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#222 NOVEMBER 2023

Sky at Night

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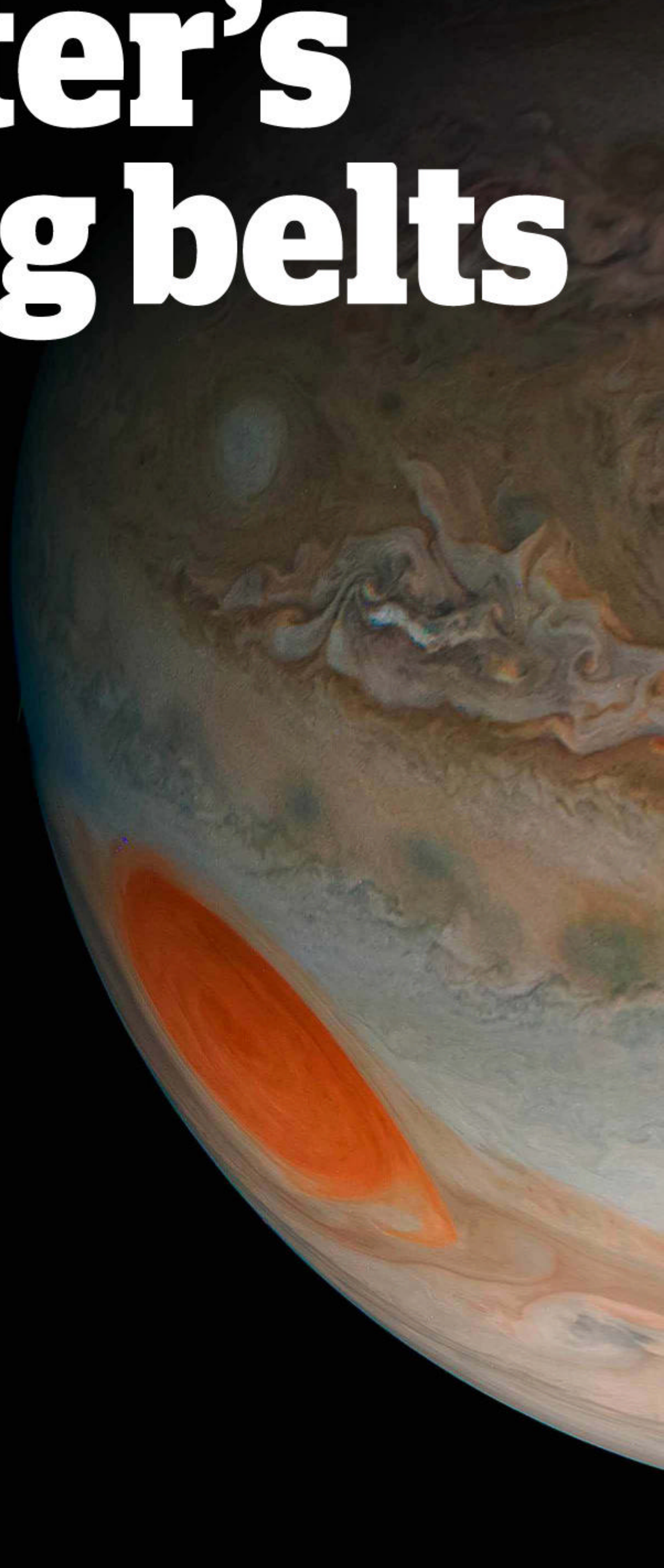
STARLESS GALAXY FIND EXCITES ASTRONOMERS

Solving the mystery of

Jupiter's shifting belts

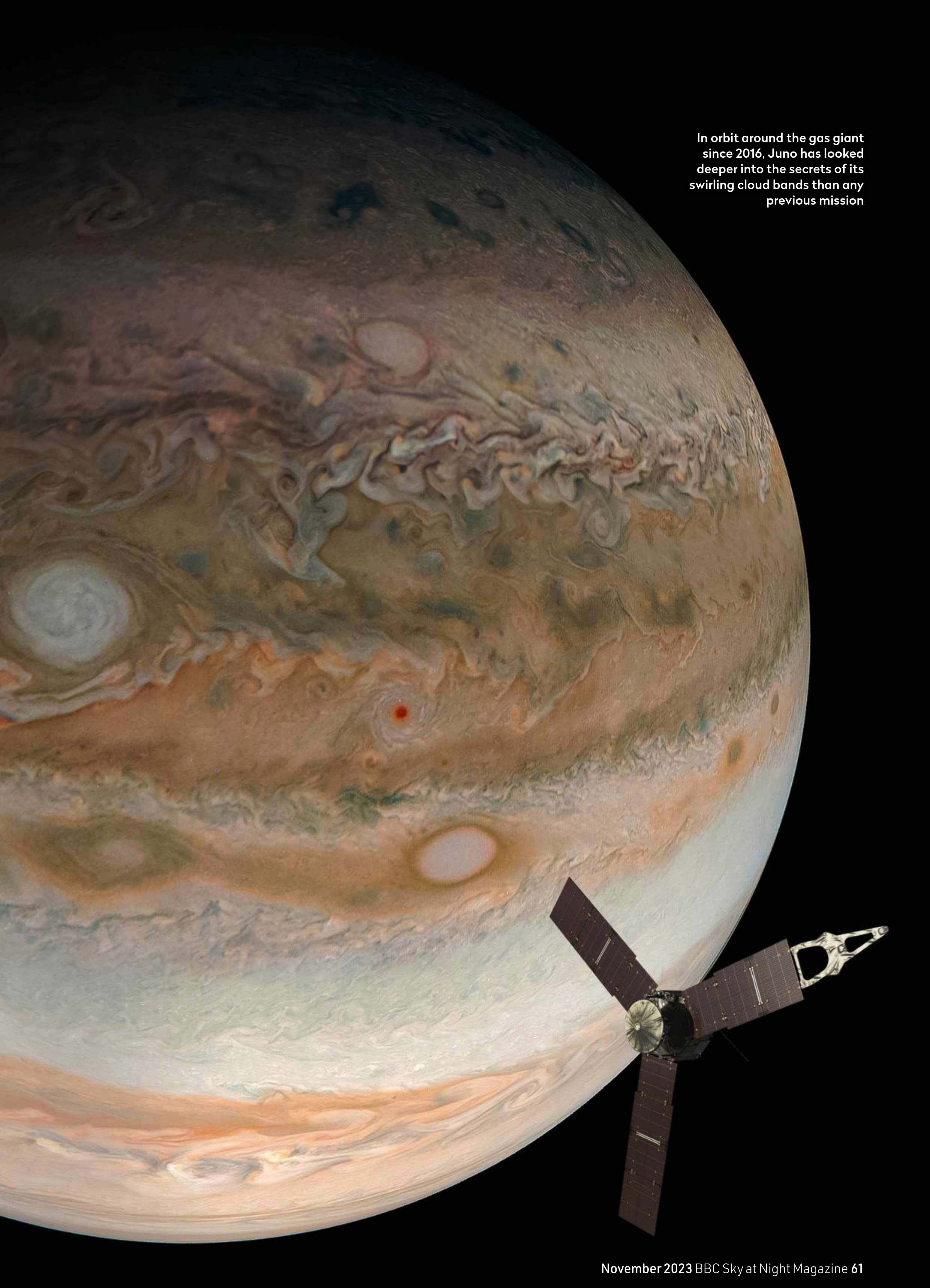


Jupiter's beautiful stripes move and morph from year to year. **Giles Sparrow** finds out how the Juno spacecraft revealed where these changes begin

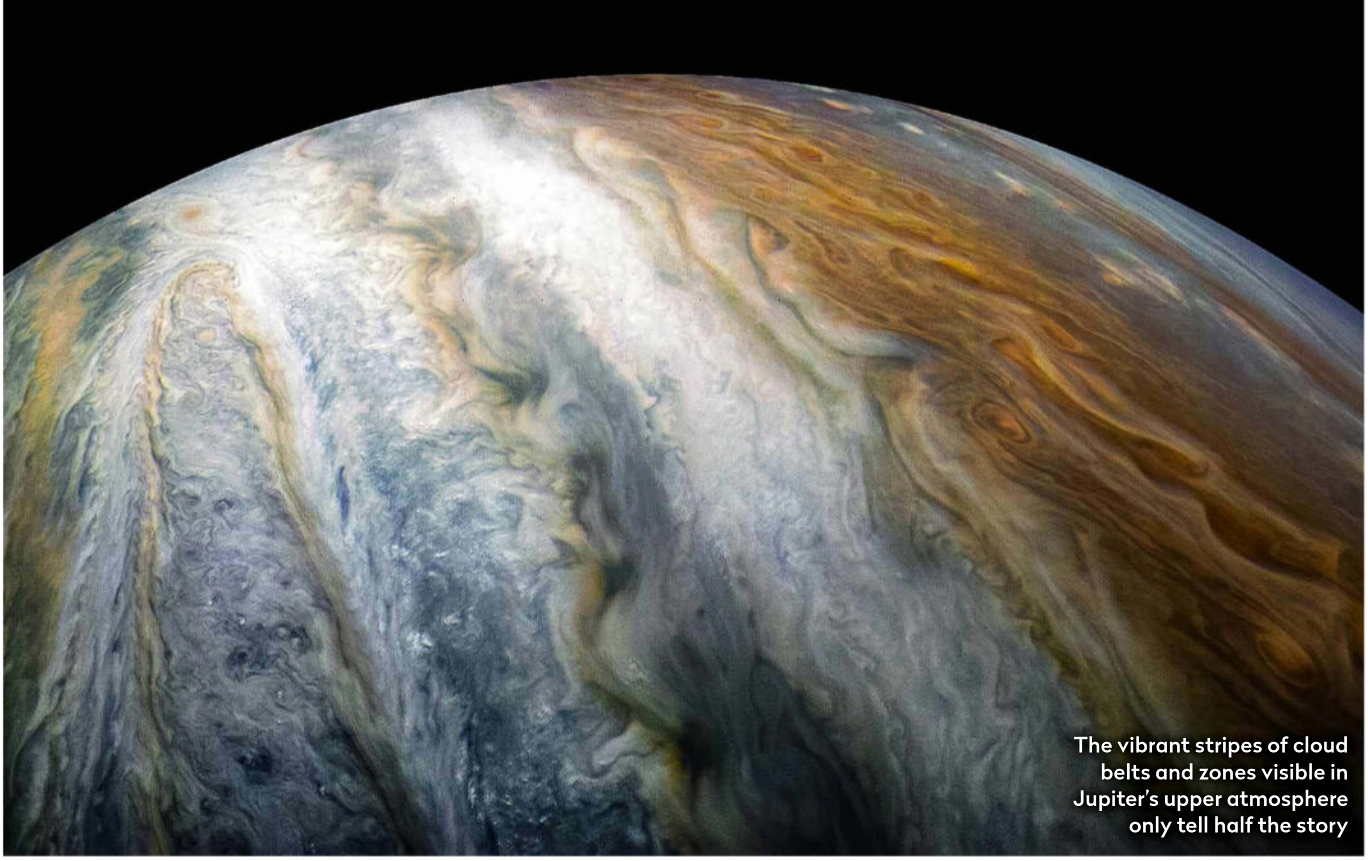
Step out under the stars this month and you won't be able to miss Jupiter. As well as being the largest planet in our Solar System, it is also at opposition this month, meaning it lies directly opposite the Sun as seen from Earth. That means the giant planet is not only visible all night but is also at its closest to us, giving backyard astronomers a great chance to observe its colourful cloud bands. These ever-changing patterns have fascinated sky-watchers for centuries, but now an international team of scientists say they've come a big step closer to understanding what drives their behaviour.

Jupiter is a bloated gas giant that could swallow 1,300 Earths, but it's composed almost entirely of the lightweight gases hydrogen and helium. The uppermost layers of its deep atmosphere are wrapped in bands of cloud that run parallel to the planet's bulging equator. Darker regions dominated by reddish, brown and blue clouds are called belts, while lighter, cream-coloured stripes are known as zones.

The striking colour differences between belts and zones are due to the way that various chemicals condense from gas into clouds of ice crystals or liquid droplets in different conditions. ▶

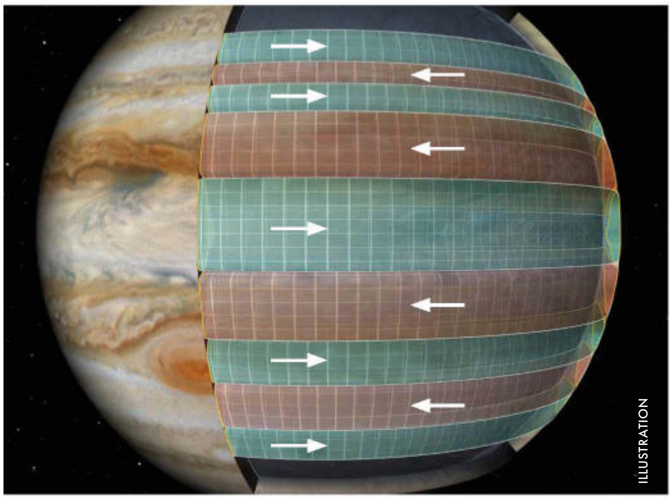


In orbit around the gas giant since 2016, Juno has looked deeper into the secrets of its swirling cloud bands than any previous mission



The vibrant stripes of cloud belts and zones visible in Jupiter's upper atmosphere only tell half the story

▶ The bright zones mark areas where gas is welling up from Jupiter's interior, rising a few kilometres higher than their surroundings into colder, lower-pressure surroundings where crystals of ammonia ice can condense and form creamy-white clouds. The dark belts, in contrast, mark areas where gas is sinking deeper into the atmosphere, experiencing warmer temperatures and higher pressures. The clouds that condense in these conditions are made mostly from ammonium hydrosulphide, ammonium sulphide and water – although none of these chemicals can themselves explain the distinctive colours of the belts, which are probably due to a 'soup' of more elusive chemical compounds.



▲ We now know that jet streams deep beneath the cloud bands move in alternate directions, whipped by stupendous winds, and at different altitudes

Jupiter can change its stripes

Alternating zones and belts form a series of stripes to the north and south of Jupiter's equator, with each distinctive band named after the latitude where it resides. So the broad Equatorial Zone around the equator itself is bounded by the North and South Equatorial Belts, then the North and South Tropical Zones, and so on. What's more, colour isn't the only difference between the cloud bands – they are also moving in opposite directions across the surface.

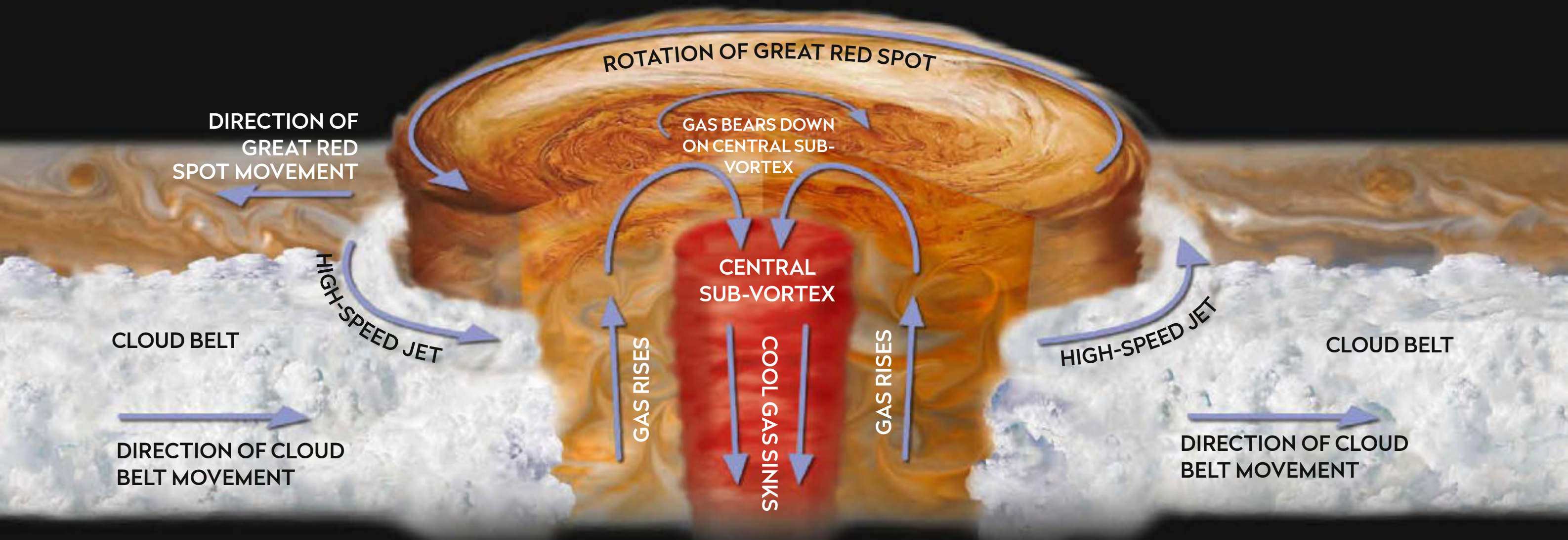
"If you look a little bit more closely, you can see clouds zipping around, carried by extraordinarily strong easterly and westerly winds," says Professor Chris Jones from the University of Leeds, an expert in planetary magnetic fields and the winds of giant planets. "Near the equator, the wind blows eastward, but as you change latitude a bit, either north or south, it goes westward. And then if you move a little bit further away it goes eastward again. This alternating pattern of eastward and westward winds is quite different from weather on Earth."

Wind speeds on Jupiter can reach hundreds of kilometres per hour and are at their strongest in jet streams that mark the boundaries between belts and zones. Opposing streams can also set large masses of air rotating, giving rise to oval storms where colours are often at their most intense.

Yet because the belts and zones have been broadly stable through centuries of telescopic observation, the fact that they can go through major upheavals every few years – before settling down again – is often overlooked. "Every four or five years, things change," explains Professor Jones. "The colours of the belts can change and sometimes you see global upheavals when the whole weather pattern goes slightly haywire for a bit."

In 2007, for instance, the Hubble Space Telescope captured stunning images showing Jupiter's entire north tropical zone turning suddenly brown and apparently merging with the belts on either side. Simultaneously, a darker streak spread along the edge of the equatorial belt just north of the equator, marking a spreading rent in the clouds that revealed darker layers below.

The transparency of the clouds has a great effect on Jupiter's heat output, as recorded by infrared images of the planet. Gravitational contraction – the slow sifting of heavier elements towards the centre of Jupiter – acts as a powerful internal energy source,



▲ What lies beneath: Juno's measurements, gathered as it was jostled by the storm as it flew by, suggest the Great Red Spot could extend a massive 300km down into the planet's atmosphere

The Great Red Spot

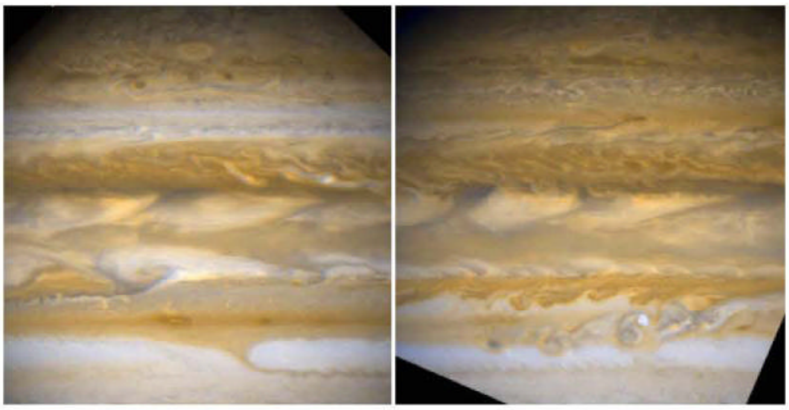
Although it's Jupiter's most constant feature, the giant storm has changed over the years

The Great Red Spot (GRS) is Jupiter's most famous feature, a vast storm that has been observed continuously for almost 200 years and was probably first spotted in 1665. Sitting on the edge of the South Equatorial Belt, it is confined between a strong westward jet stream to its north and a weaker eastbound one to its south. Winds along the edge can exceed 430km/h as it spins counter-clockwise (turning once every six Earth days), but the central eye of the storm seems largely stagnant.

While most of Jupiter's darker features are lower-lying than the pale clouds of the zones, the top of the GRS soars to 8km above its surroundings. The source of its colour (which can vary from intense red to a salmony-pink and sometimes disappears completely, leaving just a 'hollow' in the surrounding weather systems to reveal the spot's presence) is still unknown. However, most scientists believe it is created by chemicals welling up from deep inside the planet and perhaps undergoing reactions on exposure to sunlight.

In 2019, Juno made two low passes over the spot, allowing scientists to probe beneath the surface by looking for slight deflections in the probe's path caused by concentrations of mass (and higher gravity) in the region. These confirmed that the GRS probably extends to 300km beneath the cloud tops.

The GRS changes colour and occasionally disappears from view altogether



▲ Bands of white cloud turn brown in a dramatic example of Jupiter's ever-changing face, captured by Hubble between March (left) and June (right) 2007

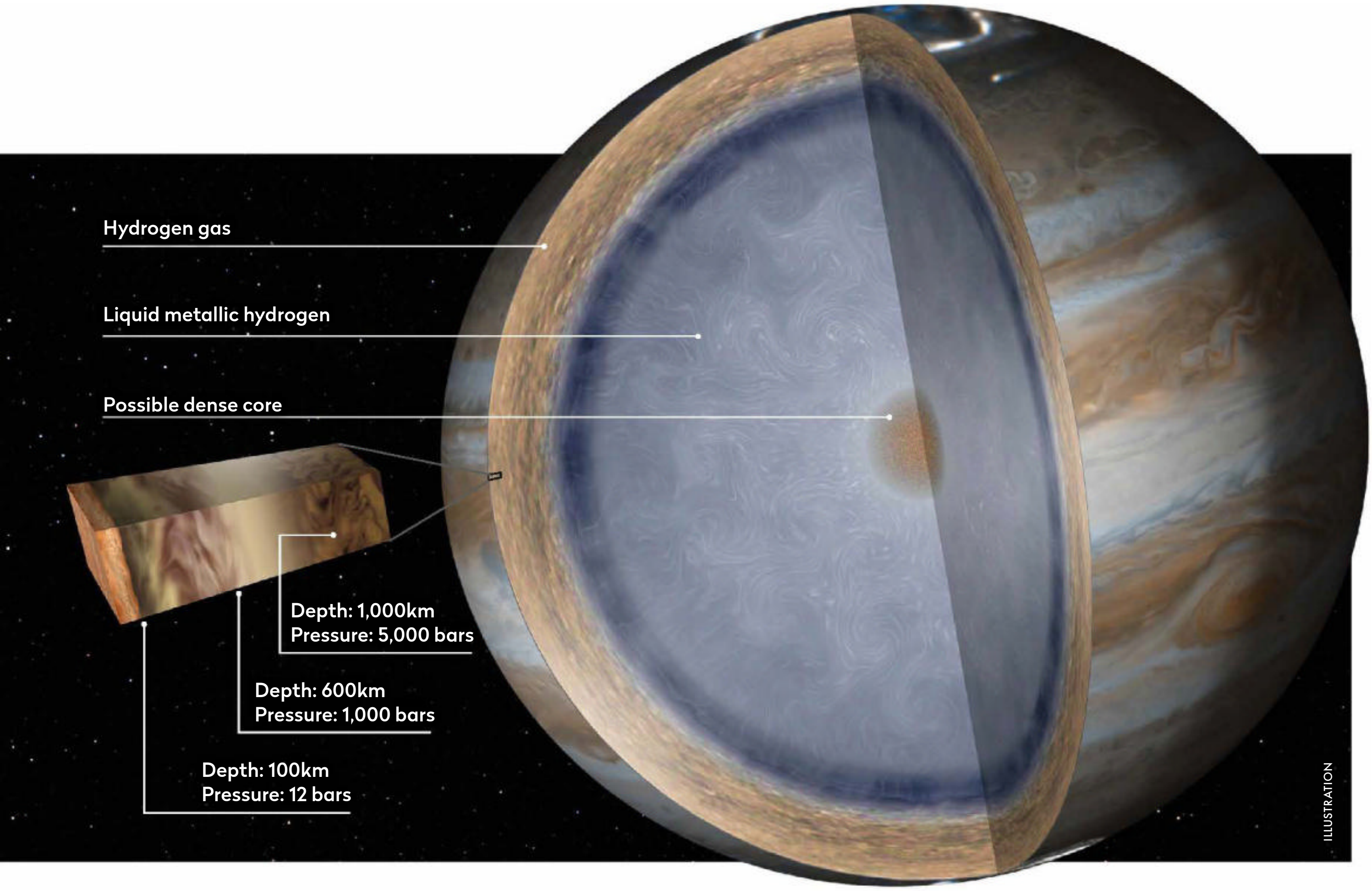
allowing the planet to emit twice as much heat as it receives from the Sun. Clouds of different kinds may be either transparent or opaque to the escaping heat, resulting in dramatic changes of intensity in infrared views.

This relationship also works in reverse, however – variations in heat from the interior can affect which chemicals condense into visible clouds at various times in different regions. In fact, infrared measurements have for some time suggested that temperature variations some 50km beneath Jupiter's cloud tops are the driving force behind the periodic changes at the surface.

Going deeper

Professor Jones, his former Leeds University colleague Dr Kumiko Hori (now at Japan's Kobe University) and others were keen to investigate the cause of the temperature changes themselves. To do this, they needed to look even deeper inside the gas giant world, to study its powerful, ever-changing magnetic field.

Even though Jupiter's interior consists almost entirely of hydrogen and helium, it still has distinct internal layers. From around 1,000km down, the pressure from above is so great that these lightweight gases are compressed to liquid form in a global ocean. The hydrogen within this vast sea remains in molecular form (with two hydrogen atoms bonded together to make an H_2 molecule), but from around 20,000km down (just over a quarter of the way to the centre), the pressure grows so great ▶



► that these molecules are split apart. The result is a dense sea of electrically charged, free-floating hydrogen ions. Bulk motions within this 'liquid metallic' hydrogen create powerful electric currents deep inside Jupiter, and as the giant planet spins on its axis in just under 10 hours, these swirling currents can in turn generate an enormous magnetic field. In fact, Jupiter's vast magnetosphere is 20,000 times more intense than Earth's, and its effects can be felt as far away as the orbit of Saturn.

Until recently, the detailed structure of Jupiter's magnetic field has been a mystery, locked away from direct observation along with other secrets of the gas giant's interior. However, thanks to data from NASA's Juno space probe, it's now possible for scientists to map the field in detail and build mathematical models of what's going on inside Jupiter.

Using one such model, Hori, Jones and their colleagues worked out how the jet streams visible at Jupiter's surface would interact with the swirling metallic fluid far below. They found that the internal field is subjected to so-called 'Alfvén waves'. These slow-moving waves are generated by torsion – twisting of the overall magnetic field – and when viewed from outside, they seem to rotate much more slowly than the magnetosphere itself. One consequence is a slow-moving hotspot of intense magnetism that moves east and west in a long, slow oscillation. Juno's observations support these predictions through their detection of an invisible, powerfully magnetised region that scientists have dubbed the Great Blue Spot.

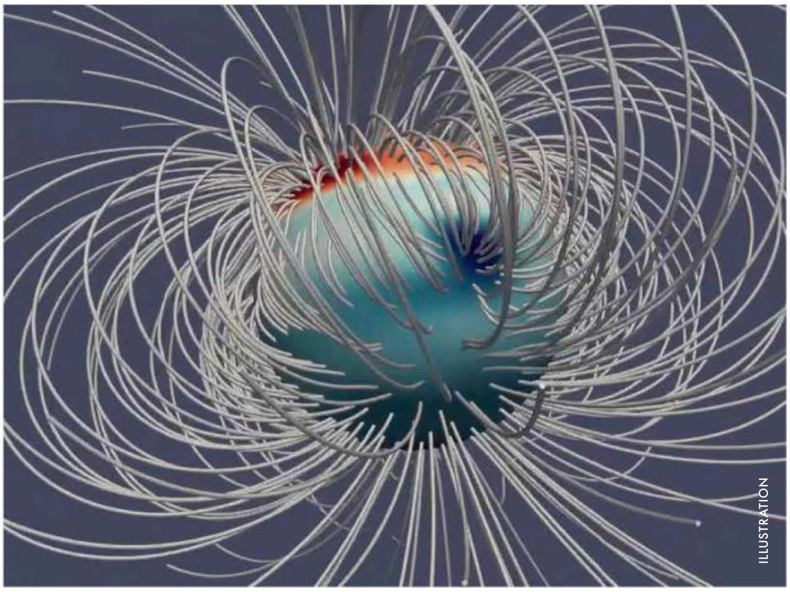
Hori's model predicts that, as Jupiter's jet streams and interior influence each other, the precise position of the Great Blue Spot not only wanders around the planet, but also sometimes reverses. The periods of the simulated reversals seems to match very well with the multi-year cycles of variations seen especially in Jupiter's North Equatorial and North Temperate belts. For most of Juno's mission at Jupiter, the spot has been moving slowly eastwards, but its motion is currently slowing and the researchers suspect this could be the trigger for a forthcoming change of direction, accompanied by disruption to the cloud bands above.

▲ The inside story: Juno's fly-bys have revealed Jupiter's deep atmospheric layers and suggest a 'fuzzy' heavy-element core

▼ The mysterious Great Blue Spot, an invisible hotspot of magnetism, appears to wander around the planet

Magnetic mystery

"There remain uncertainties and questions, particularly how exactly the torsional oscillation produces the observed infrared variation," points



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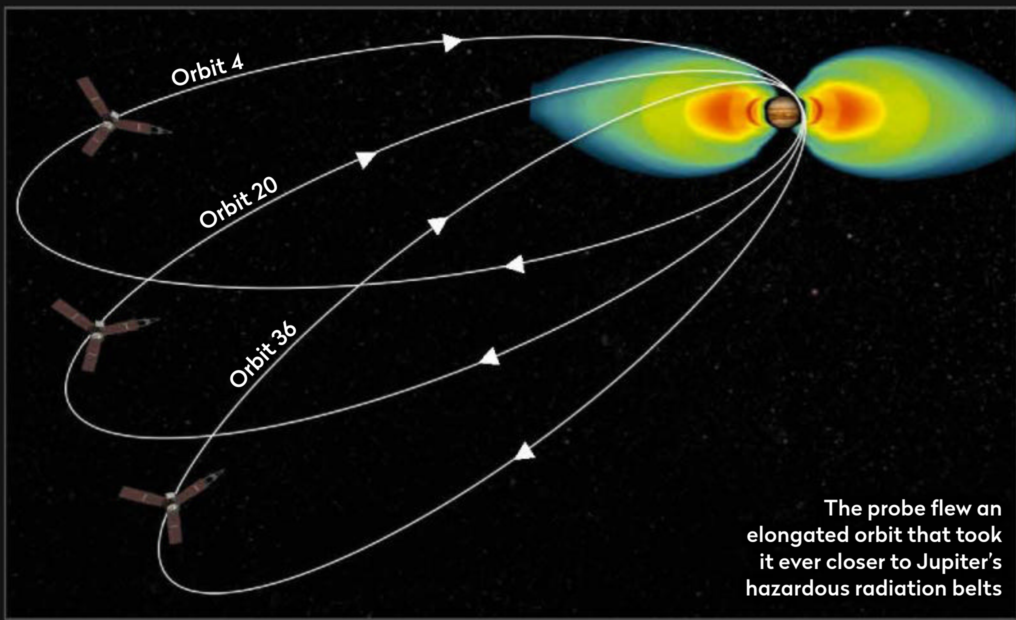
Probing Jupiter's magnetism

The planet's intense magnetic field makes it a dangerous place to study

Studying Jupiter's magnetic field in detail presents a huge challenge, not only because of the difficulty of sending probes to the giant planet, but also because the field itself traps a series of doughnut-shaped radiation belts around the planet (similar to Earth's Van Allen belts, but far more intense). For the Galileo mission (1995–2003), the first spacecraft to orbit Jupiter, these belts were a hazard to avoid, since bombardment with their high-energy particles could damage sensitive instruments. When Juno arrived in July 2016, on a mission to specifically study the magnetic field and interior, it therefore took up an unusual elongated orbit over Jupiter's poles. For most of the time, the probe remains at a safe distance well beyond the radiation belts (up to 8 million kilometres from Jupiter). However, as it approaches the plane once in each orbit, it picks up speed as it plunges towards a daring fly-by as close as 4,200km above the polar cloud tops.

This choice of orbit ensues Juno endures as little radiation as possible, and NASA engineers hoped it might survive 37 orbits and last for around three years. Fortunately, the spacecraft has shown surprising durability, allowing NASA to extend its planned mission by several years. Juno should now complete a total of 76 orbits, ending with a spectacular atmospheric plunge in 2025 that will destroy the probe and ensure the surfaces of Jupiter's moons remain uncontaminated. The probe's extended mission has provided new insights into how the magnetic field changes over multi-year timespans, as well as permitting close fly-bys of Jupiter's largest moons.



The probe flew an elongated orbit that took it ever closer to Jupiter's hazardous radiation belts

out Dr Hori. One possible link between magnetism and the colour and dynamics of Jupiter's clouds, for instance, could lie in the way that intense magnetic fields can stall or divert the upwelling of hot gas rising to the surface (a similar motion creates the cool, dark patches in the solar atmosphere known as sunspots). However, while there's much more research needed to establish the nature of the connection, the team are confident that a connection is there, and that Jupiter's weather goes through cycles influenced by its changing magnetic field.

What's more, now this link has been found, scientists might one day be able to use it in reverse. "I hope our paper could also open a window to probe the hidden deep interior of Jupiter," says Dr Hori, "just like seismology does for the Earth and helioseismology does for the Sun."

There's a long way to go before our external view of Jupiter's ever-changing cloudscapes can be put to use in measuring the state of the planet's magnetic field and internal structure. In the meantime, Juno's help in unveiling the mystery of Jupiter's atmospheric eruptions is just one of the spacecraft's major achievements. Hopefully there will be many more to come before the mission reaches its end in 2025.


Giles Sparrow is a science writer and fellow of the Royal Astronomical Society


Thanks to Juno, researchers understand Jupiter better than ever before, but there are plenty of secrets still to uncover