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Alien skies

Astronomers can now peer into exoplanet atmospheres like never before, transforming the search for life beyond Earth. So what's the plan, asks **Stuart Clark**

WHEN the first observations from the James Webb Space Telescope (JWST) were made public in July 2022, the images of deep space were so breathtakingly beautiful that it was easy to overlook the dowdy-looking graph released alongside them. The world was agog at the majestic panoramas of clouds of gas and dust from which stars are born, and the shining spiral shapes of ludicrously distant galaxies. Yet for many astronomers, the graph, a simple curving line, was just as jaw-dropping. It heralded a new era in the search for alien life.

Showing the unambiguous detection of water vapour in the atmosphere of an exoplanet called WASP 96b, it was the first proof that this powerful telescope would be able to deliver what many had doubted, namely, precise details of the contents of atmospheres on worlds beyond our solar system. Just as the beauty of some of those deep-field images captured the imaginations of the public, the quality of this unprecedented graph electrified astronomers. Suddenly, it was clear we really can peer into alien skies like never before. Finally, we have a fighting chance of spotting the subtle signals that would prove life exists elsewhere – not that it will be easy.

Now, astronomers are plotting their next moves. Having whittled down the most promising planets, they are lining up observing time with JWST to probe their atmospheres, thinking again about what signs of life we should be looking for – and sizing up the prospects of success. "I feel like we're at the beginning of a really exciting journey," says Laura Kreidberg at the Max Planck Institute for Astronomy in Heidelberg, Germany.

Exoplanetary atmospheres contain all manner of clues about what the planet is made from. We study them with a technique called spectroscopy, which takes advantage of the fact that different atoms and molecules absorb different wavelengths of light (see "Cloud spotting", page 38).

The first success in probing alien skies came in 2002, when David Charbonneau, then at the California Institute of Technology, and his colleagues used the Hubble Space Telescope to watch a gas giant world called HD 209458b, nicknamed Osiris, cross the face of its parent star. As it did so, Hubble detected a small dimming of the star's light at the wavelength absorbed by sodium. The effect disappeared when the planet moved off the face of the star, meaning it must have been caused by sodium in Osiris's atmosphere.

Alien weather

From then on, astronomers gradually began to dip their toes into analysing exoplanet atmospheres. The initial targets had to be worlds that block an appreciable amount of starlight. These turned out to be the largest and nearest examples of "hot Jupiters", gas giant planets that sit inexplicably close to their parent star, completing a single orbit in just a couple of Earth days.

For years, astronomers caught glimpses of elements and molecules in the atmospheres of such exoplanets. Then, in 2017, we saw the real power of spectroscopy when it comes to characterising worlds beyond our solar system.

Thomas Mikal-Evans, then at the University of Exeter, UK, and his colleagues used Hubble and the infrared Spitzer Space Telescope to study WASP-121b. Watching this hot Jupiter, 850 light years from Earth and about 1.81 times larger than Jupiter, revealed the first water vapour seen in an exoplanet atmosphere. But they didn't stop there. After studying WASP-121b for a full orbit, about 31 hours, the team glimpsed something extraordinary. Temperatures on the planet's dayside, facing the star, were so high that they ripped water molecules apart, producing hydrogen, oxygen and hydroxyl. The heating drove tremendous winds on the planet, sweeping these molecules round to the nightside, where temperatures dropped sufficiently for them to recombine into water. It was the first evidence for weather in another solar system.

"We were actually able to measure this happening by tracking how the spectral feature of water changed from the dayside to the nightside hemisphere," says Mikal-Evans, now at the Max Planck Institute for Astronomy.

The temperature difference was so great, the team speculated, that simple minerals like corundum, a form of aluminium oxide, could also be vaporising on the hot side and condensing into clouds on the cool side. Corundum forms the basis of rubies and sapphires, meaning the clouds on WASP-121b could be made of ruby and sapphire dust.

Until recently, however, the technology enabling spectral analysis of alien skies has had its limits. "With all of the power of Hubble and Spitzer and ground-based telescopes, we've only learned a little bit about what to expect for these atmospheres," says Kreidberg. "We have seen just the very tip of the iceberg."

With the help of JWST, we are now diving below the surface. That is because JWST outstrips its predecessors on three main counts. First is its position in space. Far from Earth's orbit, this telescope can keep its targets precisely aligned on its sensors, reinforcing the detection of even faint signals. Second, JWST has a 6.5-metre-diameter mirror, a big step

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GRAHAM CARTER

up from Hubble's 2.4-metre-diameter mirror, which allows JWST to collect a lot more light, revealing fainter details. Perhaps its biggest advantage, though, is that it works across the infrared spectrum. That is a boon because molecules love to interact with light at these wavelengths. "The infrared is the richest spectral region if you want to see absorption by molecules," says Drake Deming at the University of Maryland. And JWST's mirror is more than 7.5 times larger in diameter than previous infrared telescopes, like Spitzer.

What all of this means is that, for the first time, astronomers have a real shot at seeing the details of the atmosphere of a rocky exoplanet, which is generally considered the best bet for finding potential signs of life.

What we are looking for are smaller rocky planets with atmospheres, like Earth, that happen to orbit within the habitable zone around a star, where temperatures would allow liquid water to exist at the planet's surface. The trouble is that smaller worlds, with less gravitational heft, can only retain relatively tenuous atmospheres. (For example, Earth's atmosphere contributes less than 1 per cent to its radius.) So if we want to detect their atmospheres with JWST, these rocky worlds also have to be relatively near.

Those criteria alone hugely narrow the number of viable targets. "For rocky planets that are in the habitable zone and accessible to JWST, we're talking definitely less than 10," says Kreidberg (see "Promising planets", left).

Even then there are complications. Each of the target planets orbits its own small red dwarf star. These stars are cooler than the sun, so their habitable zones are much closer in than that of the sun, which could make it difficult for the planet to retain an atmosphere. A case in point is the poster child of target systems – TRAPPIST-1, an ultra-cool red dwarf star around 40 light years from Earth with seven known rocky planets. This star's surface temperature is less than half that of the sun's, which means its habitable zone is extremely close to the star. So although three or four of the TRAPPIST planets sit in the habitable zone, there is no guarantee that they have atmospheres. "It's possible that they're all bare rocks," says Kreidberg.

Although this particular red dwarf is today

PROMISING PLANETS

When it comes to habitable worlds we can search for atmospheres, the options are limited. These are today's best candidates.

LHS 1140b
Discovered in 2017 by the Whipple Observatory, Mt. Hopkins, Arizona, this is a dense super-Earth 6.48 times more massive than Earth, and with 1.64 times the radius. Depending on its atmosphere, its surface temperature could be very Earth-like.

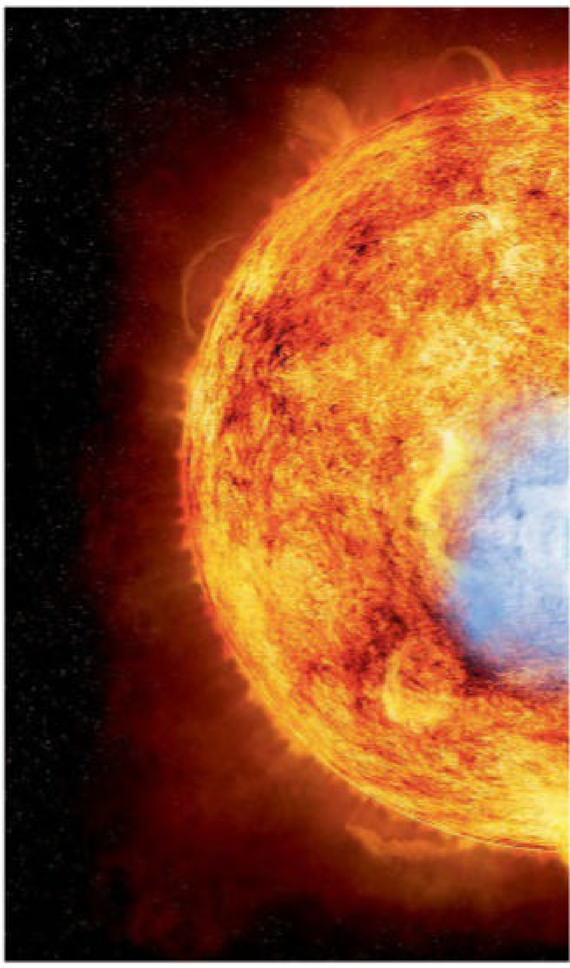
TRAPPIST-1d
The star TRAPPIST-1 hit the headlines in 2016 and 2017 with the announcement of seven planets in orbit around it. Of those, at least three might be in the ultra cool dwarf star's habitable zone. TRAPPIST-1d has 0.78 times the radius and 0.3 times the mass of Earth.

TRAPPIST-1e
Very similar in its physical characteristics to Earth, TRAPPIST-1e has 0.91 times the radius and 0.77 times the mass of our world. If the planet possesses a relatively thin atmosphere like Earth, its surface temperature could be similar to ours.

TRAPPIST-1f
With a mass of around 0.68 times that of Earth, and a very similar radius, TRAPPIST-1f is just inside the outer edge of its star's habitable zone. It would require a modest greenhouse effect to raise its surface temperature to Earth-like levels.

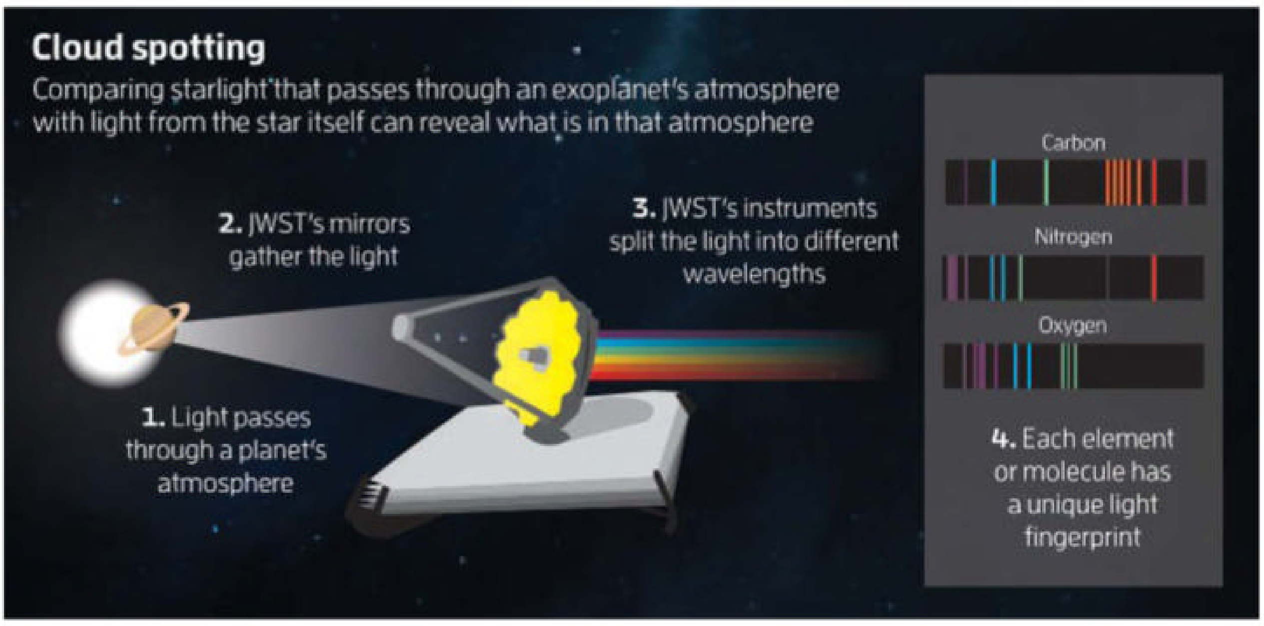
K2-18b
Discovered in 2015 by NASA's Kepler space telescope, K2-18b has water vapour in its atmosphere and is in the habitable zone of its parent star. But with 8 times the mass and 2.6 times the radius of Earth it is either a rocky "super-Earth" or a gaseous "mini-Neptune".

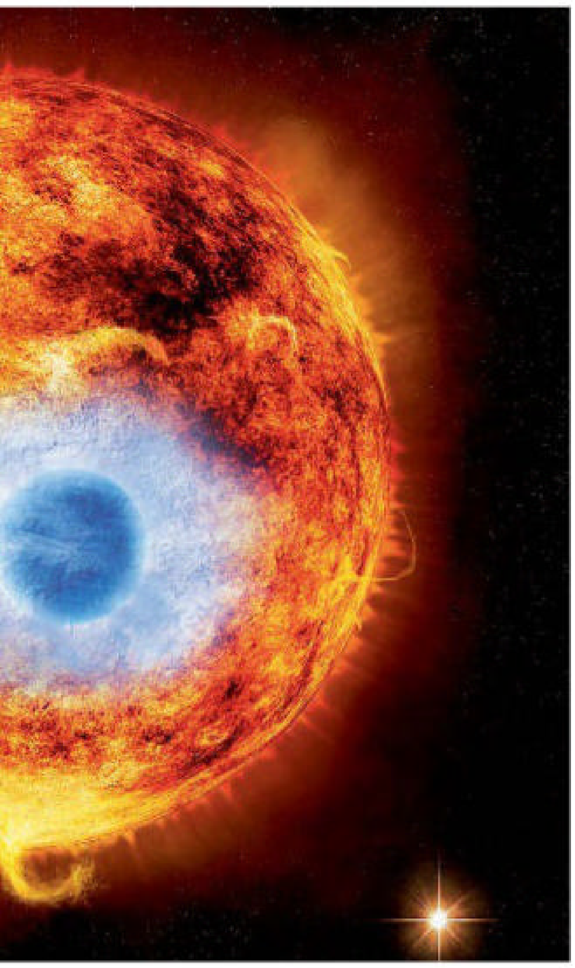
LP 791-18c
Another super-Earth / mini-Neptune, LP 791-18c was discovered in 2019 by NASA's Transiting Exoplanet Survey Satellite (TESS) mission. It has 2.3 times the radius and 5.95 times the mass of Earth and sits near the inner edge of its star's habitable zone.



Cloud spotting

Comparing starlight that passes through an exoplanet's atmosphere with light from the star itself can reveal what is in that atmosphere





NASA/CXC/M.WEISS

An artist's impression of a hot Jupiter passing its star

"It would really be delightful if we saw a biosignature we didn't expect"

cooler than the sun, the situation was reversed during its formation. A star forms when a pocket of interstellar gas contracts under the force of its own gravity. In the process, it releases a torrent of high energy radiation. Smaller stars have weaker gravity and so take longer to contract, meaning that they are releasing this flood of energy for longer than their larger cousins. This could blast away any atmospheres from nearby planets that are forming.

With all that in mind, Kreidberg will use JWST to observe the TRAPPIST-1 planets as they move in front of and behind their star. The idea is to determine the difference between their day and night temperatures, which will in turn tell her whether each has an atmosphere or not. Atmospheres tend to efficiently distribute heat around a planet, so the day and night temperatures tend to be similar. A bare rock with no atmosphere will heat up on the dayside and then radiate that energy directly into space on the nightside, giving a different temperature profile.

Once we know there is an atmosphere, it will be time to try to get a spectrum and look for the signatures of life. Based on what we know on Earth, the best things to look for are the spectral fingerprints of oxygen and methane. All living things respire; they take in one gas or substance, extract energy from it and then expel a waste gas. In the case of animals, oxygen is the input and carbon dioxide is the output. For plants, it is vice versa. In animals, metabolising food also produces other waste gases, like methane. All of this builds up in a planet's atmosphere, knocking it out of chemical equilibrium – and producing a detectable signature.

Indeed, the oxygen that we now rely on for life is an excellent example. Earth's earliest microbes obtained energy via photosynthesis and, like today's plants, produced oxygen as a waste product. Other microbes evolved to metabolise the oxygen. Seeing oxygen and methane together in an exoplanet atmosphere would be the closest thing to a slam dunk we can currently imagine. These two gases are biologically produced on Earth and otherwise wouldn't co-exist in the air. Without constant replenishment by living things, they would chemically react and vanish from the atmosphere.

Signs of life

TRAPPIST-1e is the planet that gives the best chance of such a detection. Perfect conditions would raise that chance, but seem unlikely in reality. The list of them is long. "If we're really, really lucky and the planet has exactly the atmospheric composition we are expecting, JWST performs so perfectly that we can stack up data again and again and again and again to beat down the noise, the atmosphere doesn't have clouds and there's no contamination in the spectrum from the host star, which we already know is not true," says Kreidberg. "All of those things would have to happen before we could have a prayer of identifying the biosignature."

Put like that, it sounds next to impossible, but such an assessment is based on what we know of life on Earth. "The one thing which would really be delightful is if we saw a biosignature somewhere we didn't expect," says Deming, "Everyone's thinking of rocky planets, like the Earth with solid surfaces and thin atmospheres, but maybe not."

For example, he would love to see something from an exoplanet that resembles Neptune. Roughly five times the diameter of Earth, and predominantly composed of icy materials, a number of these Neptune-class planets have been discovered around other stars. Intriguingly, some have migrated close enough to their respective stars that they could be covered in global oceans – on the face of it an excellent venue for life. And with larger atmospheres to start with, such hot Neptunes should make JWST's job easier.

When it comes to biosignatures, a new generation of researchers is starting to increasingly think outside the box. Justin Wang at the University of Colorado, Boulder, proposes looking for a set of molecules called polyhydroxyalkanoates (PHAs). These are a family of polyesters made exclusively by microbes. As such, they can be thought of as bioplastics, and wherever they occur, they seem to have some remarkable properties.

"I found many types of microorganisms that use PHA," says Wang, "and I found that in many of the [microbes known as] extremophiles, the bioplastics are the explanation for how they can survive in those environments." This is music to the ears of an astrobiologist because extremophiles, as the name suggests, live in harsh environments that most other life on Earth would find toxic. So maybe bioplastics are exactly the kind of molecules that we should be looking for.

At present, Wang thinks that such searches are more easily conducted in places like Mars, where robots can scoop up samples of dirt and process it. He can't easily think of a situation in which PHAs would build up to create a detectable signal in a planet's atmosphere. Nevertheless, the idea raises the possibility that perhaps we have thought too narrowly so far about the biosignatures we are looking for – or the places to seek them.

As researchers work their way through nearby exoplanets with JWST, we may be in for a very big surprise. The next time NASA and the European Space Agency make a big deal out of a wavy line, it could be because we have answered that big old question: are we alone in the universe? ▮

Stuart Clark is a consultant for *New Scientist*. His latest book is *Beneath the Night* (Faber)