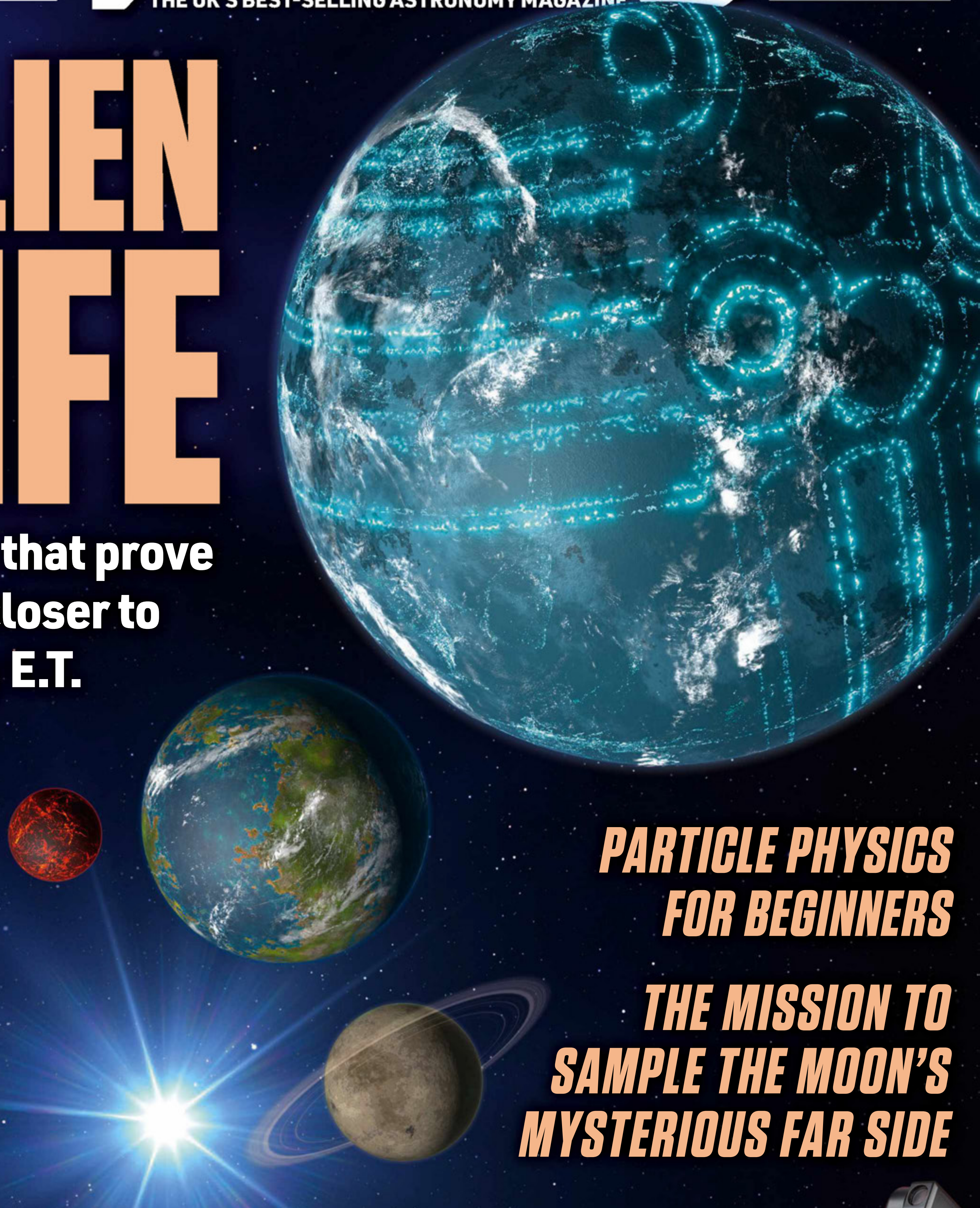

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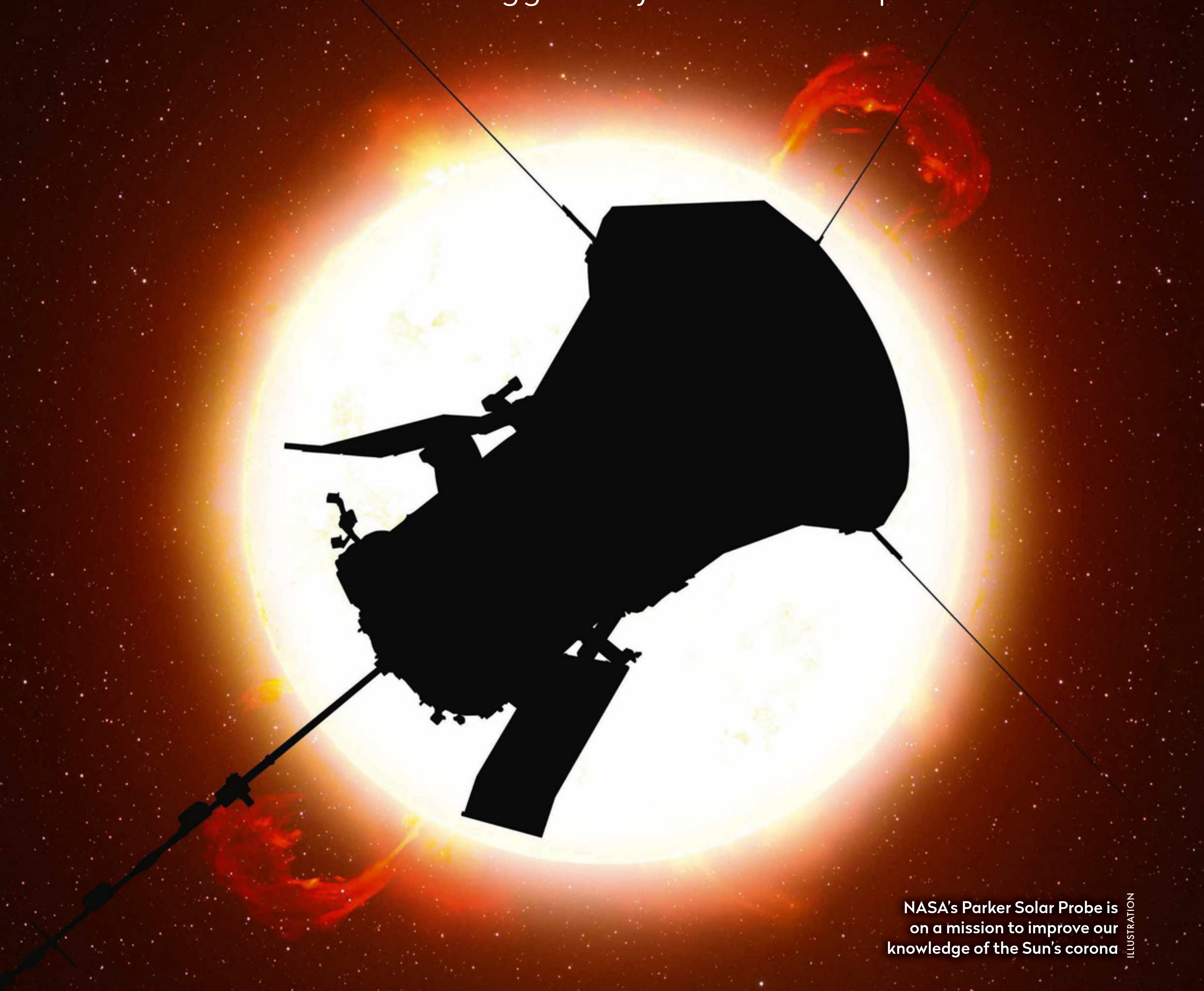
Touching the SUN

The Parker Solar Probe will come nearer to the Sun than any spacecraft in history. **Jane Green** looks at how it will solve one of our star's biggest mysteries in the process



NASA's Parker Solar Probe is on a mission to improve our knowledge of the Sun's corona

ILLUSTRATION

▲ The Parker probe launched from Cape Canaveral on a Delta IV rocket on 12 August 2018

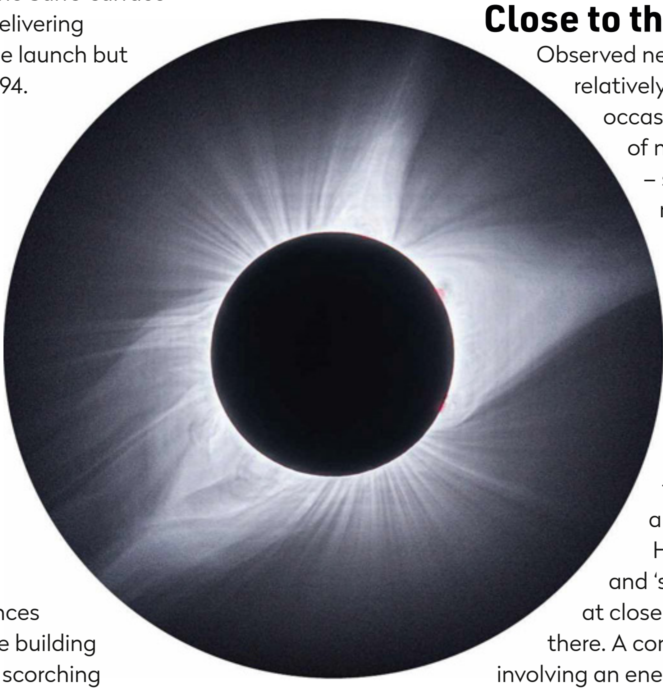
On 12 August 2018, NASA's Parker Solar Probe (PSP) blasted off from Cape Canaveral Air Force Station into the pre-dawn Florida sky on a mission to become the first-ever spacecraft to 'touch the Sun'. Later this year, on 24 December 2024, Parker will come seven times closer to the Sun than any spacecraft before it, diving through its outermost atmosphere, the corona, and in the process smashing its own speed record to become the fastest human-made spacecraft ever launched.

In yet another first, NASA named the probe for a living individual: visionary astrophysicist Professor Eugene Parker who, in the mid-1950s, proposed theories about how stars emit energy. He called this flow of energy the solar wind, and described the complex system of plasmas, magnetic fields and energetic particles comprising the phenomenon. He also posited a controversial theory for why the corona was so much hotter than the Sun's 'surface' – a theory for which the Probe is delivering evidence. Prof Parker witnessed the launch but sadly passed in March 2022, aged 94.

The goals of this modern-day Icarus are to trace the flow of energy heating the Sun's outer atmosphere, to shed light on the birthplaces of the solar wind and to explore how the wind's energetic particles are transported and accelerated. By getting up close and personal with our nearest star, it's hoped PSP will resolve another long-standing question: why the corona is so much hotter than the Sun's 'surface', a paradox known as the coronal heating problem (see page 63).

It took six decades before advances in thermal engineering enabled the building of spacecraft that can survive the scorching temperatures, high-energy radiation and magnetic fields filling the Sun's upper atmosphere, or corona. Invisible due to the overpowering brilliance of the photosphere, the corona is most readily seen when the Moon covers the Sun during a total eclipse, or when a circular coronagraph blocks our star's disc.

Temperatures in the corona exceed a colossal 1,000,000°C (1,800,000°F), hot enough to rip electrons from atoms to form plasma – where negatively charged electrons have separated from positively charged ions, creating a sea of free-floating particles with individual electric charge. This X-ray and UV-emitting material, carrying electric and magnetic fields, escapes the Sun at 1.61–3.22 million km/h (1–2 million mph) in the form of the solar wind – a continuous outflow of ionised gas filling the entire Solar System and forming a giant bubble, the heliosphere, spanning more than 16.1 billion km (10 billion miles).



▲ From Earth, the Sun's corona only really becomes visible when there is a total solar eclipse

Close to the source

Observed near Earth, the solar wind is a relatively steady flow of plasma with occasional turbulence, a consequence of magnetically-driven eruptions – solar flares and larger coronal mass ejections – exploding from the surface. Once it has travelled over 150 million km (93 million miles), though, the signatures of our star's mechanisms for heating and accelerating the wind are lost. By getting close to the solar wind's source, where it transitions from sub- to supersonic, Parker is capturing a very different picture.

However, to directly observe and 'sample' the coronal furnace at close range, Parker first had to get there. A complex flight plan was developed, involving an energy-boosting launch aboard a Delta IV-Heavy rocket and, by June 2025, 24 highly elliptical orbital loops around our star, accelerating as it neared perihelion (the closest point to the Sun in its orbits) and slowing when reaching aphelion (the furthest), cosying up with each approach.

These large petal-shaped loops mean Parker spends less time in the Sun's extreme environment, avoiding possible charging effects and radiation damage to materials and electronics, and securing data communication (see 'Parker's design features', page 65). It has taken six gravity-assisted fly-bys of Venus to slow the spacecraft down and tighten its ▶

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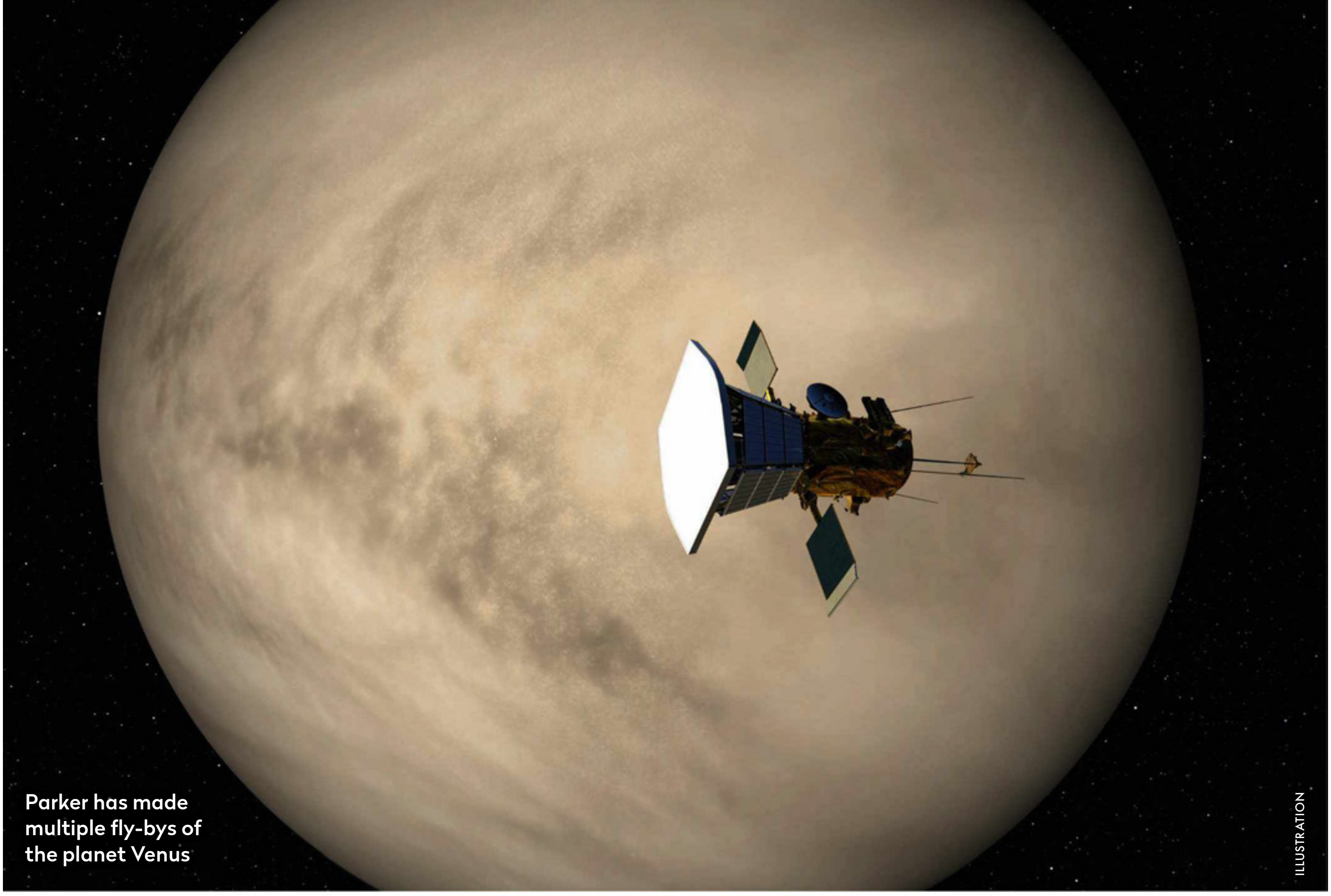


Parker has made multiple fly-bys of the planet Venus

ILLUSTRATION

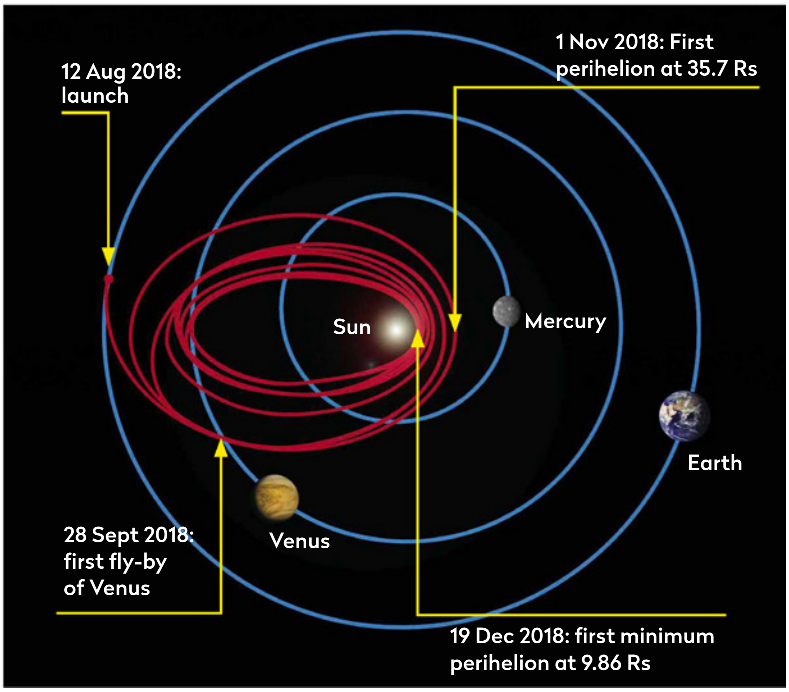
► orbit. The first, just 2,400km (1,500 miles) from Venus, put Parker in a 150-day elliptical orbit, two-thirds the period of Earth's sister planet. It made three orbits around the Sun while Venus made two. The second fly-by shortened this to 130 days; two further orbits to 112.5 days (half that of Venus) and two orbits after that to 102 days. After 237 days, the fifth encounter reduced the orbit to just 96 days, Parker making seven orbits to Venus's three.

The most recent fly-by, on 21 August 2023, shortened the period to just 92 days, slinging Parker towards its 18th close approach to the Sun on 28 December; matching its previous speed and distance records by travelling at a blistering 635,266km/h (394,736mph) and skimming just 7.26 million km (4.51 million miles) above the solar 'surface' (the photosphere) – closer than any spacecraft previously.

The final Venus fly-by is scheduled for November this year and it will pull Parker into an 88-day orbit, and onward to December's deepest coronal dive. This is when it will reach its closest distance to the photosphere, at 6.2 million km (3.9 million miles), while travelling at a record-breaking 692,000km/h (430,000mph). That's 0.064 per cent of the speed of light – fast enough to zip from New York to Tokyo in under a minute!

Parker's tool kit

The daring, car-sized Parker is delivering unprecedented data from four main instrument suites. First is FIELDS, an instrument that directly surveys the solar wind by measuring and analysing how electric and magnetic fields around the spacecraft change over time. The data has revealed rapid flips, called switchbacks, in the direction of the magnetic field flowing radially outward, resembling a zig-zagging mountain road. During each switchback – lasting from a few seconds to several minutes – the



▲ A graphical representation of the mission showing the seven Venus fly-bys. Rs = Solar Radius. For comparison, Earth is just under 215 Rs from the Sun

magnetic field whips back on itself until it points almost directly towards the Sun.

The instruments have also measured the speed of Alfvén waves – transverse electromagnetic-hydrodynamic waves – that originate near the Sun's surface but form part of the solar wind. These are embedded in the plasma but travel in the direction of the magnetic field. Scientists previously held that the velocity of the plasma was key to heating, but Parker has shown that where the Alfvén waves' speed varies, switchbacks arise, and it is these 'kinks' which may contribute to heating and accelerating the solar wind (see 'The coronal heating problem'). During Parker's sixth solar fly-by, FIELDS also showed that these switchbacks aligned with magnetic 'funnels' ►

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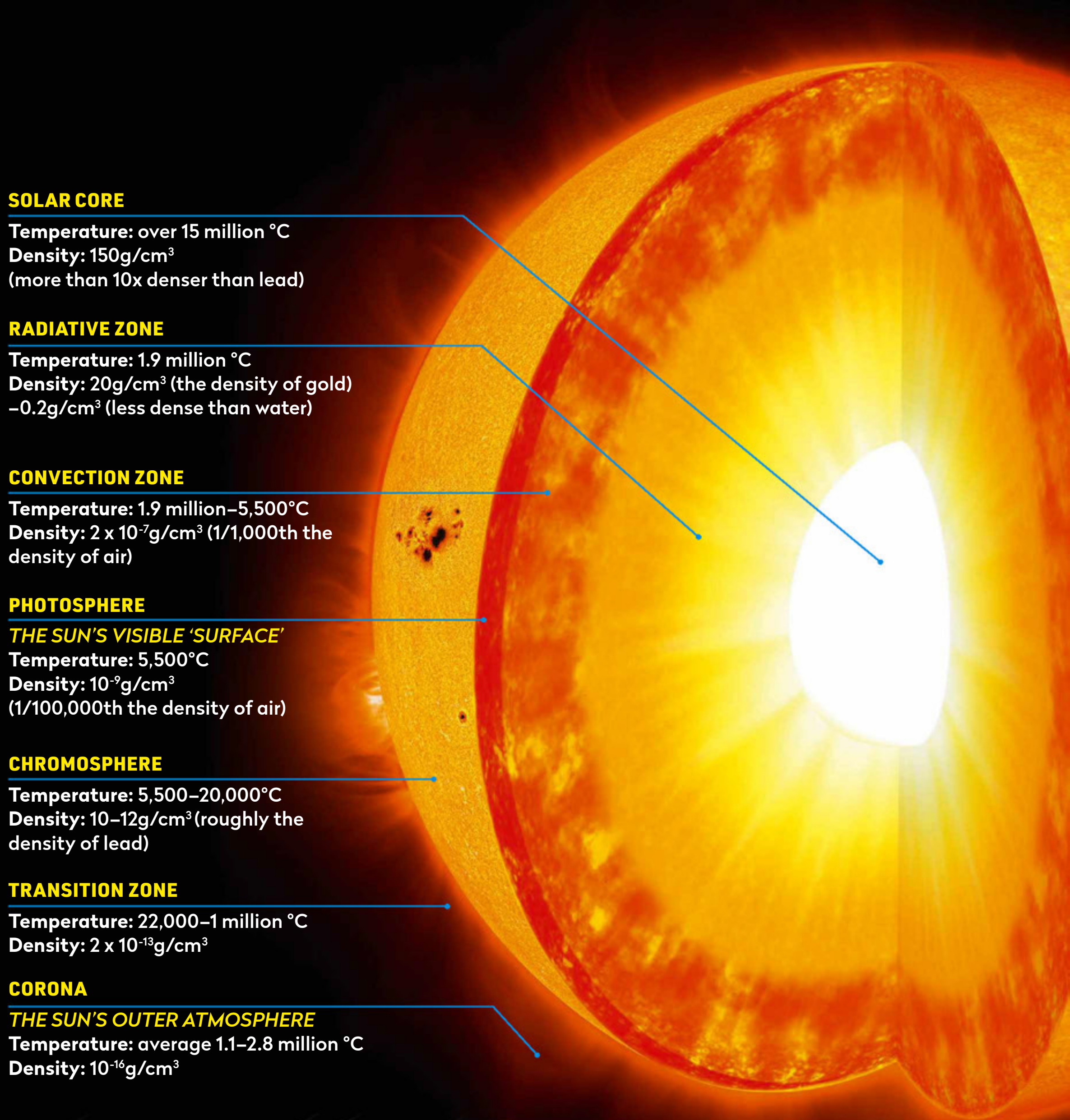
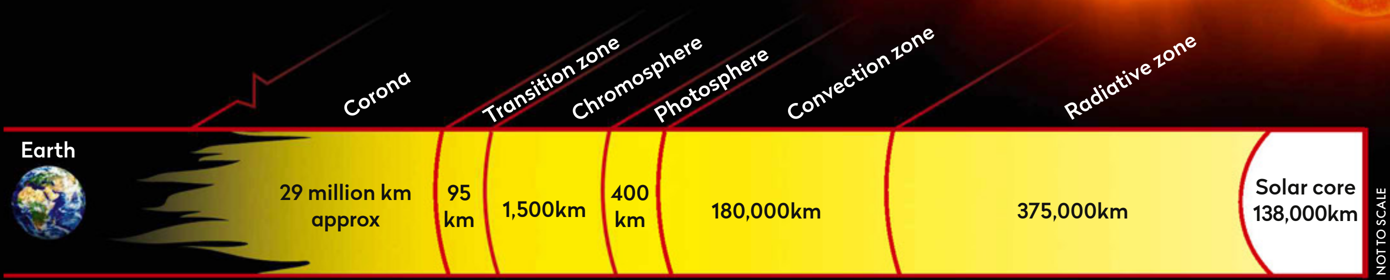
Temperature and heat in space

Unlike on Earth, where 'temperature' and 'heat' mean similar things in everyday language, in space the two concepts are very different. In the vacuum of space, an object's temperature can be thousands of degrees without it feeling hot. That's because temperature measures how fast particles are moving, while heat measures the energy they transfer. And since space is mostly empty, there are hardly any particles to transfer energy. Particles can have a high temperature and be moving very fast, but if there aren't many of them, they won't transfer much energy and so will have a low heat.



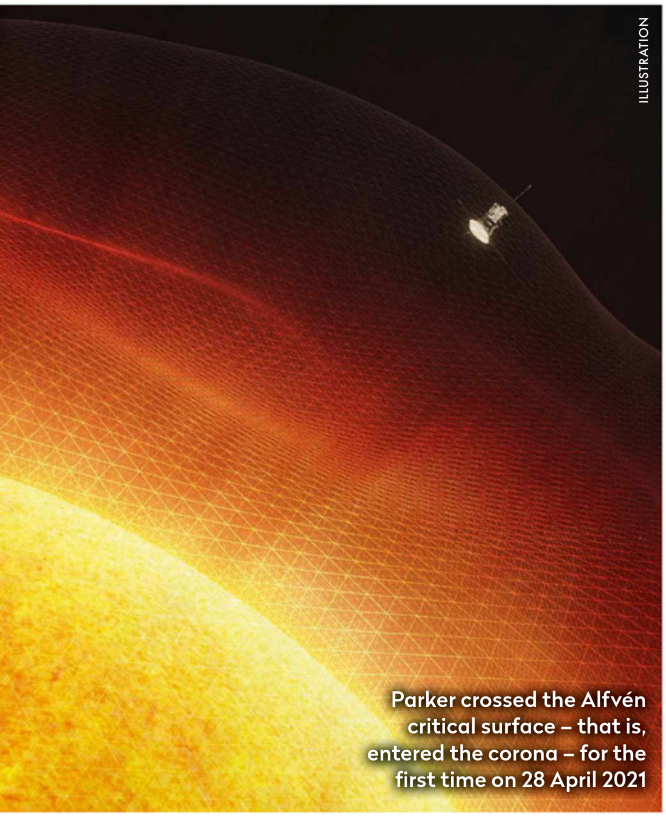


The coronal heating problem

Parker seeks to explain one of the biggest mysteries in solar physics

Stellar physics suggests that the deeper you go into a star's plasma, the more the pressure increases and the hotter the star becomes. The density of our Sun's outer atmosphere, the corona, is low. Its actual heat (energy content per cubic centimetre) is also low, producing about one-millionth as much light as the Sun's visible surface, the photosphere, 1,600km (1,000 miles) below. But although the photosphere's plasma is 10 million times denser than the corona, its temperature (a measure of how fast particles are moving) is just 6,000°C (11,000°F) compared to the corona's 1 million °C (1.8 million °F). Why? This paradox is known as the 'coronal heating problem'.

Observations from Parker are helping to unpick this long-standing mystery. They support two key explanations. First, the wave phenomenon: the Sun constantly roils with mechanical energy. Massive cells of charged plasma churn outward like bubbles in boiling water, their motion generating tangled magnetic fields which launch magnetic waves into the outer atmosphere. These waves send charged particles spinning, triggering heat-inducing 'switchbacks'. Second, nanoflares: coronal heating may be due to tiny, short-lived, million-degree jets of plasma intermittently erupting across the entire surface. Like larger solar flares, these result from magnetic reconnection, when field lines tangle and explosively realign, accelerating and heating particles in their wake. Collectively, these 'jetlets' heat the upper corona before escaping as the solar wind.



Parker crossed the Alfvén critical surface – that is, entered the corona – for the first time on 28 April 2021


As well as studying the Sun, Parker's WISPR instrument has been able to capture visible light images of Venus

▶ emerging from between supergranules – giant bubbles transporting hot plasma from the solar interior. This magnetic geometry suggested magnetic reconnection may also power the solar wind. With FIELDS, scientists have been 'listening' to the Sun too, thanks to the instrument's ability to capture and record the frequency and amplitude of plasma waves and particle interactions. By translating these into audible sound waves, they were able to hear the 'song' that is the solar wind.

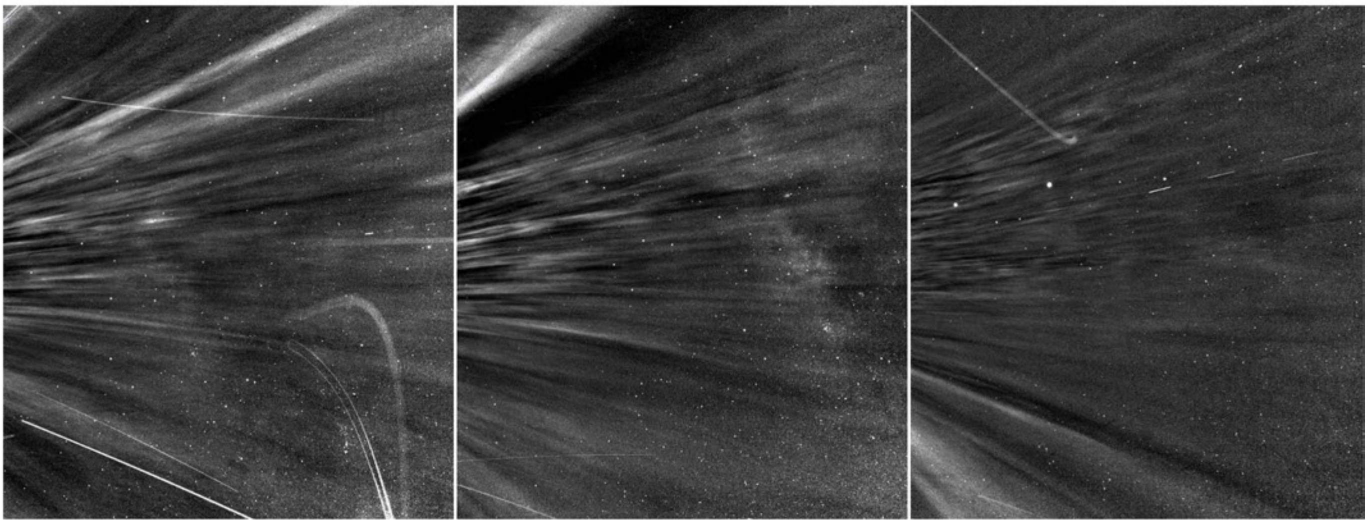
Counting the wind

Meanwhile, Parker's SWEAP (Solar Wind Electrons Alphas and Protons) instrument has been counting the most abundant, young solar wind particles – electrons, protons and helium ions – and measuring their temperature, speed, density and direction. When Parker crossed the Alfvén critical surface – the boundary where the Sun becomes the solar wind – instead of finding smoothness, SWEAP revealed spikes and valleys, attributing them to coronal streamers: giant plumes of solar material rising through our star's atmosphere.

Key to the success of FIELDS and SWEAP have been their high-resolution, unprecedented up-close measurements, resolving interactions between waves and particles at mere fractions of a second.

Parker's third instrument is WISPR (Wide-Field Imager for Solar Probe). Our Solar System is peppered with dust, the legacy of collisions within the solar nebula a few billion years ago that spawned the planets, asteroids, comets and other celestial bodies.

▼ WISPR's images of the corona reveal it to be a much more turbulent environment than was suspected



Parker's design features

How to make a spacecraft that can operate so close to the Sun

To withstand the extreme heat and radiation found in our star's immediate neighbourhood, Parker Solar Probe is protected by a 2.3-metre-diameter (7.5ft) hexagonal solar shield, weighing just 73kg (160lb) and mounted on its Sun-facing side.

This shield is 11cm (4.4 inches) thick and comprises two panels of revolutionary reinforced carbon composite with a lightweight carbon foam core. A surface layer of white reflective alumina (aluminium oxide) minimises absorption. Consequently, it can withstand temperatures reaching nearly 1,370°C (2,500°F), keeping its scientific payload at a balmy 29°C (85°F).

Parker's systems and instruments hide behind the central portion of the shield's shadow, where the Sun's radiation is fully blocked. Without this shield, PSP would become inoperative within seconds. Even so, radio blackouts can last weeks and radio communication takes eight minutes. To protect itself, PSP acts autonomously: as soon as four light sensors detect traces of direct sunlight emanating from the shield limits, reaction wheels are activated to position the craft back within the shadow.

The spacecraft itself is powered by a dual system of solar panels – photovoltaic arrays. The primary array, used when it is further than 0.25 AU from the Sun, retracts behind the shield during close approach. The smaller secondary array uses pumped ammonia cooling fluid to maintain its operating temperature, and is put to use when Parker comes close to the Sun.

Parker uses an advanced shield system to protect it from ultra-high temperatures

ILLUSTRATION

US astronomer Henry Norris Russell (1877–1957) predicted that, closer to the Sun, this dust must have superheated to high temperatures, and that hot particles would have sublimated and disappeared, leaving a dust-free zone. WISPR sees wide swathes of the corona and solar wind, the images revealing that dust does indeed begin to thin-out in a zone 13.2 million km (8.2 million miles) away from our star, decreasing steadily to WISPR's current operating limits, around 6.5 million km (4 million miles) closer in.

WISPR's 3D images have also captured shocks and other structures in the corona and solar wind, including coronal mass ejections. As Parker's speed matches the Sun's rotation, scientists have watched the outflow of material for days and seen that the solar wind is not as smooth as once thought.

During Parker's third Venus fly-by, when it was within the planet's shadow for 11 minutes, Parker crossed Venus's charged-particle 'tail'. WISPR peered through thick cloud cover to capture the first-ever images of the planet's night-side surface in visible wavelengths and, in 2020, detected a bright encircling rim, believed to be nightglow caused by oxygen atoms recombining into molecules high in the atmosphere.

Particle detectors

Parker's fourth instrument, IS⊙IS (Integrated Science Investigation of the Sun), is made up of two detectors or Energetic Particle Instruments (EPIs), which have been busy measuring tiny solar energetic particles – electrons and ions – accelerated by solar activity into storms that then rocket outward at near lightspeed, hitting Earth a few minutes later. EPI-Lo uses 80 viewfinders for widefield views of low-energy particles, while EPI-Hi uses three particle sensors to measure those with higher energies.

With PSP skirting so close to the Sun, IS⊙IS can detect 100,000 particles per second, shedding light on how they are released and revealing previously unseen energetic particle events. Its two detectors have also measured rare types of particle bursts containing high numbers of heavier elements, suggesting that these events are commonplace, that they contain a wider range of particle types and that their paths are redirected and prolonged by the switchbacks mentioned earlier.

Parker is currently 694,000km (432,000 miles) from our star's surface, travelling at 3,600km/h (2,237mph). But after mid-2025 its calculated dance with the Sun will end. With its hydrazine fuel spent, there will be no more course corrections, no ability to move the reaction wheels to reposition the communications antenna or reposition the heat shield. The spacecraft will disintegrate, leaving just the carbon disc of its head shield circling the Sun.

But with its closest approach still to come, more dazzling discoveries surely await us. This is a golden era of heliophysics exploration. By touching the Sun, the Parker Solar Probe is revolutionising our understanding of our nearest star and its relationship with Earth, improving our knowledge of space weather and, therefore, enhancing our ability to live and work in space.

Jane Green is an astronomy writer and author of the *Haynes Astronomy Manual*

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