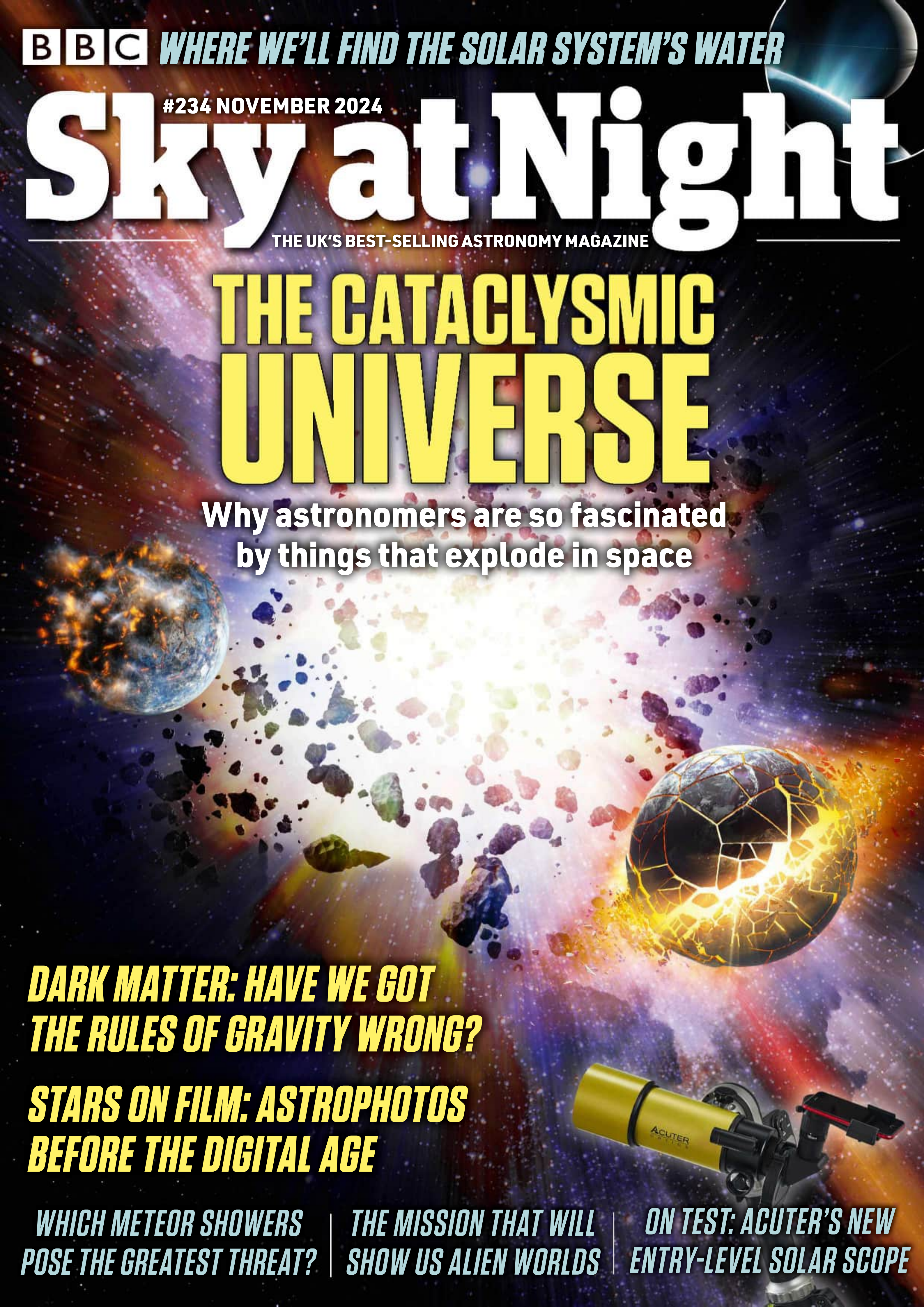

BBC **WHERE WE'LL FIND THE SOLAR SYSTEM'S WATER**

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Sky at Night

THE UK'S BEST-SELLING ASTRONOMY MAGAZINE

THE CATACLYSMIC UNIVERSE

Why astronomers are so fascinated by things that explode in space

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WHICH METEOR SHOWERS POSE THE GREATEST THREAT?

THE MISSION THAT WILL SHOW US ALIEN WORLDS

ON TEST: ACUTER'S NEW ENTRY-LEVEL SOLAR SCOPE

Close up on exoplanets

As the Nancy Grace Roman Space Telescope reaches a key milestone before its launch in 2027, **Giles Sparrow** looks at how it will provide direct views of planets around other stars

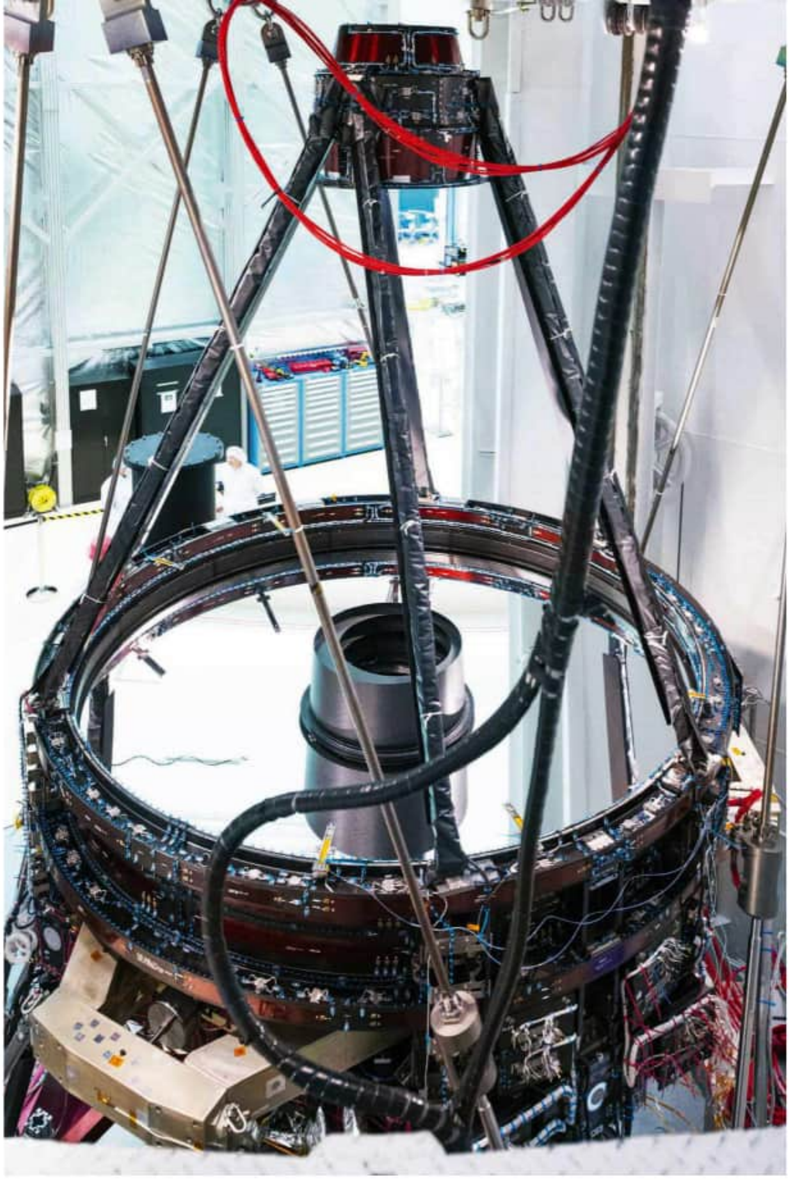
By detecting telltale changes in starlight, Roman will find and photograph thousands of gas giant worlds

ILLUSTRATION: NASA/GETTY/NASA'S GODDARD SPACE FLIGHT CENTER

In a giant clean room at NASA's Goddard Space Flight Center, engineers have just put the finishing touches to the 'bus' that will deliver its next observatory into space. The launch of the Nancy Grace Roman Space Telescope is still some 2.5 years away, but excitement is building as astronomers anticipate the next step in astronomical imaging.

With similar dimensions to the Hubble Space Telescope, Roman won't rival the James Webb Space Telescope for light-collecting power, but its unique optics and advanced instruments will help it accomplish two different objectives. Its primary goal, using a camera called the Wide-Field Instrument (WFI), is to image broad areas of the sky in a single frame, providing insights into the large-scale Universe at visible and near-infrared wavelengths. Alongside this sits a device designed to capture some of the faintest light sources ever detected. It's hoped this pioneering detector, the Roman Coronagraphic Instrument (CGI), will transform one of the most challenging fields in modern astronomy – the direct imaging of planets around other stars.

Although more than 5,600 exoplanets have now been confirmed, most of what we know has been gleaned second hand by analysing the light of



▲ All 10 of the telescope's mirrors, including the 2.4-metre (7.9ft) primary, are now assembled. They will direct light onto Roman's unique precision instruments

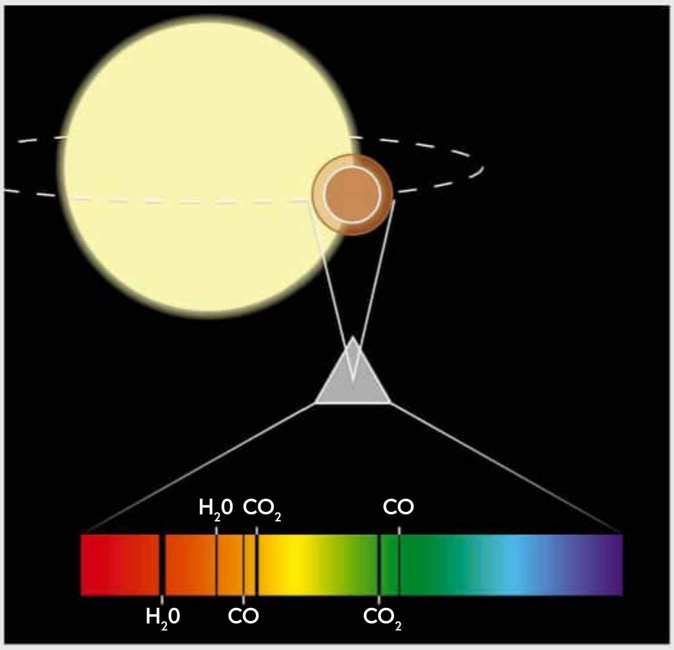
Exoplanets: the story so far

How do astronomers gather information on planets beyond our Solar System?

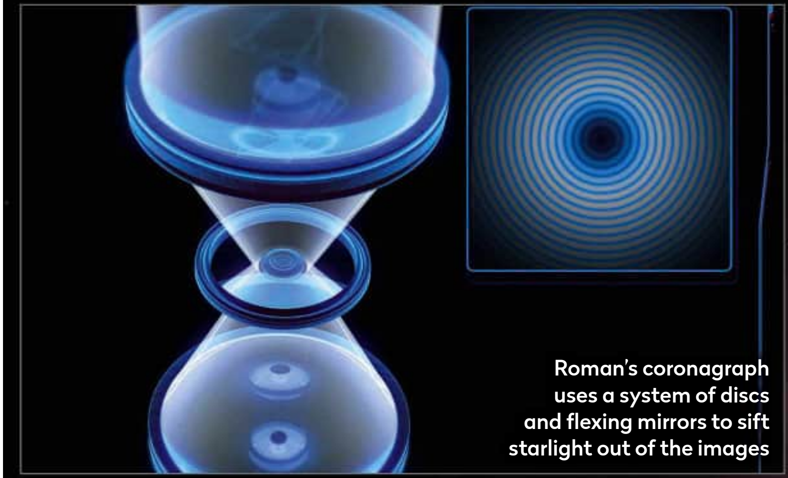
Since the first discoveries in the 1990s, astronomers have faced limits to the information they can gather about most exoplanets. Many are known only through Doppler shifts in the light of their parent stars (caused as the planet's gravity tugs the star in different directions) or from dips in brightness when a planet transits the face of its parent star, blocking part of its light. These techniques are biased towards finding certain types of planets – such as those with higher masses and those in shorter orbits – so the range of known exoplanets is unlikely to be representative of the entire population.

Measurements of Doppler shifts and transits can reveal exoplanet properties such as orbital period, mass and diameter, allowing astronomers to deduce characteristics like probable surface temperature, density and likely broad composition.

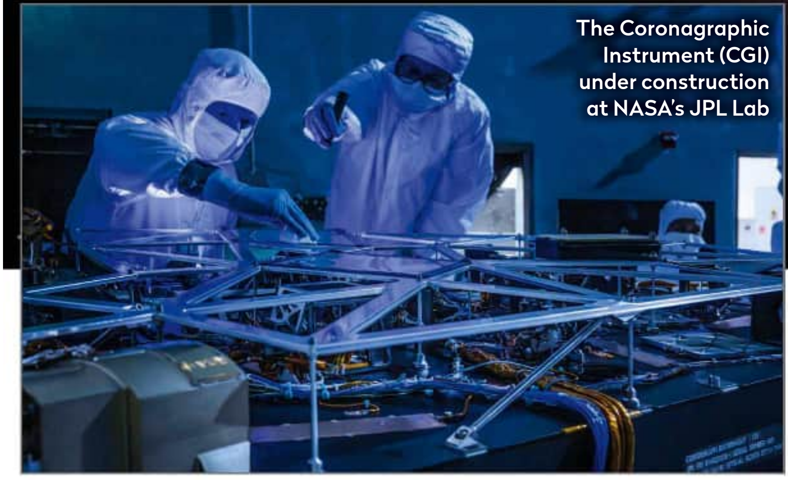
Yet direct insights into individual planets are rare because their light is so faint. Direct imaging can be used on a few young, hot gas giants, some so bright their radiation can be split into spectra for chemical analysis. Insights into the chemistry of a broader range of exoplanets can be obtained from transit spectroscopy – measurements of changes to a parent star's light as it passes through gases in a planetary atmosphere during a transit.



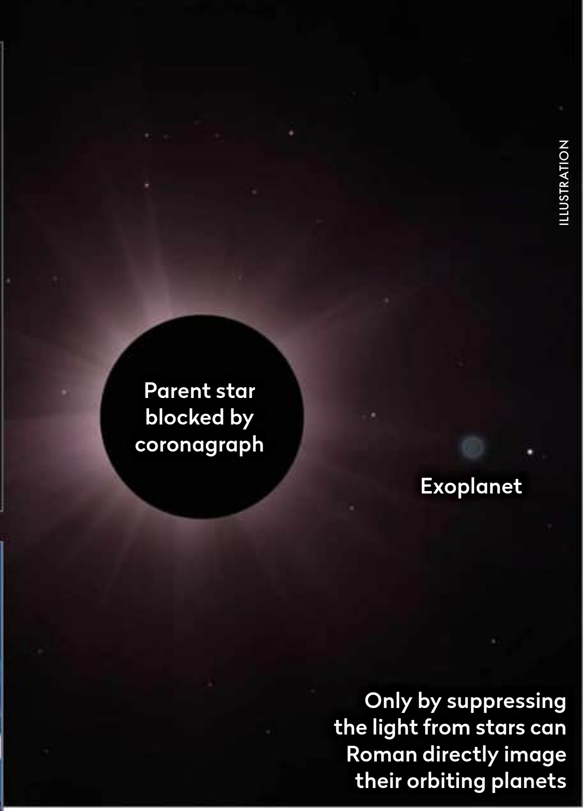
▲ Both of Roman's main instruments will use spectroscopy to analyse the starlight that passes through planetary atmospheres



Roman's coronagraph uses a system of discs and flexing mirrors to sift starlight out of the images



The Coronagraphic Instrument (CGI) under construction at NASA's JPL Lab



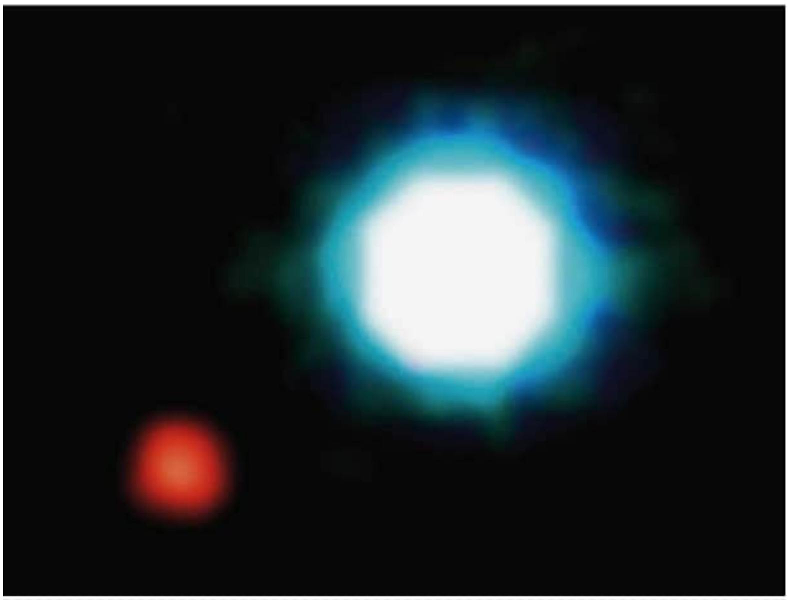
Only by suppressing the light from stars can Roman directly image their orbiting planets

their parent stars. Only in a few dozen cases have astronomers revealed exoplanets directly, blocking out the parent star's dazzling light to capture fainter radiation from nearby objects. So far, direct imaging has been possible for the brightest exoplanets: young gas giants bigger than Jupiter, pumping out large amounts of heat, light and other forms of radiation as they contract under their own gravity.

"Young super-Jupiters still glowing red-hot from the heat of their formation may be a mere 10,000 times fainter than their stars in the near-infrared, although they become cooler and dimmer as they age," explains Dr Vanessa Bailey of NASA's Jet Propulsion Laboratory in Pasadena, California. "An old, cold Jupiter twin – a Jupiter-sized planet, at Jupiter's orbital distance, around a Sun-like star – would be about a billion times fainter than its star. Because it's cold, it emits little visible or near-infrared light and would be detectable in reflected visible light. An Earth-twin would be 10 billion times fainter than its star, again in reflected visible light."

Bailey, an instrument technologist on the coronagraph, raises a second challenge: "These planetary systems are tens or even hundreds of lightyears away, and planet and star appear close to each other in the sky – often less than an arcsecond, 1/3,600th of a degree. Detecting one of those 'easy' young super-Jupiters is like seeing a firefly 20ft from a lighthouse halfway across the country."

▼ **The first directly imaged planet (red), captured in 2004 orbiting the brown dwarf 2M1207**



Blocking lighthouses

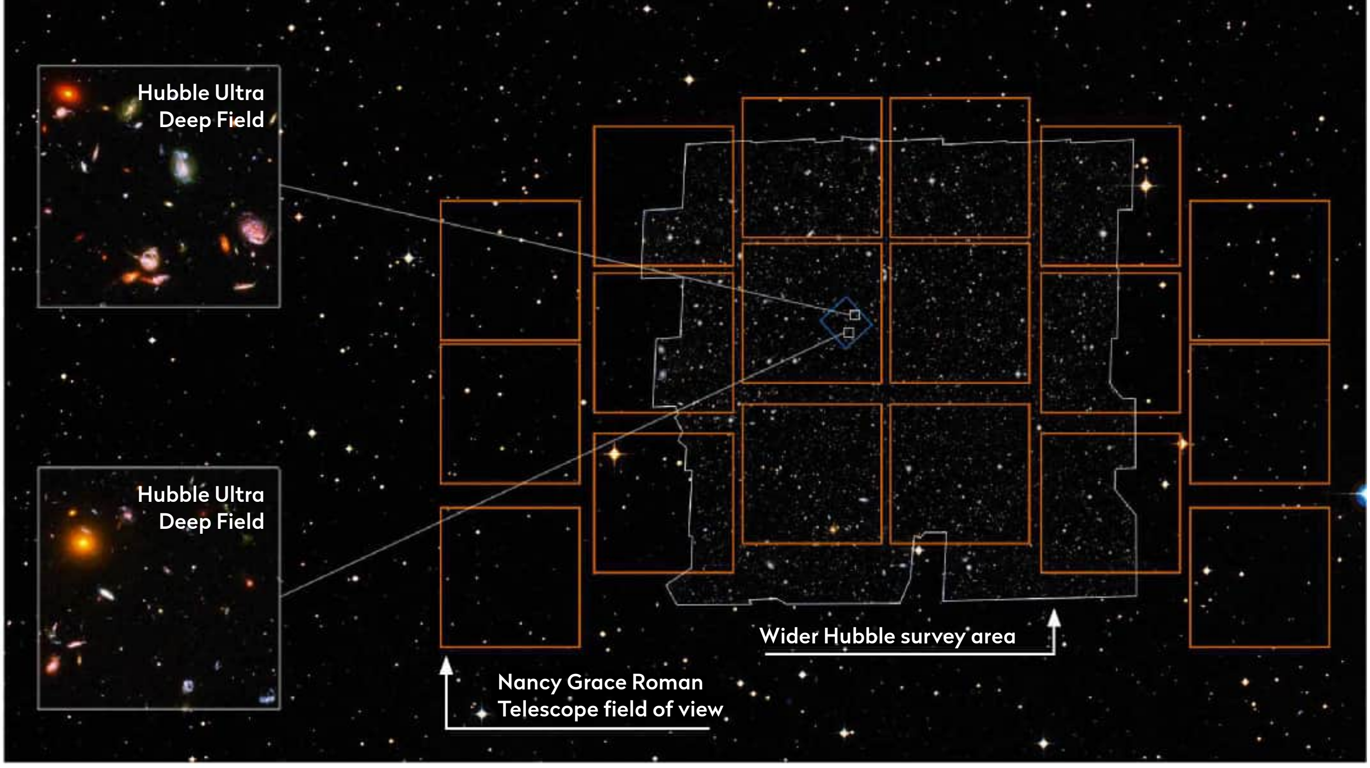
The aim of any coronagraph is to block out direct starlight while allowing light from nearby objects to pass uninterrupted.

"At its most basic, a coronagraph is an opaque spot inside the instrument that covers the star but not the planet," explains Bailey. "Due to the wave nature of light, the starlight diffracts each time it encounters an optic in the telescope and the light spreads out across the image. It's more than enough to swamp a planet that's much fainter."

"Modern coronagraphs still use an 'occulting spot' to cover the star, but they use additional optics upstream and downstream, fine-tuned to reduce the effects of diffraction and, therefore, glare."

However good optical solutions to the diffraction problem may be in theory, the behaviour of starlight before it even reaches the coronagraph can make their practical application hit-and-miss. "Coronagraph performance is limited by the quality of the images landing on them," says Bailey. "[On Earth] it wasn't until 'adaptive optics' technology – the addition of deformable mirrors that can bend and flex at high speeds to counteract the blurring of the atmosphere – that high-performance coronagraphy became possible on the ground." ▶

NASA/CHRIS GUNN X 2, ESA, NASA'S GODDARD SPACE FLIGHT CENTER,
NASA'S GODDARD SPACE FLIGHT CENTER CONCEPTUAL IMAGE LAB, ESO



▲ While it will match Hubble's sensitivity and infrared resolution, Roman will capture roughly 100 times more sky and will scan the cosmos 1,000 times faster

▶ Operating in space frees telescopes from the need to compensate for atmospheric fluctuation, but adaptive optics can play a similar role in improving performance, as Bailey points out. "The Roman Coronagraph will be the first to utilise deformable mirrors to compensate for minute aberrations. It will be able to suppress starlight hundreds of times more effectively than Hubble, Webb or current ground-based telescope coronagraph instruments."

▲ Technicians assemble the focal plane system, the heart of Roman's main Wide-Field Instrument (WFI)

Catching fireflies

Once its optics have removed excess starlight, the Roman Coronagraph still needs to capture the weak signals that remain. "Even with a 2.4-metre [7.9ft] aperture telescope, we may receive as little as one star or exoplanet photon per pixel, per minute," explains Bailey.

Like almost all modern telescope cameras, the instrument captures images using electronic CCDs (charged-coupled devices). CCDs are semiconductor chips covered in a grid of tiny, charge-storing electronic capacitors. When photons strike the grid, they generate negatively charged photoelectron particles that build up in proportion to radiation intensity. The charge of the grid squares can then be 'read', their values converted to pixels in a digital image, but this introduces 'read-out noise': random variations that swamp weaker signals.

So, the Roman Coronagraph uses an advanced detector called an Electron-Multiplying CCD (EMCCD). This adds a 'gain register' component that causes a single photoelectron to produce several thousand more electrons before the charge is stored and read out. Noise is reduced and the faintest images can be captured.

"During vacuum chamber testing, we illuminated the instrument with an artificial star and showed that we can suppress that artificial starlight by a factor of at least 10 million," Bailey says. "We're confident it will be able to detect exoplanets at least 10 million times fainter than their stars, and we think it may be able to detect planets 100 million times fainter or more."

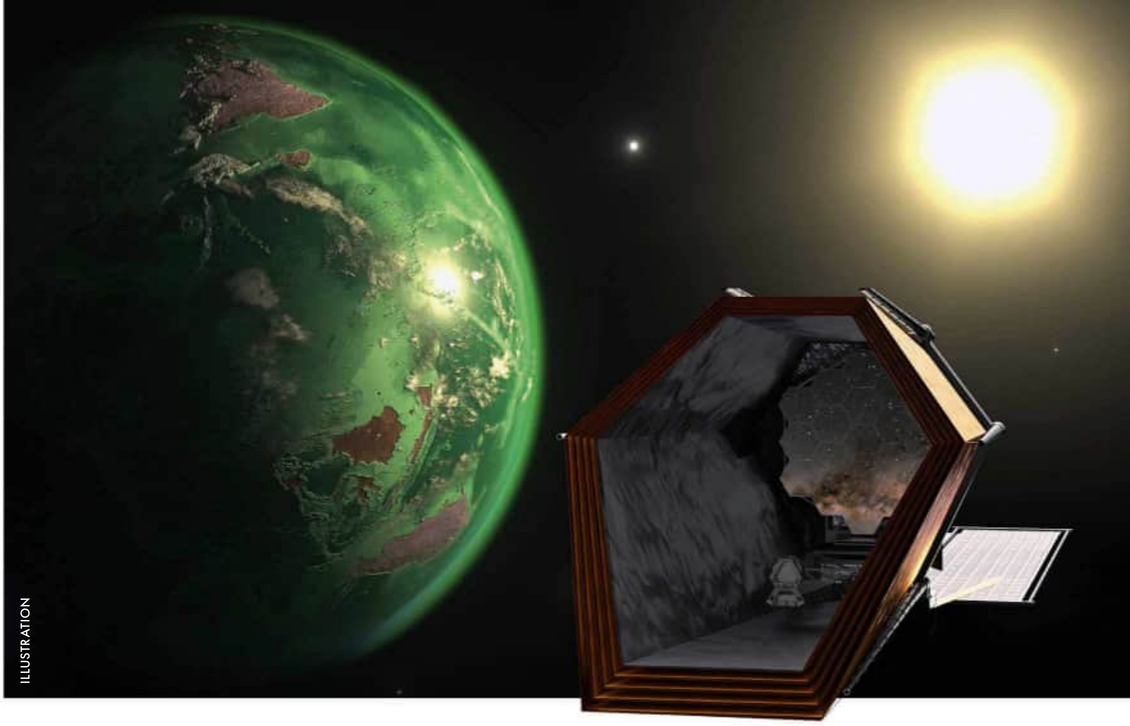
While the Roman Coronagraph is intended as an imaging instrument, it has other capabilities that could reveal more details of exoplanets and other material orbiting around nearby stars.

In polarimetry mode, it can measure the polarisation or orientation of incoming light waves. While starlight is typically emitted with random polarisation, reflections from certain materials can cause waves to align in specific ways, potentially revealing secrets of dust clouds around stars or particles suspended in the atmospheres of exoplanets. In spectroscopy mode, light from exoplanets can be split into a spectrum, revealing dark 'absorption lines' at specific wavelengths created by elements such as methane, potassium and sodium, to uncover the chemical makeup of their atmospheres.

Observing plans

While Roman's WFI will make observing time available to the global scientific community, the coronagraph is intended as a technology demonstrator, a pathfinder for instruments that could fly on NASA's Habitable Worlds Observatory

NASA/ESA/A. KOEKEMOER (STSCI) AND A. PAGAN (STSCI), NASA/CHRIS GUNN, BAKONYI SZABOLCS/ ISTOCK/GETTY IMAGES, NASA'S GODDARD SPACE FLIGHT CENTER CONCEPTUAL IMAGE LAB, ESA



▶ Roman will be a test run for the tech that NASA's Habitable Worlds Observatory will use to find Earth-like planets

(a large telescope intended to investigate Earth-sized planets around stars' habitable zones) during the 2040s. "We expect to have roughly 2,200 hours of observing time, split across multiple campaigns during the first 18 months," explains Bailey.

Plans are already advanced for the planets and systems the coronagraph might target. Based on orbital parameters and other properties of known exoplanets, astronomers can estimate their likely brightness and separation from their stars, helping them infer which objects lie within its reach.

"It's likely we'll observe a few young, glowing super-Jupiters," says Bailey, "as well as circumstellar dust discs in polarised light, since those objects are brighter. Using reflected visible light, we may be able to take an image of another cold, Jupiter-like planet, like 47 Ursae Majoris c [an exoplanet in a 6.5-year orbit around a Sun-like star, 45 lightyears from Earth]. That would be at the limit of our performance, so it'll be a nail-biter!"

If Roman can capture spectra from planets like 47 Ursae Majoris c or the broadly similar Upsilon Andromedae d (another potential observing target), it could lead to major advances. Using computer simulations, NASA astronomers have investigated the kinds of information the coronagraph might glean from the spectra of such planets, showing how it could be used to measure atmospheric composition, identify seasonal atmospheric changes such as the formation of clouds and hazes, and even probe the planet's internal temperature.

Truly Earthlike planets will remain beyond the Roman Coronagraph's capabilities – too faint or too close to their star to resolve. Yet this exciting instrument should be a significant step forward, allowing exoplanet imaging to move beyond massive newborn stars and begin to reveal the secrets of mature systems more like our own.

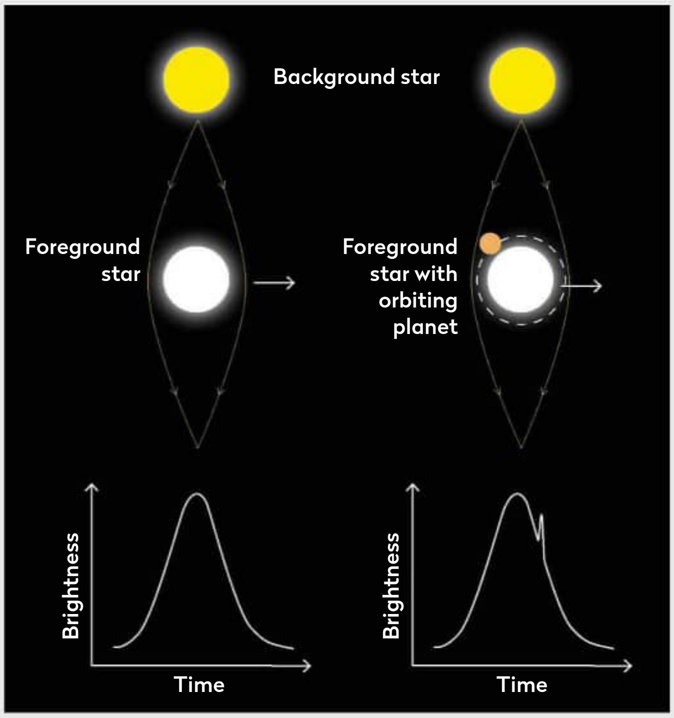
Giles Sparrow is a science writer and fellow of the Royal Astronomical Society

Roman revolution

Exoplanet imaging is just one string to Roman's bow. Here's what else the observatory will do

Named after NASA's first female executive and former chief of astronomy, the Nancy Grace Roman Space Telescope has a primary mirror with the same 2.4-metre (7.9ft) diameter as the Hubble Space Telescope, but a shorter focal length. Using its primary Wide-Field Instrument (a 300.8MP camera capable of detecting wavelengths from blue to the near-infrared), it can capture widefield views of the sky roughly 100 times greater than Hubble. Its main mission is to survey a billion galaxies across the sky, using images, spectra and other data to map the large-scale structure of the Universe and reveal the properties of dark energy, the mysterious force that appears to be increasing the rate of expansion of the Universe.

A companion survey will monitor hundreds of millions of stars towards the centre of our Galaxy. This should reveal new transiting exoplanets, but also the elusive effects of microlensing – a temporary spike in brightness caused when gravity around a foreground star (or another object such as a lone black hole) intensifies the light from another star directly behind it. Because microlensing is highly sensitive to the shape of the gravitational field, it can betray the presence of relatively low-mass planets in quite large orbits, filling in a major gap in the current exoplanet census.



▲ Roman will watch for microlensing, spikes in the brightness of background starlight which can reveal new low-mass exoplanets