# ALIENS INFERRED

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## ABSTRACT

The discovery of extraterrestrial (ET) life would be a revelation of scientific and cultural magnitude that rivals Darwin's theory of evolution and Copernicus's hypothesis that the Earth revolves around the Sun. But while conjecture about the existence of ET life predates industrialism, it is only within the past century or so that technology has developed to the point where humans can add empirical observations to centuries of wondering.

With rapid advancements in biological, chemical, and technological science, discovering ET life could be within reach. However, investigations of other planetary environments are still on the edge of technological capability and researchers may need to rely on indirect signs of life to make a detection. These signs may be difficult to interpret.

This thesis surveys some of the main techniques and technologies that researchers currently use or are developing to search for alien life. It also teases out some limitations and ambiguity inherent in contemporary data interpretation.

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*"We stand on a great threshold in the human history of space exploration," wrote MIT astrophysicist Sara Seager, in testimony delivered to the U.S. House Committee on Science, Space, and Technology on December 4, 2013.*[1] *"If life is prevalent in our neighborhood of the Galaxy, it is within our resources and technological reach to be the first generation in human history to finally cross this threshold, and to learn if there is life of any kind beyond Earth."*

## Looking for a sign

Curiosity, NASA's planetary rover, has traversed the Martian landscape for roughly eight years.[2] Its venture represents one of the highest technological efforts of its time. But now its topnotch innards—pristine and golden in NASA laboratory stock photos[3]—are obscured by a dusty and travel-worn exterior, harkening to some Star Wars universe droid technology. Moving deliberately, turning, sampling, warming up an instrument for analysis, Curiosity follows the transmitted instructions encoded by an operator on Earth, millions of miles away.

When launched in 2011, Curiosity's nominal mission was to analyze the Martian atmosphere, regolith (soil), and rocks in an attempt to determine whether Mars has or has ever had the environmental conditions required to support life. Not long after the rover landed on the Martian surface, it found small eroded stones, like those tumbled smooth in waterways on Earth. This discovery reinforced observations made by the Mariner 9 satellite in 1971 of what appeared to be riverbeds. Then Curiosity discovered organic molecules—those that, assembled correctly, quicken and live.[4]

Melissa Trainer, a researcher at NASA Goddard Space Flight Center, has worked on the Curiosity mission since 2009 and uses Curiosity's instrumentation to learn about the Martian atmosphere. "What we're really searching for right now … is not actually life, at least on other planets," says Trainer. "The current state of the art, so to speak, is actually looking for the chemistry that we think is related to life."

Conjecture about the existence of extraterrestrial (ET) life pre-dates Christ in the Western canon,[5,6,7] and is widely regarded as a subject of scientific and cultural magnitude that rivals Copernicus's suggestion that the Earth revolves around the sun and Darwin's take on the origin of species. However, it is only within the last century or so that technology has developed to the point where humans have been able to add observation to speculation and wonder.

Massive telescopes all over the Earth point to the sky, while satellite observatories speed through space, transmitting data back to Earthbound researchers. Exoplanets, planets outside of Earth's solar system, were theoretical until the early 1990s when planets were found orbiting the pulsar PSR 1257+12,[8] located about 2,300 light-years away.

Since then, more than 4,000 additional planets have been confirmed[9] by exoplanet search missions such as the now-retired Kepler satellite, launched in 2009, and the follow-up Transiting Exoplanet Survey Satellite (TESS), launched in 2018. ET life has even secured its own scientific field, astrobiology, an eclectic discipline that investigates the emergence and presence of life in the universe. Astrobiologists look to the stars but also probe life on Earth for information about what ET life might be like.

The discovery of extremophiles on Earth, creatures that thrive in environments not obviously inviting, such as scalding vents in the dark recesses of the ocean or the sun-blasted Danakil and Atacama deserts, have functionally expanded astrobiologists' sense of what kind of worlds could support alien life. This developing perspective has placed even the planets and moons of Earth's solar system, frozen or searing, irradiated and anoxic, back in the game.

With contemporary advancements in biological, chemical, and technological science, discovering ET life could be within reach. However, traveling to or even observing other planetary environments is still on the edge of technological capability and researchers may need to rely on indirect signs of life to make a detection. These signs may be subtle, difficult to interpret, and inconclusive.

## Something Curious

Curiosity sends landscape images of the surface of Mars.[10] They are oddly familiar. Cliffs. Mountains. Rocks. Broad desert plains. They could almost have been taken on Earth, maybe in the Badlands of South Dakota or the Desert Mountains in Nevada. But their provenance is betrayed by the absence of anything obviously alive. There is not one scorched plant.

With notable exceptions, when modern scientists talk about finding life on Mars, they are talking about finding evidence of past, extinct life. Curiosity was sent to investigate ancient Martian environmental and climate features.[11] The NASA Perseverance rover, which launched in summer 2020, will follow-up on Curiosity's work, looking for evidence of ancient life itself, perhaps microbial fossils or left over chemical signatures.[12]

However, using Curiosity's onboard instruments, Trainer's team discovered something extant and odd: an unexplained seasonal fluctuation in atmospheric oxygen and methane levels. Methane and oxygen are both considered potential biosignatures, a chemical or phenomenological sign of life. On Earth, both methane and oxygen ($O_2$) are produced in abundance by living organisms but can also be generated through non-living processes. Regardless, researchers hypothesize that a seasonal chemical fluctuation detected in an atmosphere could itself be a biosignature,[13] even if the fluctuating gas wasn't oxygen or methane.

For instance, carbon dioxide ($CO_2$), which is easily produced by both living and non-living processes, fluctuates seasonally on Earth because of plant respiration. During summer in the Northern Hemisphere, plants' consumption of $CO_2$ increases as they build biomass and decreases in the winter as plants die or go dormant. Subsequently, $CO_2$ levels in the Northern Hemisphere decrease in the summer and increase in the winter.

Trainer says seasonal fluctuation on Mars could be driven by non-living chemical processes. Seasonal changes in temperature, relative humidity, airborne dust, and ultraviolet (UV) radiation could be altering Martian atmospheric chemistry. "The thing is that, with the measurements we have of those parameters, nothing is tightly correlated," says Trainer.

Could it be life? Hardy alien microbes persisting in the regolith, rocks, or deeper underground?

“That's what makes it kind of intriguing. It's a question we always have when we find something unusual,” says Trainer. “But as responsible scientists … that is the explanation of last resort. I would want to go through every single possible other explanation.”

“It's very clear there's a lot more going on Mars than we currently can understand.”

### Finding exoplanets

TESS, NASA’s Transiting Exoplanets Survey Telescope, does not function like a backyard telescope through which an observer can look at the night sky during a certain part of the year and see Mars, with its red tinted light. TESS doesn’t “see” exoplanets directly.

An entire star system may show up in imaging as a single pixel of light. To detect orbiting planets, TESS keeps patient watch for that pixel to dim slightly and then brighten up again. The first time, this could mean any number of things, a cloud of space dust perhaps, but, with time, maybe after a couple of weeks, the pixel dims again. A couple of weeks later, right on time, it dims again.

There’s a planet orbiting the star. When the planet passes between the star and the telescope observer—a movement called a transit—it blocks an amount of the star’s light, which then shines again unencumbered as the planet continues on its way.[14] With each cyclical waver, this tiny pixel of light transmits more information.

The amount of time that the light is dimmed, the distance and brightness of the star, and other follow-up observations can be used to calculate the size and mass of the exoplanet. Once the size and mass have been calculated, astronomers can determine what sort of planet it is likely to be, dense and rocky like Earth, or gaseous like Jupiter. From the orbital distance, the exoplanet’s distance from the star, astronomers can calculate likely temperature ranges. They can use this information to help them deduce whether liquid water could be stable there, a hallmark of habitability.[15]

Finding exoplanets, for all its techno-glory, is not the same as finding aliens. These exoplanet-star systems twinkle from a position impossibly far away, places that neither humans nor robots are likely to travel with any current technology. To learn if any of these worlds have life, astrobiologists need to look for biosignatures from a distance.

### Analyzing atmospheres

In the late 1990s and early 2000s, Sara Seager, now the Deputy Science Director for TESS at the Massachusetts Institute of Technology (MIT), figured out how to use spectroscopy, a method for analyzing the properties of light, to study exoplanet atmospheres.

“When I was in grad school, [researching exoplanets] was very risky because a lot of people didn't believe they were planets,” recalls Seager, reflecting on the late ‘90s, when she was at

Harvard. “Other people who believed they were planets didn't think we'd ever be able to do more than find them. Not study their atmospheres by any means. But I did it because it was a brand-new field and people were too scared to work on it.”

Starlight looks to the human eye as if it is just one thing: shiny, bright, whitish light. But light is actually composed of different wavelengths, and different stars produce distinct wavelength patterns depending on their physical properties. Spectroscopy works by separating out the wavelengths, similar to how a prism separates sunlight into a rainbow.

When an exoplanet passes in front of its star during a transit, the chemical components in the atmosphere absorb certain wavelengths of the light. “[By] looking at the star by itself and then the star when the planet is in front of it, you're actually able to find out what's in the planet’s atmosphere,” says Seager.

Spectroscopy is the foundational method by which scientists study exoplanets today, and by which they hope to detect biosignatures outside of the solar system.[16] But planetary atmospheres are complex and dynamic. They may have different compounds in different concentrations, as well as clouds, hazes, water vapor, and suspended dust particles, all of which can absorb and deflect light in unique ways.

Relatively simple lab experiments, in which spectroscopic readings are taken for light shining through a pure $O_2$ sample, for instance, have yielded a catalog of familiar spectra. But when starlight passes through an unknown and unique atmosphere, the readout on Earth, trillions of miles away, might be an unintelligible mess.

## Making atmospheres

Sarah Hörst, a planetary scientist at Johns Hopkins University, is attempting to shed some light on this issue by researching the spectra derived from diverse atmospheric combinations that she creates in her laboratory.

“We’re trying to … fill in the gaps with some of our understanding about what might be possible in some of these atmospheres,” says Hörst. “We can simulate a pretty big range of atmospheric conditions.”

She combines target atmospheric gases in a cylindrical chamber and then exposes them to faux starlight, a technique that acknowledges the effects that the starlight itself has on atmospheric chemistry. When starlight is absorbed by atmospheric gases, it injects additional energy into atmospheric chemical processes, catalyzing reactions that may not occur without it. This is called photochemistry.

In Earth’s atmosphere, for example, sunlight cleaves $O_2$ molecules which recombine to form $O_3$, the basis of the ozone layer that protects Earth life from deleterious UV wavelengths. The $O_2$ is then replenished by photosynthesis. Oxygen in Earth’s atmosphere exists in disequilibrium. That is, because of the chemical processes that are occurring in the atmosphere, $O_2$ can exist in contemporary concentrations only because it is being actively replenished by life.

If beings from an alien civilization were to get a good spectrum of modern Earth, they might see the relative concentrations of $O_2$, methane, $CO_2$, and other gases. They'd be able to figure out what kinds of wavelengths the Sun produces. But to suggest that Earth is an inhabited planet, they would have to understand how all of the atmospheric compounds react with one another and how they react with sunlight. They would have to verify that, given what they know about Earth, contemporary concentrations of $O_2$ should not be stable unless something was continuously producing it.

Like high concentrations of potentially biogenic gases and seasonal gas fluctuations, atmospheric disequilibrium is, itself, considered to be a potential biosignature on exoplanets.[17] But an atmospheric disequilibrium could also be caused by non-living processes such as photochemical reactions driven by flares and material projections from the host star.[18] Like Trainer and the Curiosity rover team, alien astrobiologists looking at Earth would need to have a better understanding of how the entire planet works to makes sense of a potential biosignature.

But how would an astrobiologist learn how an exoplanet works when all of their data comes from a single pixel of flickering starlight, trillions of miles away?

## Planetary modeling

"The holy grail for us to try to understand what's a biosignature, and what's not, is, we want to know something about … production rates that are creating the gases that we see in the atmosphere," says Giada Arney, a research scientist who works on next-gen satellites at NASA Goddard Space Flight Center. "Unfortunately, that's one of the things you can't directly detect from the planet spectrum. It's one of the things that you have to infer using models."

Theoretically, a sophisticated and highly accurate model of planetary systems could allow an astrobiologist to plug in spectrum information and then get the computer's help in deciding how likely it is that the potential biosignature is actually created by life. In addition to her work on observational technology, Arney works on developing chemical and climate models that simulate exoplanetary environments.

Potential inputs into planetary models can come from a variety of sources. Calculations derived from the exoplanetary transits and other observations give researchers information about the size, mass, density, and temperature of the planet. The mass and density provide information about the exoplanet's gravitational forces. In addition to providing a snapshot of atmospheric gases, the spectrum of the planet, as well as that of its star, is potentially imbued with information about the chemical makeup of the entire star-exoplanet system. A model can also be programmed to apply the principles of chemistry and photochemistry.

But researchers such as Arney cannot just build these sorts of models and run with them; they need to vet them using observations of real planets, a bit of a catch-22. "It's gonna be tricky," says Arney. "We need to have good models that are well-validated."

Earth’s solar system presents opportunities to validate planetary models; each planet and moon offers a different example of the possibilities for atmospheric composition, photochemistry, and their interactions with geological processes such as volcanism. And since the planets and moons are relatively near-by and available for spectroscopy, satellite and rover missions, and in some cases, human-operated craft, they provide a means for researchers to check the models that they are building against real, presumably uninhabited, planets.

## Distinguishing life

“Everywhere we go on Earth, every rock, every natural sample we pick up … it’s all basically over-printed with life,” says Trainer, “When you learn how a planet works by living on a planet full of life, and then you go to a planet that doesn't necessarily have life, all your understanding of that cycling and the chemistry … is going to be biased somewhat by what we've learned on Earth.”

In addition to her work on Mars with Curiosity, Trainer is deputy to the lead scientist on the Dragonfly mission to Saturn’s largest moon, Titan, set to launch in 2026. Dragonfly, which is a planetary rover like Curiosity, except that it also flies, will be used to explore Titan’s surface.[19] Observed from space, the surface of Titan is familiar: there are rivers and oceans. Clouds form.[20] There are storms.[21] But the entire moon is far colder than anywhere on Earth: minus 290° F. Planetary scientists believe that the liquid on Titan is not frozen solid because it is composed of methane and ethane, whose freezing points are far lower than that of water.

Titan is an interesting subject for comparative planetology because the organics-rich haze that envelopes the planet could be similar to one thought to have enveloped the early Earth before the rise of oxygenic photosynthesis. Researchers believe that formation of the ancient Earth haze may have been dependent on methane producing microbes, but Titan’s haze is believed to be driven by abiotic photochemical processes in the atmosphere. Comparing what is understood about early Earth’s haze to Titan’s haze may yield better information about correctly identifying biosignatures on a methane rich exoplanet. [22,23]

“[There’s] this chemistry that happens in the atmosphere that we can't study on Earth, because on Earth, the biology dominates so much of it, but on Titan, we can observe what happens when you have a planet that is basically a giant organic reactor,” says Trainer, “No matter what we find … it's going to be mind-blowing, and [will] totally rewrite our understanding of how stuff works.”

## Hot Jupiters

At this point, much of this atmospheric modeling and lab work is largely preparatory. Researchers currently lack the observational technology to search for life signs on most of the thousands of exoplanets that have been discovered. They’ve gotten a look at only a handful of exoplanet atmospheres—most of them belonging to “hot Jupiters,” giant gas planets orbiting close to their star.

While unlikely to be inhabited by any familiar life form—they are too hot and have no rocky surface—hot Jupiters are interesting to planetary scientists and astrobiologists alike because their massive hot atmospheres produce a more blatant spectral signal than smaller, cooler, rocky worlds, making them much easier to observe with present day technology.

"These observations of hot Jupiter-type atmospheres are surely paving the way … to the study of habitable planets," says Yuka Fujii, an astrobiologist at the Tokyo Institute of Technology who recently led a comprehensive scientific review[24] that examined the prospects of current and potential future imaging technology for investigating exoplanets. She says that the process of studying hot Jupiters allows astrobiologists to develop instruments and methodologies on these "easier" targets. Then they can take what they've learned and apply it to more realistically habitable planets.

Researchers will have the chance to apply hot Jupiter lessons soon, when the James Webb Space Telescope (JWST), NASA's "top science priority," launches in 2021.[25] The largest telescope ever launched from Earth,[26] JWST is set to propel the discipline forward, shifting the focus to cool, rocky planets, in the habitable zone of their star.

## The launch of the James Webb Space Telescope

A rocket, roughly 50-meters tall, will propel JWST into space. Within thirty minutes, the craft will clear the Earth's atmosphere and, by the beginning of the second day, will have passed the orbits of both the Hubble space telescope and the Moon.

A few days into its journey, Webb will begin to transform. The sunshield platforms will fold out from the body of the satellite, and then the instrumentation compartment and mirrors will assume a new position farther away from the sunshield and propulsion systems.

A stack of sun shield membranes will inch out of their compartment like slow hauled sails. Stretched silver and taut, the membranes are as thin as a human hair—but will reach the size of a tennis court. Their purpose is to protect the working parts of JWST from the Sun. The sunny side of the telescope will regularly reach temperatures of 190º F, approaching the boiling point of water. But the working instruments shielded by the thin veil, will operate at 385º F below zero, a temperature that could liquify air.

As the days pass, more components will fold out of JWST and lock into place, including eighteen metallic hexagons that will connect to create the telescope's 6.5-meter collecting surface. In its final form, JWST will look a lot like a giant, golden cable satellite dish traveling through space protected by an even larger silvery veil.

Roughly thirty days after its launch, a fully transformed and operational JWST will assume an irregular orbital pattern that exploits the gravitational forces of the Earth, Moon, and Sun. The orbital pattern and sun shield allow JWST to always be pointing out into space, avoiding the glare of the Sun, Earth, and Moon.[27]

JWST is a groundbreaking mission that will address many different astronomical goals, not just the search for ET life. For instance, it will allow researchers to look far enough into space to observe the origins of the very earliest stars after the Big Bang. JWST will operate in the near infrared spectrum, which will allow researchers to see inside previously opaque dusty "star nurseries" to observe forming stars and planets.[28,29] In short, many astronomers are going to want scope time and everyone has to share, including astrobiologists.

## The limits of the James Webb Space Telescope

Megan Mansfield enrolled as an undergraduate at MIT in 2012, planning to major in physics or chemistry, but in her first year, she attended an event that included a live broadcast of an asteroid that was being tracked by an observatory in Hawaii. The asteroid showed up as a white dot in the center of a window that was open on a computer screen.

"It doesn't sound that exciting," says Mansfield, "He was on a computer and talking to a guy in Hawaii who was looking at this asteroid. But it was so cool. I was like, 'I definitely want to be an observer someday. This is what I want to do'."

Mansfield is now a planetary sciences Ph.D. candidate at the University of Chicago. She has used both the Hubble and the now-retired Spitzer Space telescopes to study hot Jupiters, and has also published theoretical work in anticipation of JWST coming online.

"James Webb will … give us a chance to start learning what the atmospheres of potentially habitable planets are like. We haven't really been able to do that yet, just because those planets are so small," says Mansfield. According to Mansfield, JWST may not be able to detect biosignatures on exoplanets "except in a few lucky cases," but will be used "to look for things that would be, we think, prerequisites for life." For instance, JWST might be able to spot water in a planet's atmosphere.

A gas like $O_2$ would be more of a challenge for JWST to detect than water vapor, even on the same planet. It would not be impossible for JWST to spot $O_2$, but it would likely take more observation time of a single planetary target than will realistically be available. However, at this point, identifying a suite of cool rocky planets with atmospheres and water vapor would be a huge step forward. And particularly promising exoplanets could potentially win additional scope time or be followed up on by future missions.

## Red dwarf systems

JWST's best exoplanetary targets will likely be planets that orbit small, dim red dwarf stars, the most abundant type of star in the Milky Way galaxy.[30] Yellow star systems, like our own, will be too bright to easily evaluate. However, it is not known whether a red dwarf star system could support life. Red dwarf stars produce ionizing radiation for longer as they are forming than yellow stars do, so there is some concern that the atmospheres of habitable zone planets could have been fried long before life could develop there.[31]

But scientists don't know. Exoplanet science has a history of challenging prevailing narratives about star-system physics and development. Before the first exoplanets were discovered, astronomers thought that they had a pretty good understanding of how star systems work. The thought was that gas giants, like hot Jupiters, formed far away from their star, and rocky planets formed closer in. But one of the first exoplanets discovered was a hot Jupiter orbiting very close to its star.

“That totally threw a wrench in our idea of how planets form,” says Mansfield, “and so there's just a ton of stuff we still don't know about these systems.”

Thus, a red dwarf’s evolution could be misunderstood, or its radiation might not be deleterious enough to obliterate the atmospheres of its accompanying planets. Analysis of the Trappist-1 system, a red dwarf system roughly 40 light-years from Earth, which hosts seven Earth-size rocky planets in its orbit,[32] may provide researchers with an excellent opportunity to address this question.

Three of the Trappist-1 planets are considered to be in the habitable zone, where liquid water would be stable. Three planets are closer to the star, where they would likely be too hot to maintain liquid water. And one is out beyond the habitable zone where water may freeze. This configuration creates a functional controlled experiment that will allow researchers to compare the effects of the same red dwarf star on atmospheres of planets at different distances.

They may find, for instance, that all of the Trappist-1 planets were able to hold on to their atmosphere, which would bode well for the search for life around red dwarf planets. Or they could find that only the atmospheres of the most distant worlds survived. Whatever researchers learn can inform their approach to investigating atmospheres in the next system that they analyze. Since JWST time will be limited, figuring out where planets with surviving atmospheres are most likely to be located will create a strategic advantage for astrobiologists.

Whatever researchers may find orbiting red dwarf stars, JWST is unlikely to be able to analyze the atmosphere of a small, rocky planet like Earth orbiting a bright Sun-like star.

## The Earth twin

With only one example of a confirmed inhabited planet in the universe, it makes sense to look for another planet like Earth. But in all the decades of searching, nothing like Earth, a small, rocky, temperate, watery world, with an atmosphere filled with gases beloved by familiar life forms, has yet been discovered, much less investigated.

The transit technique is biased toward finding planets that are both much closer to their star and transit more frequently, making them easier to notice. Also, cool, small rocky plants get outshined by yellow stars; they don’t produce or reflect much of their own light. And, at this point, even if candidates were discovered, there is not technology available to analyze them.

## Innovation

But astrobiologists are planning their next move, and Seager is playing the long game. “My goal is finding the Earth twin or [to] make sure it happens,” says Seager. “Let's say I don't live long enough or … funding doesn't come through, then I train my protégés so we will make it happen.”

There are two major technological advances that are probably necessary to find and study an Earth twin, both of which facilitate direct imaging—actually being able to get eyes on a planet, as opposed to inferring that it is there through flickering starlight. One advance is refining ways to block most of a star's light so that smaller, dimmer orbiting planets can be resolved.

One method of doing this is by using a coronagraph, which is a technology already in place in certain ground-based telescopes. A coronagraph is an instrument embedded inside a telescope that occludes the starlight.[33] Images of star systems captured using this technology look like a dark circle surrounded by a faint starburst, and then, subtle and dim orbiting planets.

Seager advocates for the implementation of an additional starlight blocking technology called Starshade. Starshade is a massive sunflower shaped veil that would travel into space attached to an observational satellite, but then be released to operate separately under its own power. Attached to the satellite, Starshade would remain cylindrically tucked and furled, unrecognizable.

But upon the initiation of its release sequence, like some sci-fi springtime, petals would emerge from the cylinder. Oriented first perpendicular to the mid-plane—then rotating as Starshade completes its unfurling—the petals turn and lock into a parallel orientation around an expanding midsection, embodying its decidedly floral aesthetic and finalizing its transformation.[34]

Once transformed, Starshade would fly thousands of miles away from its parent satellite and maneuver into the correct and precise orientation to block the starlight, allowing the orbiting planets to come into view.[35,36] Any large shape thus positioned would drown out much of the star's light, but not to the degree required. Starshade's petals control the diffraction of the light around the shade, making it much more effective than, for instance, a giant occlusive circle.

When NASA put out the call for applicants to develop Starshade, an idea originally dreamed up in the 1960s, Seager applied, hoping to participate as the resident exoplanet atmospheres expert. NASA responded to her application by asking her to be a lead scientist on the team, which proceeded to develop Starshade from a fun idea to highly plausible near-term technology. "We could build it anytime, if you gave us a blank check," says Seager. "We could get it done in about six or seven years."

The second advance necessary to locate and analyze an Earth twin is that space-faring satellites need to get bigger. "Collecting area is really what we need," says Seager. "Photons are our currency … just collecting light."

NASA has several big satellite telescopes in the feasibility and design phase. Arney worked on developing the Large Ultraviolet Optical Infrared Surveyor (LUVOIR), which would possess the largest collecting area of any other potential NASA satellite. Two different versions were designed, and the largest would be more than twice the size of JWST.[37]

With that kind of collecting area, and by operating in the ultraviolet, visible, and infrared wavelengths, LUVOIR would likely be able to locate Earth twin-type planets. It would also possess the ability to detect the most telling biosignature gases.

Both LUVOIR and Starshade are promising innovations but, at this point, exist as hypothetical, future projects that are contingent on funding. Soon JWST will extend the human gaze farther than ever before, but it still won't be able to get eyes on the gold-standard Earth twin, and maybe not even see the most straightforward potential biosignature, $O_2$, on any planet at all. Astrobiologists will have to wait, as the state of the art slowly advances, piecewise, over decades and generations of scientists.

## The long game

Barring a clear signal from a technologically capable society, Earth's first alien encounter, especially outside the bounds of our solar system, is unlikely to be conclusive, "We won't know for sure. We'll find signs of life and it'll be very invigorating and it'll help keep the search going," says Seager. "But we can't know for sure."

The first hint of ET life could be a promising spectrum. Researchers could pass it around, investigate it with the most advanced models of the time, follow up with more observations, debate about it at research conferences, and everyone might even finally agree that there's not a great non-living chemical explanation for the readings. But that would not prove it was life.

"So it could be [we] found oxygen … is that made by life or is it some weird atmosphere in our catalogue of weird atmospheres?" says Seager.

She draws a comparison between the contemporary search for extraterrestrial life and the Copernican Revolution and points out that, despite the latter's expeditious namesake, it didn't happen overnight. Copernicus theorized that Earth revolved around the Sun, but there were astronomical models in place at the time that could accurately predict the positions of the stars and planets in the night sky if the Earth was the center of the universe.

What Copernicus had, really, was a hypothesis. But then Galileo used the freshly invented telescope to observe the crescent phases of Venus, the configuration of which suggested that an orbit around Earth was impossible. And then Newton developed his law of gravity, which Edmond Halley used to predict that a particular comet would round the Sun once again in seventy-five years. The comet arrived on schedule. But by then, more than 200 years had passed since Copernicus had introduced humanity to a Sun-centered planetary system narrative.[38]

We may be somewhere in the middle of the Alien Revolution, at a time when the theory is sound, the tools are coming online, but the universe is still quiet. "That's how I see it happening. It's not going to be this 'Eureka' moment," says Seager. "It might be something very subtle that takes years, decades, or centuries for us to believe in."

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