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JUNO

The mission that rewrote the story of Jupiter

As NASA's Juno mission nears its end, **Nicky Jenner** explores the secrets it has uncovered about the Solar System's largest and most enigmatic world

JUPITER: IMAGE DATA: NASA, JPL-CALTECH, SWRI, MSSS
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It's difficult to fully grasp the enormity and extremity of Jupiter. The planet – a striped behemoth of swirling gas with around 100 moons, one of which is larger than Mercury – dominates the Solar System, flooding space with its magnetism and exerting its powerful gravity over everything nearby. The planet contains most of the 'stuff' left over after the birth of the Sun, and is so influential that it's played a central role in shaping our patch of space into the system we see today.

It's no wonder that we've had Jupiter firmly in our sights from our earliest forays into space exploration. We first sent spacecraft there in the 1970s with NASA's Pioneer and Voyager probes, which swung past the planet and observed it from space. NASA's Galileo probe stayed a little longer, taking up residence around Jupiter from 1995 to 2003, and was shortly succeeded by another NASA orbiter that's still peering down at the gas giant today: Juno.

A gift to Jupiter fans

"NASA sends a probe to deep space – that is, beyond Mars – every decade. Juno was selected for this in 2005," says Juno scientist John Leif Jørgensen of the Technical University of Denmark. "Previous probes had only been transitory or orbited Jupiter's equator, offering very limited views of high latitudes. But higher latitudes contain much more information about a planet's morphology, surface and interior, so we proposed a polar orbiter."

Such an orbit is subject to harsher radiation and is more complex to operate – but it's been worth it. "With Juno, practically all ▶

Juno and the Giant: the intrepid spacecraft has spent nine years peering beneath the clouds of the Solar System's king

▲ **Left to right: Pioneer 10 gave us our first close-up of Jupiter in 1973; Voyager 2 captured the Great Red Spot in stunning detail in 1979; and Galileo observed the faint ring system in the 1990s. But it was orbiter Juno that delivered the closest, longest look at the gas giant**

▶ possible observations have become superior to those offered by any other mission."

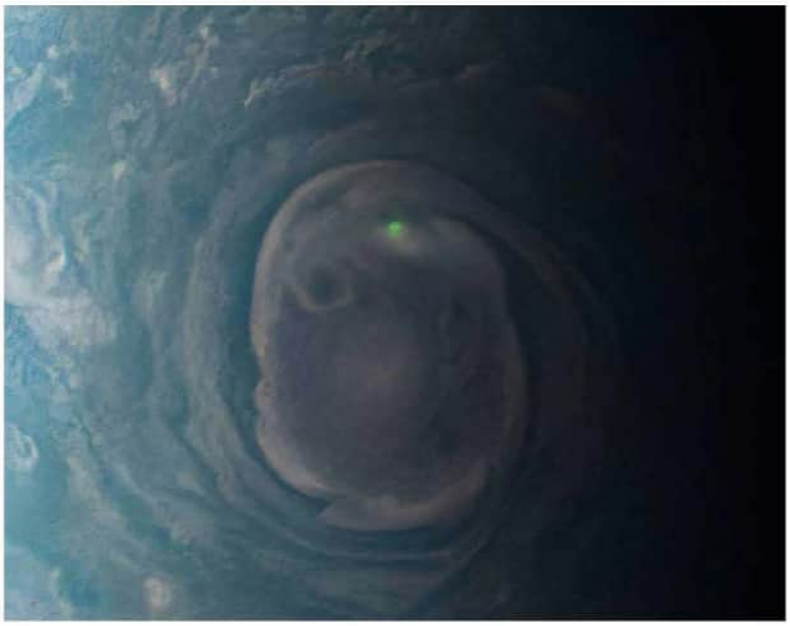
From its vantage point skimming over Jupiter's poles, Juno is working to solve the mystery of how the planet formed and has evolved in the billions of years since. Following its arrival at Jupiter in 2016, the spacecraft has dug beneath the planet's obscuring clouds, investigated its core, studied its striking aurorae and raging storms, and mapped its magnetic field. It's explored the structures, materials and movements we see in the atmosphere, and looked at how Jupiter's moons (particularly the largest four) interact with the planet and its wider environment, bringing all of this together to paint a clearer picture of Jupiter's history – and, by extension, that of our Solar System.

"Juno's impact on our science is almost immeasurable," says planetary astronomer Tom Stallard of Northumbria University, who has dug into the upper atmospheres of the gas giants for decades, via missions such as Cassini and the James Webb Space Telescope. "It has profoundly shaped our modern understanding of Jupiter and its near-space environment."

Finding weird weather

So, what has Juno revealed about Jupiter? First, there's the weird weather. Juno has spotted violent lightning and electrical storms raging on Jupiter. Unlike lightning storms found here on Earth, which involve water-laden clouds, Jupiter's are tied to clouds of ammonia, and sling water-ice crystals and slushy, ammonia-rich hailstones – 'mushballs' – down into Jupiter's atmosphere. As these storms need liquid water, we thought they sprang to life deep within large water clouds; however, Juno has revealed that they actually rage far higher up, where temperatures hover at around –88°C (–126°F). Here, ammonia acts a bit like an antifreeze, enabling water to stay liquid, form droplets and support huge storms that electrify and illuminate the swirling cloud tops.

Juno has also spied short-lived flashes of light known as 'sprites' and 'elves' in Jupiter's upper atmosphere (sparked by lightning discharging energy in rapid millisecond-long bursts). And it's dug down to the roots of the famous Great Red Spot, finding this colossal storm extends down for around 300km (185 miles). Jupiter's bands of eastward and westward winds – which move at different speeds and are expressed as Jupiter's characteristic caramel-toned stripes – also slice surprisingly far down into the planet. Jet streams seen by Juno at the cloud tops are still blowing 3,000km (1,800 miles) deeper down.



▲ **Juno spotted lightning flashes near Jupiter's north pole, later revealed to come from high-altitude ammonia clouds**

Then there's the cyclones. Thanks to its unique orbit, Juno snapped the first clear views of Jupiter's poles, showing enduring clusters of whirling cyclones many thousands of miles across – some larger than Australia. Juno initially spotted six at the south pole and nine at the north, arranged in a flower-like pattern with one central cyclone and numerous stormy 'petals', before watching a smaller seventh cyclone form at the south pole in 2019. According to Juno's measurements, these windstorms rage at an intense 360km/h (225mph), not dissimilar to the most extreme tropical cyclones on Earth.

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Juno found that the Great Red Spot isn't just wide – it extends 300km below the cloud tops...

...and that Jupiter's aurorae (seen here in infrared) superheat the planet's atmosphere

▲ Juno's data showed the poles each host a central cyclone surrounded by smaller vortices

The spacecraft has also spotted striking aurorae at Jupiter's poles, revealed how particles 'surf' along magnetic field lines to form these bright emissions, and found that aurorae are actually responsible for heating Jupiter's whole upper atmosphere to surprisingly high temperatures. Juno has seen auroral dawn storms springing to life on the dark (night) side of Jupiter – large, spectacularly bright storms that grow even more luminous as they rotate into the planet's dayside in the early morning.

Secrets beneath the swirls

"Juno was the first spacecraft to fly repeatedly over the polar auroral regions of an outer planet. Its incredible images of the aurorae are amongst the most detailed ever taken away from Earth at any planet," says Stallard. Juno has also measured how the aurorae fling particles up into Jupiter's atmosphere, measurements that "are now fundamental to our changing understanding of Jupiter's aurorae [and have] dramatically changed our view of how Jupiter's aurorae form".

Juno also revealed a lot more about the interior of Jupiter. Before the mission, we were debating whether Jupiter has a solid core of ice, rock and metals, or whether it's basically gas all the way ▶

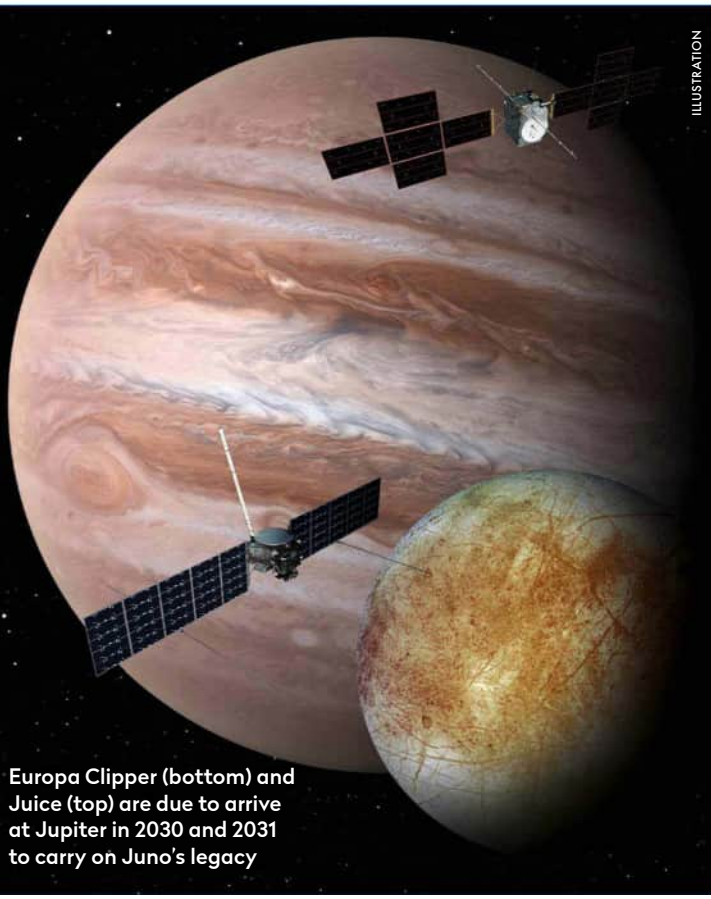
Destination: Jupiter

Taking up Juno's mantle, two new robotic probes are en route to Jupiter and its mysterious moons

Come 2031, a pair of new robotic explorers will be investigating Jupiter and its moons: ESA's Jupiter Icy Moons Explorer (Juice, for short) and NASA's Europa Clipper, both of which are currently winging their way through the Solar System on their way to the giant planet.

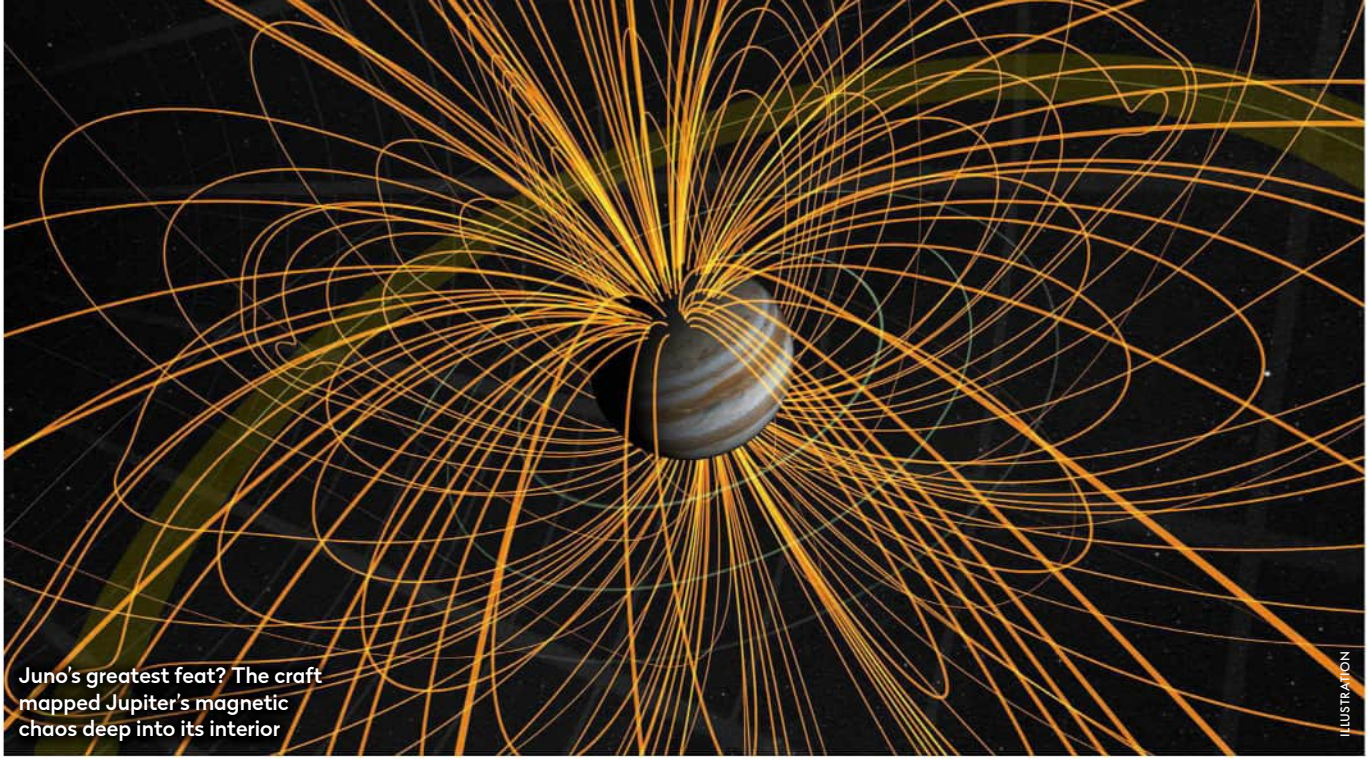
Juice is due to arrive at Jupiter in July 2031 and will explore the entire Jovian system before honing in on Jupiter's three large and likely ocean-bearing moons: Europa, Ganymede and Callisto. The subsurface oceans on these moons may contain the building blocks for life, making them especially exciting in our hunt for habitable worlds other than Earth. Towards the end of its mission, Juice will hop over to Ganymede, making it the first spacecraft ever to orbit a moon in the outer Solar System.

Europa Clipper, expected to arrive in April 2030, will focus more closely on Europa. The spacecraft will orbit Jupiter and whirl round to closely pass Europa nearly 50 times, snatching repeated glimpses of the moon's environment and assessing whether it could be friendly to life. Together, the two spacecraft will build on the legacy of Juno to hunt for the ingredients of life, advance our understanding of Jupiter and Ganymede's magnetism, and explore the gravity that squeezes and squashes Jupiter's moons as they circle the immense planet.



ILLUSTRATION

Europa Clipper (bottom) and Juice (top) are due to arrive at Jupiter in 2030 and 2031 to carry on Juno's legacy



Juno's greatest feat? The craft mapped Jupiter's magnetic chaos deep into its interior

ILLUSTRATION

NASA'S SCIENTIFIC VISUALIZATION STUDIO | NASA, JPL-CALTECH | IMAGE DATA: NASA, JPL-CALTECH, SWRI, MSSS IMAGE PROCESSING BY GERALD EICHSTÄDT | NASA, JPL-CALTECH, SWRI, ASI, INAF, JIRAM | NASA, JPL-CALTECH, SWRI, PU

▶ down. Each has implications for Jupiter's origin. In the former case, rocky debris clumped together into a solid lump that then grabbed gas from its surroundings, while in the latter, Jupiter instead began life as an infant star before collapsing inwards. Juno has found Jupiter's core to be larger, more diffuse and 'fuzzier' than we expected, containing up to 15 per cent of Jupiter's mass and spanning around half of Jupiter's radius. This may point to an origin story somewhere between the aforementioned routes: one where a baby Jupiter, forming as a planet, suffered a direct, powerful impact that disrupted its interior.

One of the most exciting findings from Juno concerns Jupiter's magnetism. Juno has dug into Jupiter's fuzzy core, finding signs of an internal dynamo, and discovered a surprisingly asymmetric magnetic field across the planet's northern and southern hemispheres. It's also revealed that Jupiter's internal magnetic field evolves with time (a phenomenon also seen on Earth, known as 'secular variation', and driven by Jupiter's deep, dominating winds) and spotted crashing waves and vortices at the outer edges of Jupiter's magnetic field, where this region bumps up against the stream of radiation flooding into space from the Sun.

Nicky Jenner is a science writer and editor specialising in space and environment

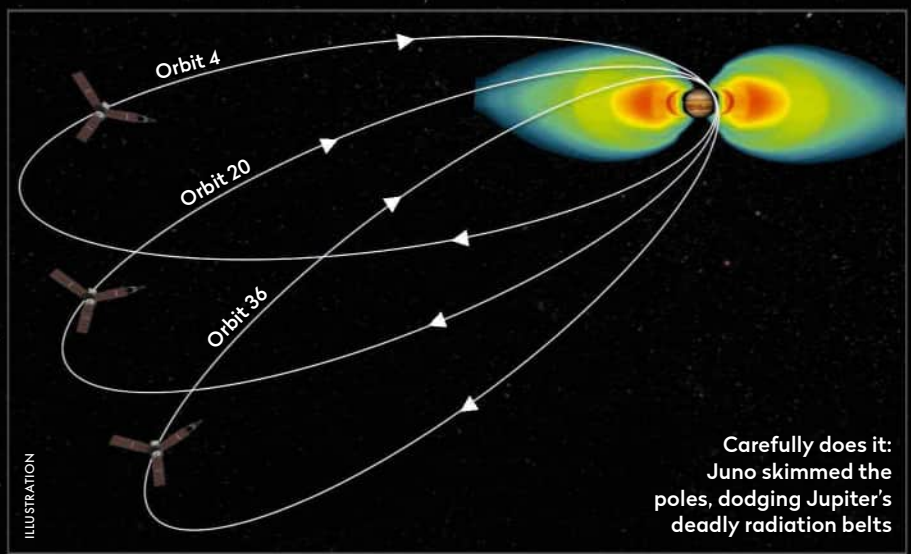
Killer magnetism

Spacecraft have to be tough to survive Jupiter's incredibly strong magnetic field

Jupiter's magnetic field is truly immense. It extends far beyond the planet itself and is the strongest in the Solar System aside from that of the Sun. This field scoops up and accelerates particles to blistering speeds approaching the speed of light, acting as a giant cosmic particle accelerator. These super-hot particles exist in doughnut-like radiation belts wrapping around Jupiter's middle; they can damage electronics when they collide with spacecraft, and so missions such as Juno are carefully planned to keep their probes protected.

To avoid the worst of the planet's radiation, Juno orbits on a highly stretched orbit that skims Jupiter's poles. This orbit dodges the densest parts of the radiation belts, spending as little time in them as possible, and loops through a thin, relatively radiation-free gap sitting just inside Jupiter's radiation belts (similar to one around Earth that hosts most of our satellites). Even so, "it's one of the most hostile environments a spacecraft has ever flown through," says Stallard.

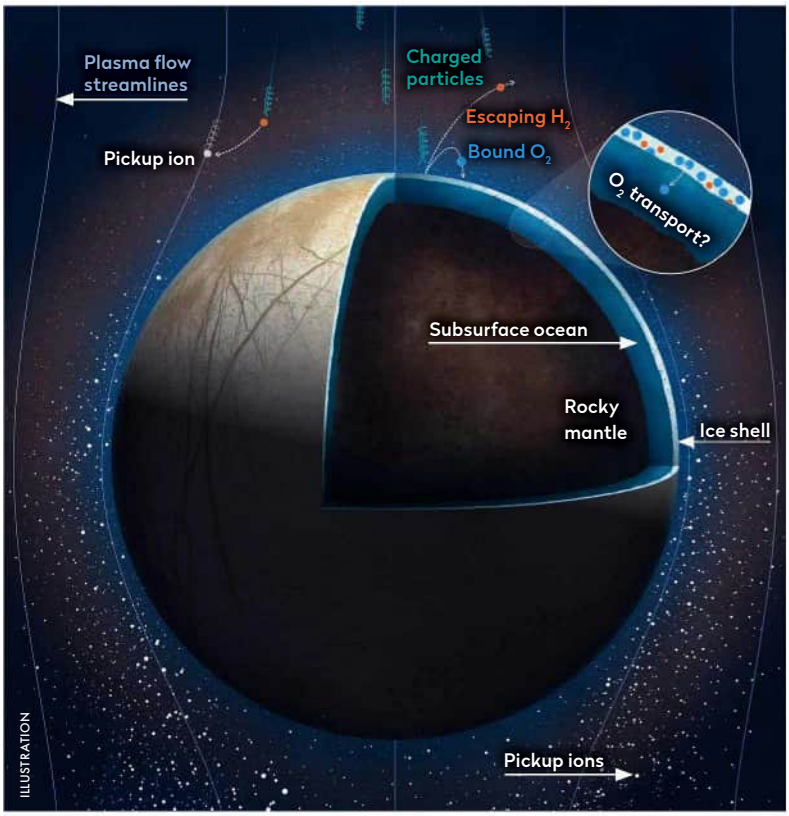
The orbiter's core instruments are also locked within a radiation-safe vault made of titanium. Juno's principal investigator, Scott Bolton of Southwest Research Institute in San Antonio, Texas, calls Juno "basically an armoured tank". While not robust enough to block radiation entirely, the vault is sufficient to significantly slow radiation damage to the probe's science instruments, enabling them to live longer.



Carefully does it: Juno skimmed the poles, dodging Jupiter's deadly radiation belts

ILLUSTRATION

Juno captured the volcanic peaks at Io's poles, then (inset) a record-breaking eruption in late 2024



▲ Another moon revelation: how radiation and energetic particles break Europa's ice into hydrogen and oxygen

"For me, Juno's greatest achievement was its detailed measurement of Jupiter's surface magnetic field, something almost impossible with any other spacecraft," says Stallard. "It flew so close to the planet, it was able to model the magnetic field down into the interior. In doing so, it revealed a wonderfully distorted field structure. This confusing field tells us that Jupiter has something strange going on in the outer layers of its interior, twisting up magnetic field lines in a unique way."

Zooming in on the moons

It's not just the planet itself that Juno helped us to understand; its satellites came under scrutiny too. Jupiter's hottest moon, Io, is thought to be the most volcanically active world in the Solar System, with this activity driven by the tugging and squeezing of its parent planet as it whirls round in an extremely close orbit. Juno has found signs of still-warm magma lying just below the moon's surface, spotted molten lava lakes and hotspots, and – in January of this year – witnessed the most extreme volcanic event in the moon's known history, when a hotspot larger than Austria spat out over six times the energy output of all the world's power plants. Additionally, rather than Io hosting an ocean of magma, Juno has instead found that the moon's 400 or so volcanoes are each fed by their own individual cauldron of hot magma – a finding that reshapes what we thought we knew about volcanism on rocky worlds.

From fiery Io to frozen Europa: Juno found that Jupiter's fourth-largest moon is highly likely to harbour a vast, salty ocean beneath a thick, icy crust, making it a prime target in our hunt for life. With this in mind, Juno has searched for oxygen on this moon – and found it. As charged particles flow past and collide with Europa, they break surface ice into hydrogen and oxygen, throwing the latter into the atmosphere and potentially down into the subsurface ocean.

Ganymede – the largest moon not only of Jupiter, but the entire Solar System – is also thought to have an ocean. During a close fly-by, Juno spotted mineral salts and organic (carbon-containing) compounds – perhaps remnants of ocean brine that once reached the surface. The spacecraft has also imaged the polar regions and rest of Ganymede in detail, spotting scratches and craters, and captured the moon casting a shadow on Jupiter during an eclipse.

Juno completed its prime mission in 2021 and was granted an extension through 2025. It's currently slated to end in September, but that's not set in stone. With NASA still reviewing its budget for 2026 and beyond, the spacecraft may yet have more scientific discoveries ahead. Whenever its final day comes, it's likely to be sent on a self-destructive 'death plunge' into Jupiter's clouds, to avoid any chance of contaminating Jupiter's moons – which, thanks to this plucky probe, we now know are among the most promising places to search for life in the Solar System.