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Sky at Night

THE UK'S BEST-SELLING ASTRONOMY MAGAZINE

AFTER THE ISS

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DANCE OF THE MOONS

See stunning transits & eclipses on Jupiter

HOW WE'LL FIND SIGNS OF LIFE ON ALIEN WORLDS

SOLVING THE MYSTERY OF JUPITER'S SHIFTING STRIPES

EXPLORE THE DEEPEST EVER VIEW OF THE ORION NEBULA

6 WAYS TO PREDICT AN AURORA DISPLAY

STARLESS GALAXY FIND EXCITES ASTRONOMERS

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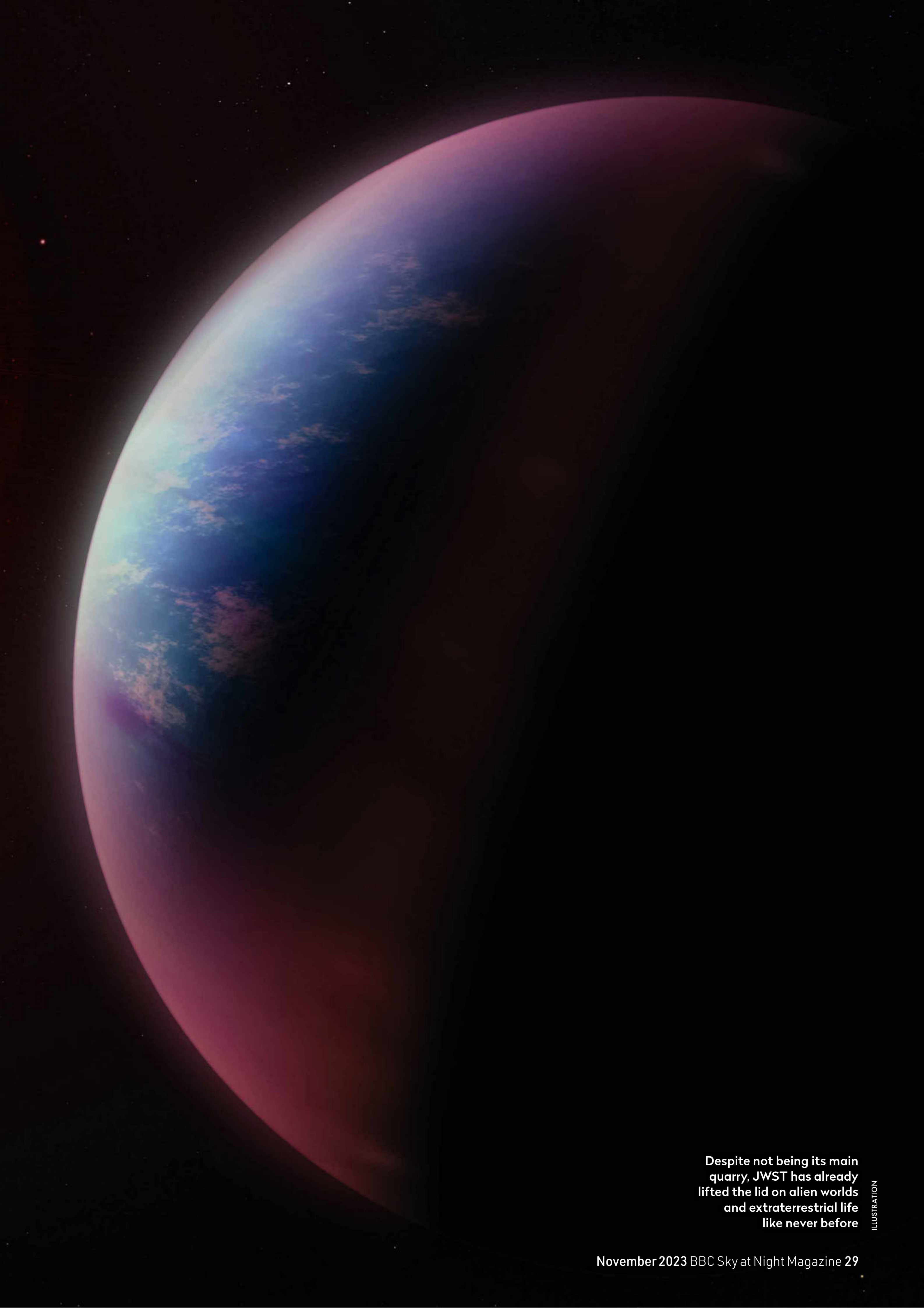
Exploring alien worlds *with the* JWST

The infrared observatory is delving deep into the atmospheres of every kind of exoplanet, as **Ezzy Pearson** finds out

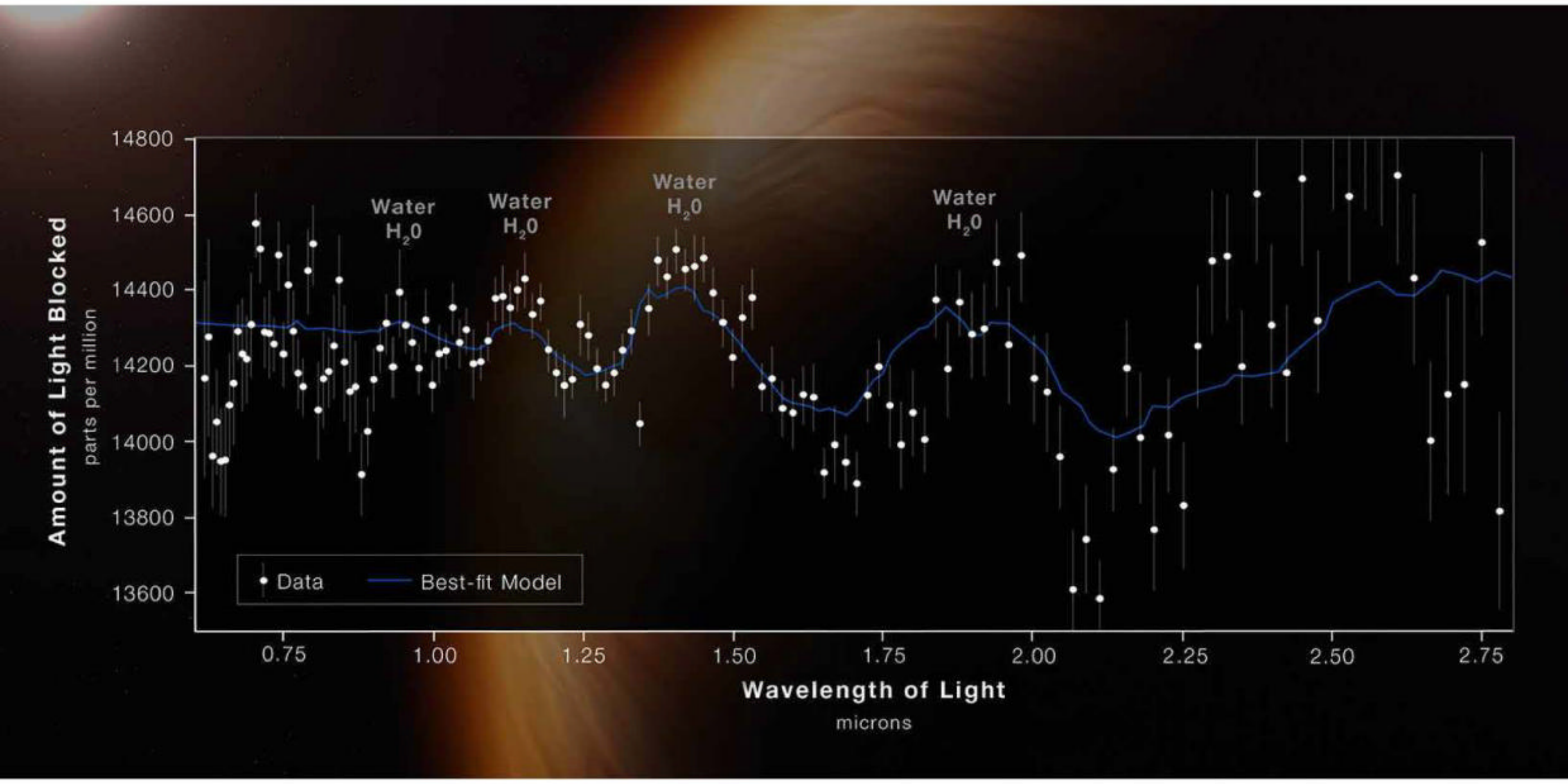
In the 1980s, as NASA was putting the finishing touches to the Hubble Space Telescope, discussions began to turn to what the agency's next grand orbital observatory would be. The design they came up with was a huge, 6.5m-wide infrared observatory that could peer back through distance, dust and even time to view the dim light of the earliest galaxies, and which we now know as the James Webb Space Telescope (JWST).

At the time of those first discussions, humanity had yet to even find a hint that there were planets orbiting around other stars. That changed in 1992, when it was announced that the first-ever confirmed alien world had been found around PSR B1257+12, sparking three decades of exoplanet exploration. ▶



Despite not being its main quarry, JWST has already lifted the lid on alien worlds and extraterrestrial life like never before

ILLUSTRATION



▲ **Astonishingly precise measurements of the starlight from WASP-96b revealed a distinct signature for water vapour**

▶ Astronomers have now catalogued over 5,000 verified exoplanets, with as many more awaiting official confirmation.

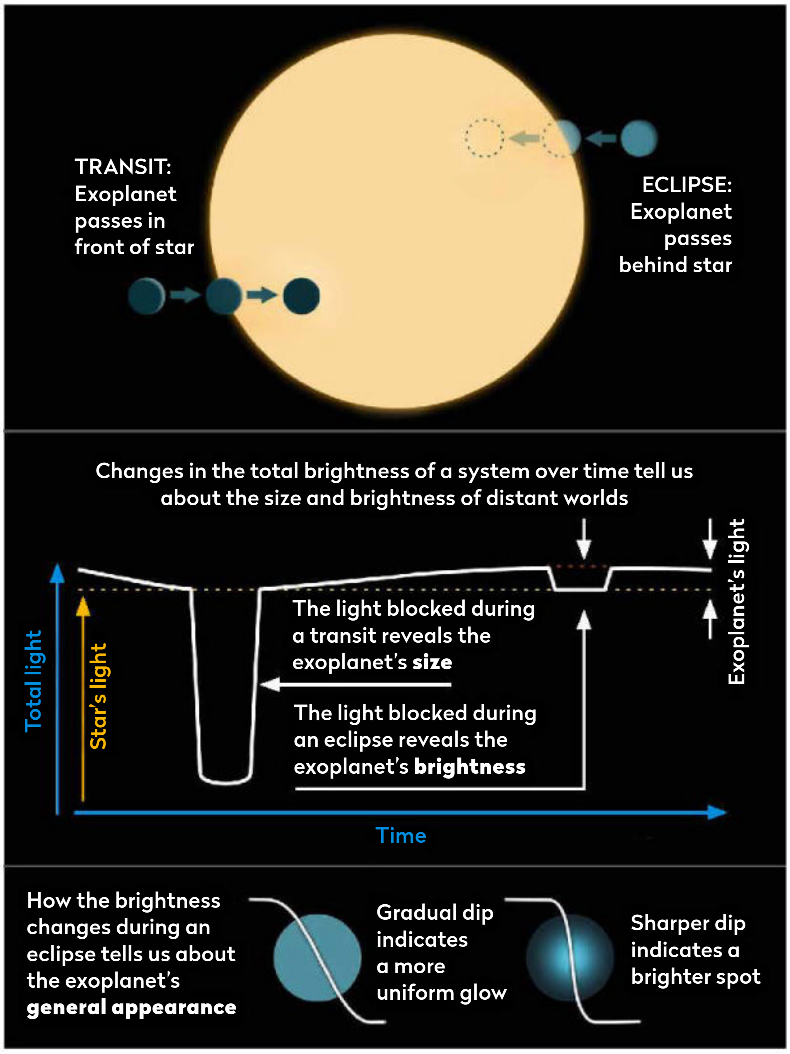
For most of these worlds, however, we have only a few scant details – perhaps only how long they take to orbit, their size and their mass. This is enough information to roughly gauge a planet's density and so reveal if it's mostly made of heavy rock or less dense gas; but it doesn't tell you what the planet is actually like. This is where JWST steps in. Though it wasn't designed for it, the telescope can look into an exoplanet's atmosphere and even pick out planets themselves as they orbit around their host star. What's more, it can do it around more types of planet than ever before.

"JWST is looking across the whole range of exoplanet sizes," says Hannah Wakeford from Bristol University. "We have things that are rocky and smaller than Earth, all the way up to gas giants twice the size of Jupiter."

Sifting through starlight

Wakeford and her team investigate what are known as transiting exoplanets. These planets pass in front of their star (from the perspective of Earth), blocking out a tiny bit of the star's light. Most exoplanet-hunting missions, such as NASA's Kepler or TESS (the Transiting Exoplanet Survey Satellite), find their planets by looking for tiny dips in a star's brightness. Once these have pinpointed the location of a likely planet, JWST can slew in for a closer look.

"With JWST we're specifically trying to measure the planet's atmosphere," says Wakeford. "We can do that by looking at the light shining through that atmosphere. Imagine a picture from the International Space Station looking through Earth's atmosphere



▲ **Even brightness changes of just two per cent allow JWST to glean a wealth of information about an exoplanet's size, brightness and general appearance**

If JWST could see us, it would be the first telescope that could tell Earth apart from worlds like Venus

Eyes on Earth

Our own Solar System highlights why planetary atmospheres are so important

It may be one of the most capable exoplanet investigators ever devised, but there are many planets JWST can't see, including those like our own. Earth is far too small for direct imaging, and while JWST can see Earth-sized planets via the transit method, it can only do so around dim stars. To find our planet against the bright Sun would require observing as many as 100 transits. Given that Earth transits the Sun only once a year this would mean a century of observation, just for one planet.

Even if JWST could see our planet, astronomers would struggle to understand what they were seeing. "If we could measure our Solar System we would see Earth and Venus and make the assumption they were both the same, when they are most definitely not," says Wakeford.

It's an easy mistake to make. Venus and Earth are roughly the same distance from their star, and the same size and density. And that's all we know about most exoplanets. Only when comparing their atmospheres do the real differences show. Earth's geological history has allowed it to maintain a nitrogen-rich atmosphere, temperate enough for oceans to form. Venus's volcanic past has resulted in an atmosphere that's almost entirely carbon dioxide, where the surface pressure is 92 times Earth's and temperatures reach 475°C.

Until now, planetary geologists have only been able to test their theories about such differences against the limited number of worlds in our Solar System. As JWST reveals more about exoplanet atmospheres, the more we grow our understanding of what chemistry and geology makes one planet end up like Earth and another like Venus.

at sunset. We're able to see an imprint of what the atmosphere is made of in the light we're measuring."

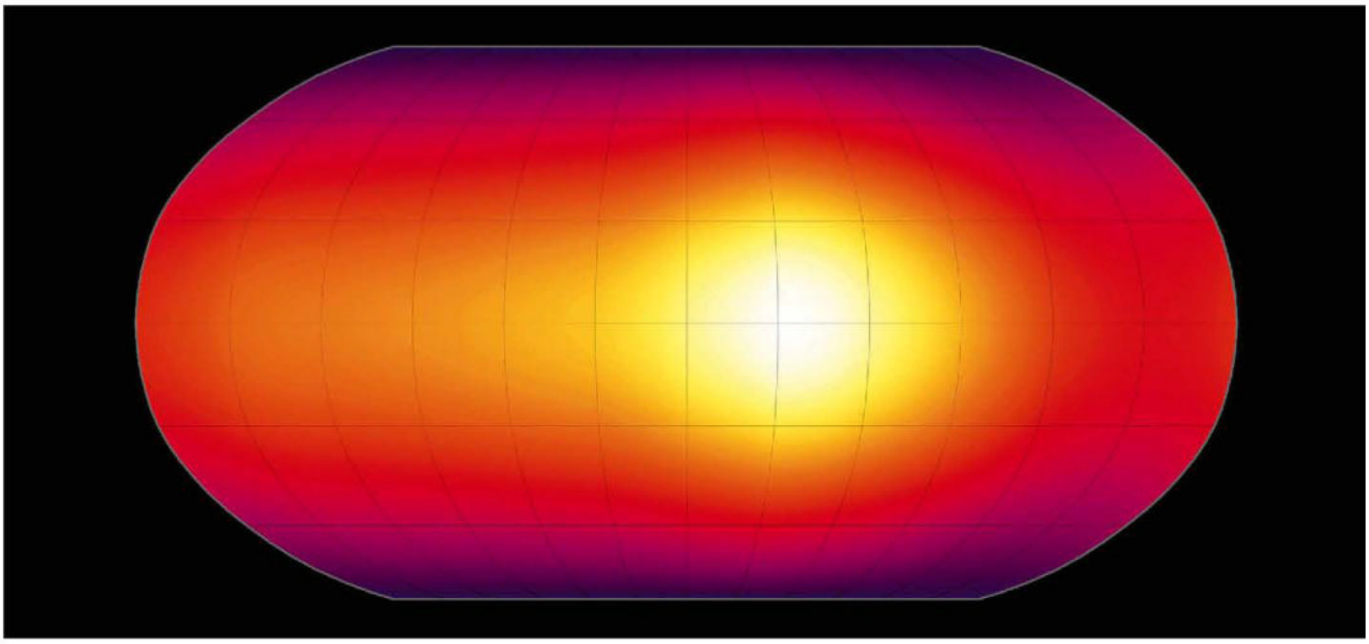
This imprint is left behind as the molecules within the atmosphere absorb some of the starlight as it passes through. The same type of molecule always absorbs the same wavelengths, leaving a dark band in the starlight that can be detected using a technique called spectroscopy.

JWST can detect a great many molecules, including water vapour, as was showcased in the atmosphere of WASP-96b and the first-ever spectra of an exoplanet discovered by JWST, back in July 2022. As well as being a key ingredient in the evolution of life, it is also a vital part of many geological processes. Knowing how much is out there on other worlds will help exoplanet scientists better understand how planets grow and evolve.

But there are many more things JWST can find in the skies of alien worlds, including carbon-based chemicals such as carbon dioxide and carbon monoxide, both of which it detected for the first time on WASP-39b last year.

"On Earth, we call those greenhouse gases because they absorb infrared radiation. Our atmosphere is filled with these gases, so it blocks that light. This is the first time we've been able to get spectroscopy of these carbon-based gases in the atmospheres of so many different planets," says Wakeford.

JWST is also able to observe a planet when it passes behind its star and becomes eclipsed. This produces a much smaller dip as the star blocks the ▶



▲ A map of gas gaint HD 189733b, showing differences in temperature across its surface, from analysing its eclipse and transit behaviour

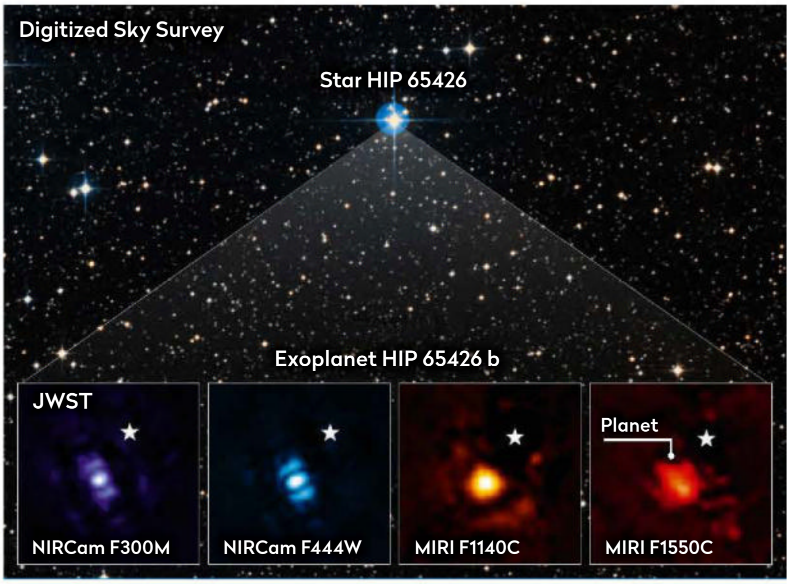
▶ infrared light given off by the planet. "Eclipses give us information on the thermal structures of the atmosphere, so how the temperature changes with altitude in the atmosphere," says Wakeford. "The temperature is really key for the chemistry that we're going to see."

Neither method is easy, however. "JWST was designed to pick up really faint galaxies in the early Universe," says Sarah Kendrew, who is part of the JWST operations team on behalf of the European Space Agency. "We're looking at nearby stars that are super bright. Exoplanet observations definitely push the boundaries of what we can do."

The dip astronomers are looking for is only two per cent, often less, of the total stellar brightness. To make it out, JWST must monitor from before the transit begins until after it ends, keeping the star centred to pixel-level accuracy. Each transit lasts six to eight hours, but if there is more than one planet in a system, observing runs could be even longer.

"The first year of observations had a programme that stared at a star for over 40 hours," says Kendrew. "Before launch we didn't know how stable the observatory would be over that kind of timescale, but actually it's incredible. Over 40 hours the biggest drift we saw was a fraction of a pixel. There's a programme coming up that wants to stare for over 55 hours."

While both transits and eclipses only observe planets indirectly via their effect on starlight, JWST is powerful enough to make direct observations of not just planets, but the discs of dust and gas that create them, known as protoplanetary discs. While planets only reflect optical light, they radiate out their own infrared light in the form of heat, albeit



▲ **JWST's first-ever direct image of an exoplanet, gas giant HIP 65426 b, used coronography to block its star's light**

Is there anybody out there?

Alien life could be waiting in the cosmos, but we need to learn enough to recognise it

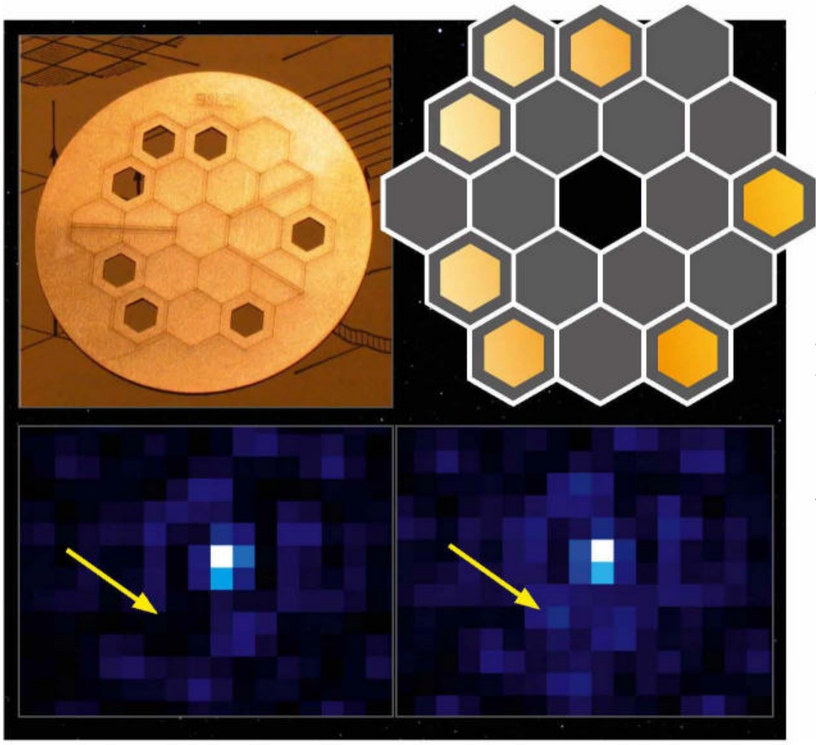
It's one of humanity's biggest questions, but could JWST be the telescope to tell us the answer?

Unfortunately... no. To be observed using the transit method, a planet must orbit close into its star, where it will be bombarded by deadly radiation. Even if some organism did manage to evolve despite this onslaught, JWST is only able to identify the gases within a planet's atmosphere.

The limitations of this have already been highlighted by the potential sighting of dimethyl sulphide on K2-18b that was announced in September 2023 (read the full story on page 12). On Earth, the only known source of dimethyl sulphide is from living organisms, such as marine phytoplankton. However, K2-18b is a sub-Neptune planet, a category of exoplanet that's not well understood at all. We don't know what its atmosphere should look like in the absence of life well enough to say that this gas is definitely created by life rather than some other chemical or geological process.

"One of the key things in the search for life is that it takes everything," says Wakeford. "From understanding how the first stars formed, which then cause the supernova to create the elements that are making up these subsequent planetary systems, to whether it is important that galaxies are colliding, all the way down to understanding if the environment in which our Sun formed was a key ingredient for the prevalence of life on Earth. There's a whole story that we have to go through. The beauty of JWST is that it gives us access to every stage of that story."

Phytoplankton, Earth's only source of dimethyl sulphide, a chemical possibly found on K2-18b



◀ **Top: a mask blocking all but seven of JWST's mirrors allows the Near-InfraRed Imager and Slitless Spectrograph (NIRISS) to be used for interferometry. Bottom: simulated interferograms of a star on its own (left) and what it would look like with a planet (right)**

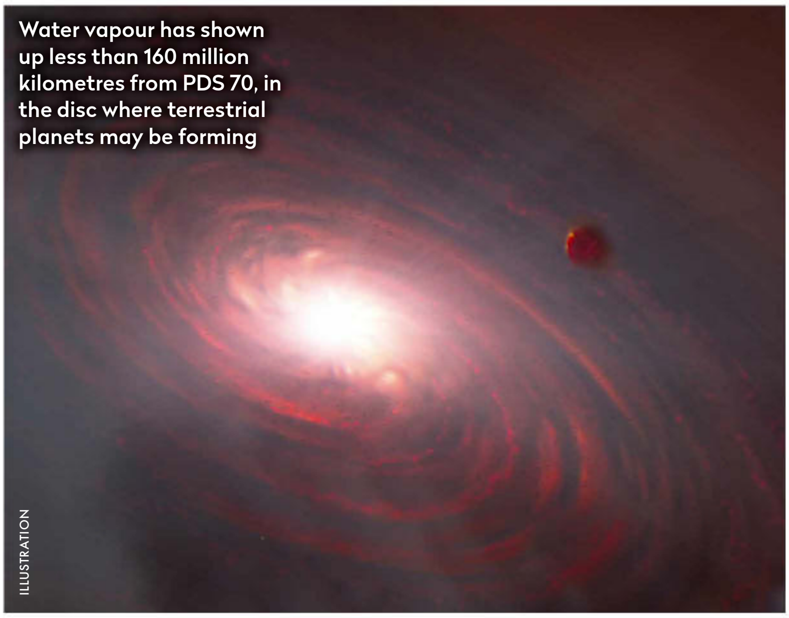
Ezzy Pearson is *BBC Sky at Night Magazine*'s features editor. Her book *Robots in Space* is available through History Press

considerably less than the star. To prevent the planet being drowned out, JWST employs a method known as coronography.

Battling the glare

"We have special masks that do the coronography, where we do imaging but block out the light from the central star to image the discs or planets," says Kendrew.

This was how JWST was able to find water in the inner regions of the protoplanetary disc around the star PDS 70. This region is where rocky planets form, but previous studies suggested the star's radiation evaporated all the water away, so the discovery reveals that infant terrestrial planets could have access to water after all.



Water vapour has shown up less than 160 million kilometres from PDS 70, in the disc where terrestrial planets may be forming

JWST has one final method of observing planets directly, using a different kind of mask with seven holes in it. This transforms the space observatory from one giant telescope into seven small ones, working together via a technique known as interferometry. As much of the light is lost, it can only be done on bright objects such as stars, but it improves JWST's resolution by up to two and a half times. This allows astronomers to resolve close-set objects that would otherwise appear as a single blob – such as a star and its surrounding planet or protoplanetary disc.

Both mask techniques can determine a planet's size, its orbit and even do spectroscopy on the atmosphere just like the transit method, but they do so on very different types of planets. The wider the separation between planet and star, the easier it is to differentiate the two. One planet observed by JWST, VHS 1256b, is four times further from its star than Pluto is from the Sun, but JWST was still able to detect silicate clouds rising like smoke through its atmosphere.

JWST's range is what makes it such a powerful tool. By looking at infant planets emerging from protoplanetary discs, all the way through to those much further on in their lifespans, JWST will help planetary geologists build their theories about how exoplanets grow and change over time.

But perhaps most interestingly, JWST can find which planets don't have an atmosphere at all. When it looked towards red dwarf TRAPPIST-1, it was expected to find a similar atmosphere to Venus. Instead it saw no trace of a thick carbon-dioxide-rich atmosphere. Meanwhile, the system's innermost planet reflects so much light, it suggests any atmosphere it ever had has been stripped away entirely. Such discoveries will help answer one of exoplanet science's most pressing questions.

"At what point does a rocky planet become a gas giant?" says Wakeford. "There's this transition of planets from rocks – terrestrial planets like Earth – to gas giants like Uranus and Neptune. Is there a cut off, where everything goes 'No, we're too big now. We're a gas giant'? We genuinely have absolutely no clue whatsoever, so that's one of the key goals of JWST, to look at those kinds of planets in a way we've never been able to before."

JWST has already made a good start on its quest to better understand exoplanets, having already observed 111 different planets, with another 65 lined up in its second year. Slowly but surely, it is building an inventory of what our Galaxy's planets look like, taking humanity one step closer to understanding how our world came to be.

NASA/ESA/CSA/A CARTER (UCSC)/THE ERS 1386 TEAM AND A. PAGAN (STSCI), WIRESTOCKISTOCK/GETTY IMAGES, ANAND SIVARAMAKRISHNAN (STSCI) X 2, NASA/ESA/CSA/J. OLMSTED (STSCI)

Explosion fingers

Only 500 to 1,000 years ago, an explosion occurred in the heart of a dense cloud of gas known as Molecular Cloud 1. The explosion sent out waves of material which struck the surrounding gas, heating it and causing it to glow, creating these bright 'fingers'. The red colour indicates areas of molecular hydrogen, but the green tinge seen at the tips of the fingers shows areas of hot iron gas.

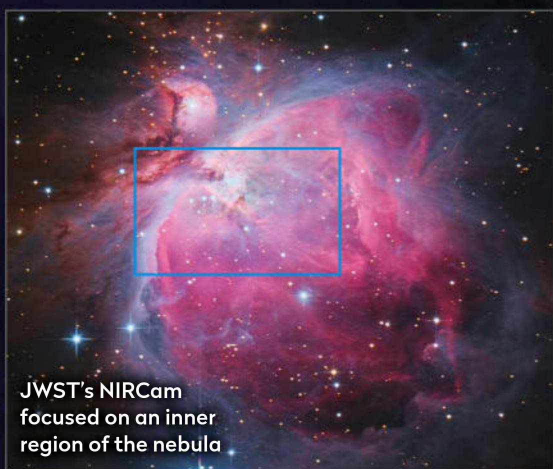
Deep inside the Orion Nebula

The James Webb Space Telescope has taken the deepest ever image of this favourite of the autumn and winter skies

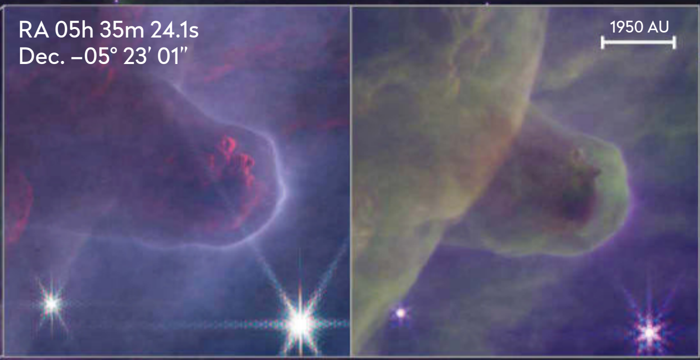
This image of the Orion Nebula, taken using JWST's NIRCam instrument, reveals its finer details like never before. One of the most famous deep-sky objects in astronomy and a perennial favourite of astrophotographers, the nebula sits only 1,500 lightyears away and is the closest major star-forming region to Earth.

As with previous Hubble and Spitzer images, it focuses on an inner region surrounding the Trapezium Cluster of stars. The region is filled with gas and dust, which clumps together to form stars, only for the wind from those infants to carve out the gas creating a network of delicate structures. However, the dust obscures the view of most telescopes. Only JWST is able to pierce through.

The image is one of the largest JWST mosaics created to date. It reveals outflows of gas from stars, dusty planet-growing discs around young stars, and photodissociation regions where the radiation from massive stars shapes the chemistry of the gas around them. It is a treasure trove for astronomers investigating the early history of stars.

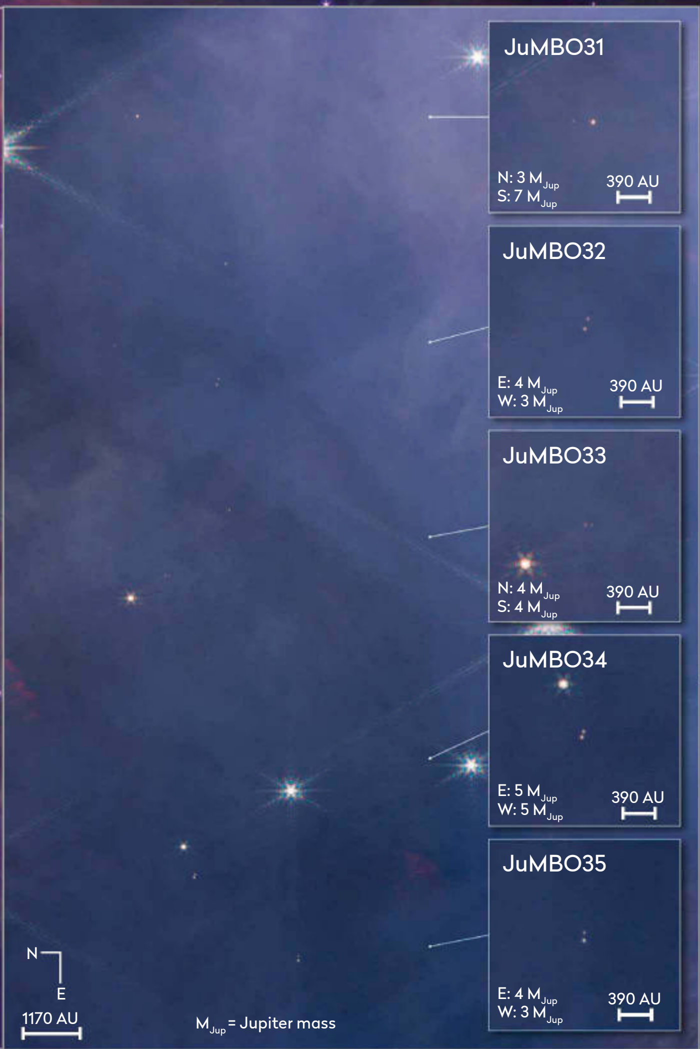


JWST's NIRCam focused on an inner region of the nebula



Piercing the veil

JWST observes at various wavelengths to show different aspects of the nebula, such as these expanding fronts driven by forming stars. The shorter wavelengths, on the left, best show discs, outflows and stars. Meanwhile, longer wavelengths, seen on the right and in the main image, highlight the intricate filaments of dust.



Neither star, nor planet

Astronomers combing through the images discovered dozens of pairs of large, gassy objects. They are around the mass of Jupiter, making them too small to have formed as stars according to our current theories, yet they are also free-floating, unlike most planets. These strange objects may have been ejected from their original planetary system, but intriguingly, mostly exist in pairs. How could they have survived the chaotic ejection process together? They've been dubbed Jupiter-mass binary objects (JuMBOs) and could be a new class of binary object.