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Signs of life

We keep spotting molecules associated with biology in alien atmospheres. Can these "biosignatures" prove we are not alone? By **Philip Ball**

"DON'T be excited," says Sara Seager. She is talking about putative signs of life from observations of the atmospheres of other worlds, and her words are a sobering counterbalance to hyperbolic headlines.

Of course, a genuine sighting of the signature of life beyond Earth would be anything but humdrum. On the contrary, it would be momentous. Given that we have investigated just a tiny fraction of the many billions of planets assumed to exist in our own galaxy, it would imply that life is abundant in the universe.

That explains the steady drumbeat of stories about molecular "biosignatures" spotted on other worlds, thanks mainly to the James Webb Space Telescope (JWST). Last September alone, it detected carbon dioxide on Jupiter's icy moon Europa that appears to come from its potentially life-friendly concealed ocean and, possibly, dimethyl sulphide on exoplanet K2-18b, a chemical produced on Earth only by living things. "Tantalising sign of possible life on faraway world," was the BBC's take.

But Seager, an astrobiologist at the Massachusetts Institute of Technology, urges caution for good reason: when it comes to evidence for extraterrestrial life, the remote detection of molecules tends to be inconclusive. Even if the detection proves reliable – and that is often a big if – there may well be a plausible non-biological explanation for a chemical's presence.

To make sense of such findings, then, and to calibrate our excitement about the chances they herald aliens, it pays to get to grips with the promises and pitfalls of the biosignatures we search for. Can they ever provide definitive proof of life?

When astrobiologists talk about seeking atmospheric biosignatures, they are referring to molecules known to be associated with life on Earth that we can detect from afar. We do this by looking at how the intensity of light from a host star at different wavelengths changes as a planet moves across its face, whereupon some of that light may be absorbed by the planet's atmosphere. Different types of molecule absorb light at characteristic wavelengths, and so if we see that the intensity of starlight diminishes at certain wavelengths during a transit, this indicates the presence of a given chemical.

We have never been better equipped for this search. Not only has the power of JWST to resolve spectra massively boosted our ability to probe the chemistry of worlds beyond our solar system, but we have ever more places to look for these exoplanets, too. There are currently more than 5500 such worlds confirmed, with a range of planetary types far more diverse than in our solar system. Better still, some of the most promising habitable candidates – planets intermediate in size between Earth and Neptune, with a rocky core and global oceans beneath a hydrogen-rich atmosphere, known as Hycean worlds – are also some of the easiest to study.

As for which molecules we want to see, for a long time it was all about water. NASA's astrobiology programme adopted an informal slogan: "Follow the water." We know liquid water is essential for all life on Earth, so the idea was that we should look for worlds with it on their surface. This gave rise to the idea of a "habitable zone" around a star in which planets orbit at the right distance to potentially have water in this form.

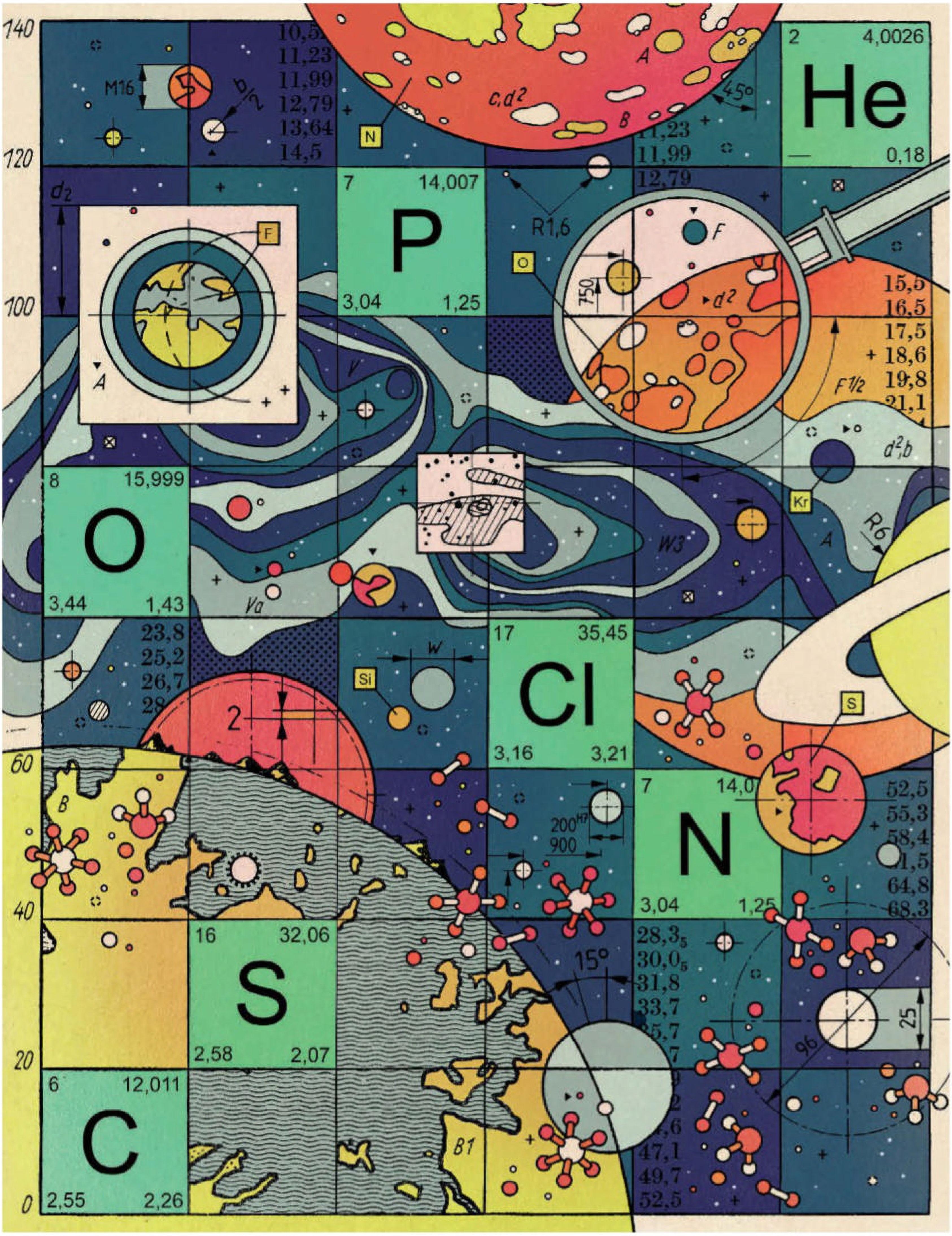
But this only gets you so far. "We assume life requires a liquid, and there's lots of reasons why water might be the best option," says Sarah Hörst, a planetary scientist at Johns Hopkins University in Maryland. "But water is one of the most abundant molecules in the universe." In general, its presence beyond Earth is therefore neither surprising nor automatically suggestive of life.

Seeing it in the atmospheres of small, rocky planets is different, says Seager. Because atmospheric water molecules will be split by ultraviolet light from the parent star, it would only persist in rocky-planet atmospheres if it were continuously replenished by a surface source, such as oceans. So seeking water on exoplanets can narrow the options of where to look more closely – but it doesn't in itself amount to a reliable biosignature.

Familiar gases

Oxygen has also long been considered a potential sign of life. As a very reactive element, it too will only persist in large amounts in an atmosphere if it is continually supplied afresh. On Earth, that happens mostly via photosynthesis in plants and bacteria – because of life, in other words – which explains why oxygen has been a favourite gas for astrobiological searches for decades, says Seager. But that, she adds, also gave rise to a "cottage industry" of people explaining how it might be produced by geological, photochemical or other non-living processes.

And then there is carbon dioxide. It isn't difficult to account for this in non-biological ways. Volcanoes on Earth spew it out aplenty. But the interest in detecting this molecule is ›

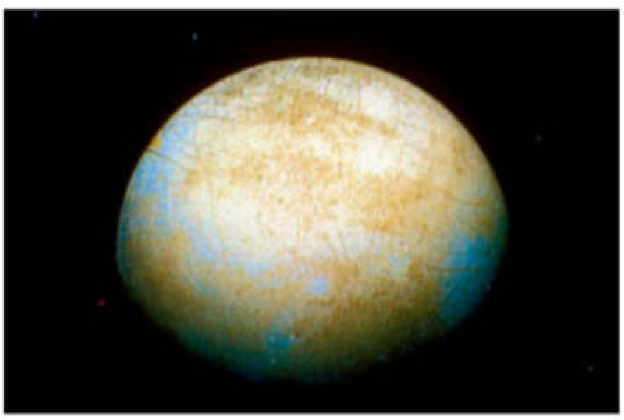


CHRISTIAN GRALINGEN

"Some molecules can't be created by anything but life, as far as we know from Earth"

more about establishing that there is carbon around from which complex organic molecules – and perhaps ultimately living organisms like the carbon-based ones on Earth – might be made. That is why the sighting of CO_2 bubbling out of Europa's sub-ice water ocean is intriguing. This chemical isn't thought to be stable on the Jovian moon's surface, so the source of it must be relatively recent.

A more plausible biosignature might be found in some combination of familiar gases on other worlds. Oxygen and methane, for instance, won't coexist in an atmosphere that is in chemical equilibrium – as they react to produce other substances – but only when some process, like life, is present to keep topping their levels up to maintain what researchers call a non-equilibrium state. "If you saw oxygen and methane together, that was thought to be a very good sign," says Nikku Madhusudhan, an astronomer at the University of Cambridge. The trouble is that every atmosphere is somewhat out of equilibrium, says Hörst, because the parent star is constantly dumping energy into it. You would need to see one that is wildly out of equilibrium, as on Earth, to get excited.



GRANGER – HISTORICAL PICTURE ARCHIVE/ALAMY

We have spotted carbon dioxide on Europa, one of Jupiter's icy moons

If you add more molecules into the mix, however, the case that they were being made by life gets stronger. If we detected oxygen, methane and nitrous oxide on a rocky planet, for example, "it would be hard to argue that it's not due to life", says Madhusudhan. "To make all three in similar proportions as on Earth is very hard [any other way]."

No one has found such a mixture yet. But another, equally telling kind of biosignature might come from gases other than the common ones: molecules that, as far as we know on Earth, can't be created by anything other than life.

One is dimethyl sulphide (DMS), which, on our planet, is released into the air as a by-product of the metabolic reactions of some plankton. Hence the excitement around the recent announcement by Madhusudhan and his colleagues of its detection in the atmosphere of exoplanet K2-18b, some 124 light years away in the constellation Leo.

Seager says that if the detection checks out, it would be an exciting hint of life: "For now, it would be hard to explain DMS in any other way." However, any such excitement would be premature at this point, she adds, because the discovery remains highly tentative. She stresses that the first question to ask about such biosignature detections isn't "is it life?", but "is it real?".

Trying to detect such chemicals is complicated, especially for planets around red-dwarf stars like K2-18. Because they are dimmer than our own sun, drops in brightness due to planets passing in front of them are easier to see – that is why these stars are favoured as places to seek exoplanets. But Seager says red dwarfs also tend to have changeable surface spots like sunspots that complicate the starlight spectrum even before taking the atmospheres of transiting worlds into consideration. What's more, these stars are prone to solar flares that threaten to bake their planets, diminishing the prospects of life.

Searching red dwarf systems for biosignatures, then, is much like the old story of hunting for your lost car keys under a street lamp: we look not where is most likely, but where we are able to look.

It's aliens! Or is it?

It might always be difficult to trumpet the discovery of life on another world based purely on the detection of a telltale molecule or two in its atmosphere (see main story). But the truth is that no one really expects the first detection of extraterrestrial life to be clear-cut. Rather, it will be all about how much confidence we can place in a claim.

With that in mind, in 2021, a team of NASA scientists proposed a framework called the Confidence of Life Detection scale to offer the public – and journalists – an indication of the credibility of each new claim. The idea was inspired by scales such as the one used to indicate the true risk of collision with asteroids that pass near Earth, designed to avoid constant headlines of apocalyptic "near misses".

The NASA team suggests a seven-level scale that starts with "detection of a signal known to result from a biological activity". The next steps include, for example, sources of contamination being ruled out and alternative, non-biological explanations being shown to be implausible. The final level demands independent observations of actual biological behaviour in situ on a planet – something that doesn't seem possible from remote-sensing data, such as atmospheric spectra, alone.

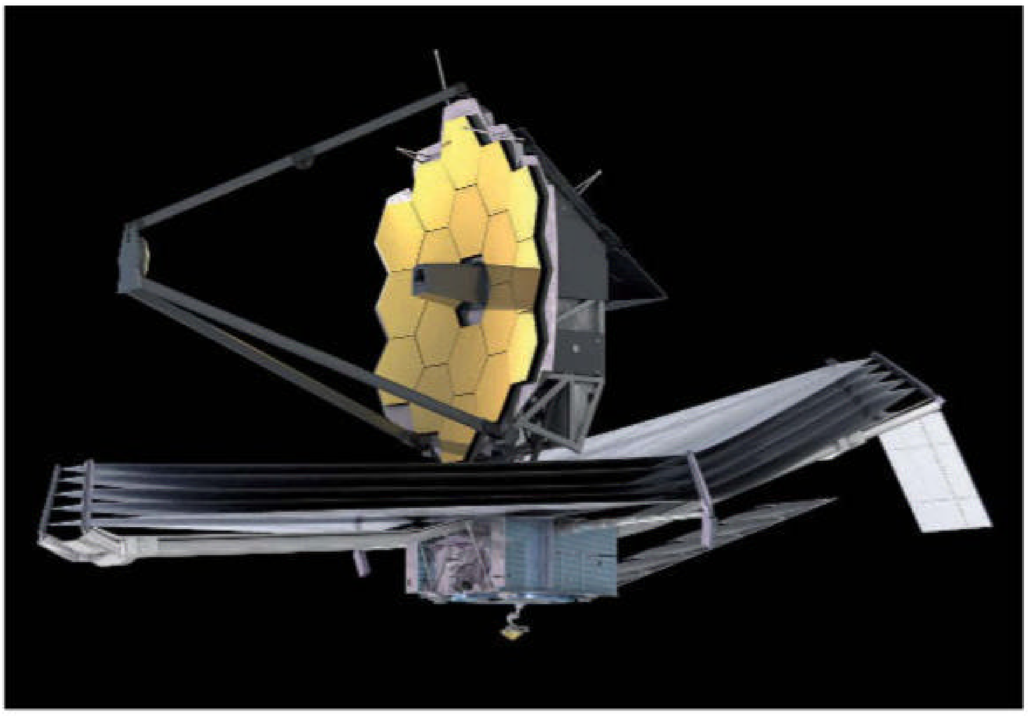
Yet Madhusudhan is confident that something will turn up all the same. "Knowing what I know, I would be very surprised if we don't detect one of these molecules with high confidence in Hycean worlds in the next five years," he says.

Would that mean we have found life? "That is not clear," he says. On other worlds, we can't be confident that even molecules like DMS can't be generated by something other than life (see "It's aliens! Or is it?", left). "Just because it's only made biologically on Earth doesn't mean that's the only way to make it," says Hörst. "It's really hard to do this work without being Earth-centric." The problem is that we just don't – and maybe never will – know enough about the planetary environment on K2-18b to rule out all other possibilities. Are there volcanoes? Is there an ocean? Was there a recent comet impact on the surface? "We just don't have all of the information we need to be able to model the chemistry in exoplanet atmospheres," says Hörst.

Known unknowns

US planetary scientist Carolyn Porco, who led the imaging team for the Cassini mission to Saturn, endorses that note of caution. "For all the compounds that have so far been found elsewhere – from the very simple like oxygen, methane and CO_2 to the more complex, like amino acids [found in some meteorites] – one can only say that those molecules also exist on our living planet." As a result, she says, "exoplanet researchers have an impossible task if they wish to discover life on inaccessible planets, because I think they will never know enough about the chemical environment to be confident of detecting evidence of life via identification of compounds".

Hörst's experience with Saturn's moon Titan illustrates how a lack of contextual information can derail the science. For several decades, planetary scientists were puzzled that Titan had lots of methane, CO_2 and carbon monoxide in its atmosphere in ratios that didn't seem to make any sense. Some suggested that they could be put there by life processes. "The piece of information we were missing was that Enceladus [another moon of Saturn] has these plumes that shoot out water into the Saturnian system," she says, "and some of that ends up in Titan's atmosphere, where it gets converted to carbon monoxide."



ALEXANDR MITIUC/ALAMY

The James Webb Space Telescope transforms our ability to probe alien atmospheres

"The solar system community has been trying to warn the exoplanet community for years that we have a history in the solar system itself of wildly misunderstanding things," says Hörst. "It's only been 60 years since we were writing papers about forests on Venus!"

All of which might seem to suggest that the search for molecular biosignatures in the atmospheres of distant planets is something of a fool's errand – or at least not the best way to find life beyond Earth. "I'm very sceptical that we're going to find definitive proof of life outside the solar system just using remote sensing data [like the spectra of atmospheres]," says Hörst. In that case, short of a robotic spacecraft actually landing on a place like Europa and seeing microorganisms in the salty global oceans underneath the moon's icy crust, evidence for life elsewhere will remain tentative for years to come.

But astrobiologists haven't given up on the idea that there could be definitive atmospheric biosignatures. Some think that we can use artificial intelligence to look for characteristic "life signals" in complex mixtures of molecules. Others, meanwhile, reckon that measuring "molecular complexity" could do the trick, on the grounds that only life processes can produce such complexity above a certain threshold. That idea draws on a broader principle called assembly theory, which Porco think is particularly promising. "The idea needs to be put through its paces, and it's being vetted now in the planetary science community," she says. "It might meet a roadblock up ahead, but right now, if I were a betting woman, I'd bet on assembly theory."

The other possibility for a biosignature that might convince everyone of the existence of aliens would be the detection of a molecule so bizarre that we simply couldn't conceive of it having been made by anything other than a technologically advanced civilisation: a so-called technosignature.

Seager says that molecules containing lots of fluorine are one candidate, like the chlorofluorocarbons (CFCs) that we once released copiously into our atmosphere, until we realised that they destroy the ozone layer. "Life almost never uses fluorine," she says. But we do, and not just in CFCs. "We make nitrogen trifluoride and sulphur hexafluoride. So if we saw nitrogen trifluoride [in an exoplanet atmosphere], I'd be thrilled," says Seager.

Meanwhile, says Hörst, astrobiologists should try to avoid stoking public cynicism with false alarms. "Astronomers risk becoming the boy who cried wolf," she says. "If and when we do detect life elsewhere in the universe, that would be hugely profound. But in my interactions with the public, a lot of people think we've already found life on Mars. That makes me sad."

Yet if the hype can be avoided, the prospects are tantalising. "I think we'll come out of the JWST era with a lot of interesting new planets to study," says Hörst. Whether we will know for sure if we have company in the cosmos is another matter. ■

Philip Ball is a science writer based in London. His latest book is *How Life Works*