# The next search for Earth-like worlds

The Kepler spacecraft has found thousands of likely extrasolar planets. The next step is to characterize those worlds to learn if any of them harbor life. **by Liz Kruesi**

Using the Kepler space telescope, scientists have found about 100 possible planets orbiting in their stars' habitable zones, regions where liquid water could survive on planetary surfaces. Kepler-62f, illustrated here, is one such world. The next steps in exoplanet searches will bring scientists closer to finding worlds that host life. NASA/AMES/JPL-CALTECH (PLANET); NASA/KEPLER MISSION (KEPLER)

Just over 20 years ago, astronomers first detected signs of planets outside our solar system. Initially, they expected to find solar systems like ours, but they quickly realized that isn't how nature works. In fact, one of the first exoplanets discovered is about Jupiter's mass but circles its Sun-like star closer in than Mercury's orbit. Surveys over the past two decades have dug up similarly odd-looking planetary systems. But that doesn't mean scientists haven't found some similarities. They've discovered, for example, a world with a density nearly identical to Earth's and also confirmed nearly 200 planetary systems that hold multiple worlds.

NASA's Kepler spacecraft has participated greatly in the discoveries. After its launch in 2009, this observatory dug up thousands of likely worlds and showed that planets are common, before its mission ended recently due to equipment failure. Scientists think that out of Kepler's candidate planets, some 100 orbit in their stars' habitable zones. Within this distance range from the star, a planet would receive the right amount of stellar energy for liquid water to survive on the planetary surface. A recent study using data from the spacecraft found that one in five Sun-like stars likely has an Earth-sized world in its habitable zone.

While Kepler and its planet-hunting siblings have provided a wealth of tantalizing clues to potentially habitable worlds, there's still a lot to discover before astronomers can say they've found an Earth twin, the holy grail of exoplanet research. And, of course, they need to detect life's signature. What will it take to find it?

## Tally thousands of worlds

Astronomers hunt planets by studying stars and looking for slight changes in their light that can signal one or more orbiting worlds. That's how they've found nearly all of the more than 1,070 confirmed exoplanets so far. In one detection method, for example, scientists analyze how light from a star shifts slightly due to an orbiting planet's gravitational force. As such a world moves away from Earth, its star's motion and speed are affected to keep the system balanced, shifting the star's detected radiation toward slightly bluer colors. As the planet begins to move toward Earth, it exerts force on its sun in the opposite direction, resulting in the star's radiation appearing redder.

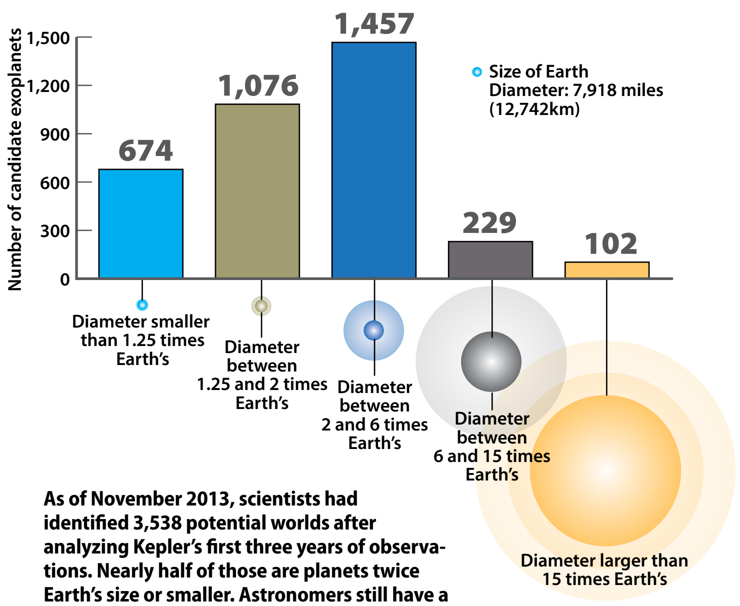
Using this "radial velocity" detection method, scientists can measure those color changes and determine the mass and orbit of the planet that's pulling on its star. So far, astronomers have detected more than 540 worlds using this technique. The discovered planets tend to be massive and near their host stars — the type of worlds that contribute the greatest amount of gravitational pull. For the first decade of exoplanet discoveries, the radial velocity technique bagged nearly all the worlds.

But that changed in the mid-2000s when scientists began employing the transit method more often. If a telescope sees a slight decrease in the amount of light from a star, it could result from a planet passing in front of, or transiting, that star from the telescope's point of view. The amount of light that the world blocks depends on its diameter (a bigger planet obscures more light than a smaller one that orbits at the same distance from its star).

**Liz Kruesi** *is an associate editor of* Astronomy. *The search for exoplanets has fascinated her since high school, when the first worlds outside the solar system were just being discovered.*


**The Transiting Exoplanet Survey Satellite, scheduled for a fall 2017 launch, will look for planets orbiting stars within a few hundred light-years of Earth.**

## Planet demographics




**As of November 2013, scientists had identified 3,538 potential worlds after analyzing Kepler's first three years of observations. Nearly half of those are planets twice Earth's size or smaller. Astronomers still have a lot of data to analyze; they expect to uncover many more worlds.** *ASTRONOMY*: ROEN KELLY, AFTER NASA

In 2006, the French National Space Agency launched the first space observatory to hunt exoplanets this way — the Convection Rotation and planetary Transits (CoRoT) mission. CoRoT observed several thousand stars in each of four different fields and found some 30 planets (plus another hundred candidates).

In 2009, NASA launched Kepler — CoRoT's "big brother." This telescope was capable of providing astronomers with the statistics of how many Earth-sized planets orbit Sun-like stars. For nearly four years, Kepler stared at more than 150,000 suns in the same patch of sky, looking for tiny changes in brightness. As of late January, astronomers have identified more than 3,500 candidate worlds and confirmed 242 in just about half of the Kepler data. The craft's observations showed both scientists and the public that worlds around other stars are common and which sizes of planets are more widespread.

The Kepler team was forced to end the mission in the summer of 2013 after two of the craft's four stabilizing wheels went kaput. With just two wheels left, the observatory could not remain fixed on the same patch of sky. Scientists are a crafty bunch, however, and in December 2013, they announced a possible way to rejuvenate the project (see "Kepler's second chance" on p. 48).

Even if the mission doesn't resume, researchers will find more worlds in the telescope's unanalyzed data. The Kepler team "believes there are hundreds of small planets, many of them in or near the habitable zones of their stars, that have not yet been found in the data," says Principal Investigator Bill Borucki of NASA's Ames Research Center in Moffett Field, California. That will hopefully keep scientists busy until the next large-scale exoplanet searches begin.

### Look for the neighbors

No other spacecraft can currently find worlds at the pace set by Kepler. But astronomers have two space observatories scheduled for 2017 launches to push forward the search — one from the European Space Agency (ESA) and the other from NASA.

ESA's CHaracterizing ExOPlanet Satellite (CHEOPS) is a small-scale transit mission. CHEOPS will observe 50 stars, one at a time, that scientists know host super-Earth-sized to Neptune-sized planets (those between 1.25 and six times Earth's diameter) and look for other worlds. Astronomers also will scour the stars' light to tease out the masses of those other planets. By combining the known mass information with the newly observed diameter data obtained from the transit observations, researchers will be able to calculate the density of those worlds and thus theorize what they're composed of.

NASA's Transiting Exoplanet Survey Satellite (TESS) will operate similarly to Kepler and will look for minute brightness changes in a star's light. However, whereas Kepler focused on a small section of the sky — about 100 square degrees — for years, TESS will "basically paint the sky in stripes that go from the ecliptic up to the poles," says Principal Investigator George Ricker of the Massachusetts Institute of Technology (MIT). "We dwell on each stripe for about a month, and then we step to the adjacent stripe." Over its two-year primary mission, TESS will monitor nearly the entire sky — about 40,000 square degrees.

> **To search for life, astronomers look for gases that "don't belong" according to chemistry and physics models.**

More specifically, the satellite will study the 500,000 brightest and nearest stars, those within a few hundred light-years, in hopes of finding all candidate worlds in our Sun's neighborhood. "We want planets that are close to Earth," says Sara Seager of MIT, "because the closer planet-star systems are, the brighter they are. And the brighter they are, the more photons we can get. And the more photons we can get, the more information we can get." Researchers can then use that data to learn about a world's traits, like atmosphere and weather.

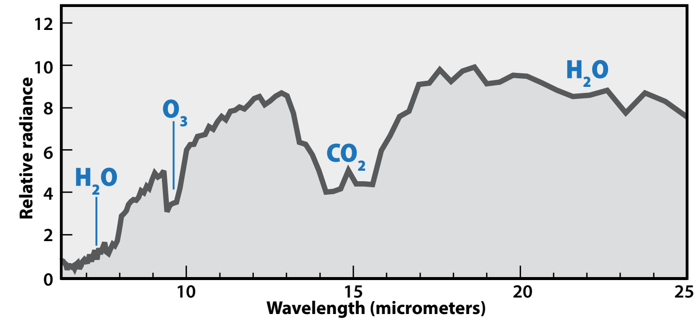
Scientists want to find worlds that orbit their stars within the habitable zone. In our solar system, Earth sits within this orbit, while Venus doesn't. (Mars actually does too, which is a major reason why scientists continue to study it with hopes of finding signs of past life. They have confirmed that the Red Planet once had flowing water.)

A smaller and cooler star's habitable zone, like that of a red dwarf, lies much closer to that sun than that of a hotter star's. Planets nearer to their stars move faster and orbit in less time than those that lie farther away. For example, in our solar system, Mercury moves at about 107,000 mph (172,000 km/h) and completes a full rotation around the Sun in 88 days; Saturn travels with an average speed of roughly 22,000 mph (35,400 km/h) and takes 29.5 years to orbit the Sun. Scientists need to detect at least three dips in light to categorize the signal as something orbiting a star, so if they want to detect possible life-hosting worlds in less time, they study cooler stars. TESS' "sweet spot," says Seager, is big Earths orbiting small stars.

This type of star is also the most common in the galaxy. (In fact, scientists have found 248 red dwarfs within 32 light-years of our solar system, compared to just 20 like our Sun and 10 even hotter and larger stars.) Astronomers expect TESS to find hundreds of Earth analogs and super-Earths — worlds between one and about 10 times the mass of our planet. But this mission will tell them little about those worlds themselves.

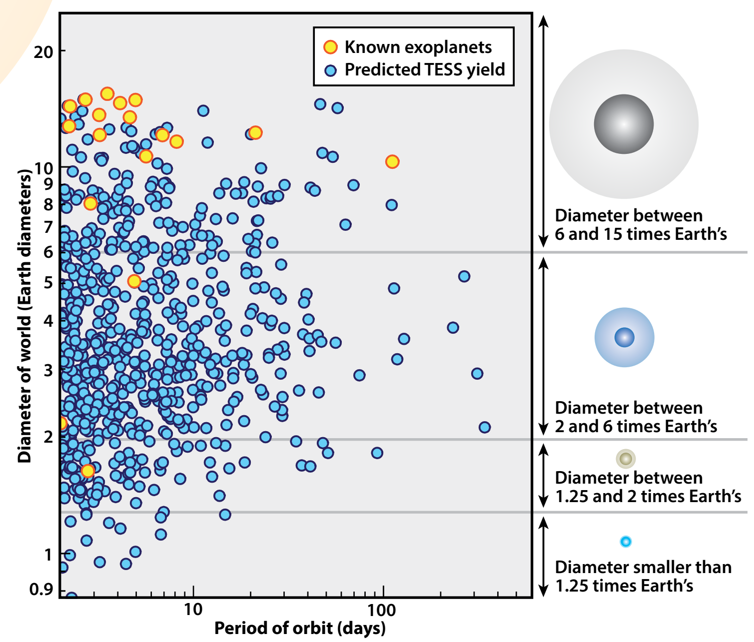
Using TESS data, scientists will identify the best objects to analyze further with additional projects that could uncover the planets' makeups. Those future projects include NASA's next big space observatory — the James Webb Space Telescope, scheduled to launch in 2018.

## Earth's biosignatures

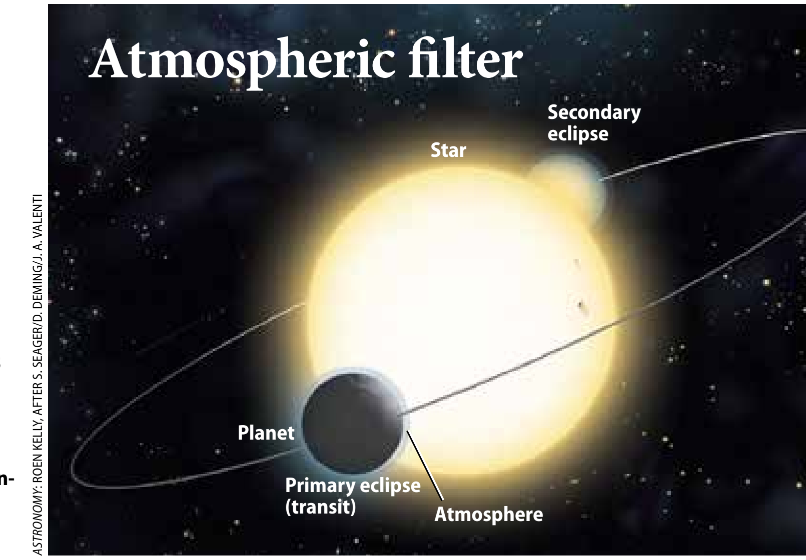



**When the Mars Global Surveyor traveled to the Red Planet, one of its instruments observed Earth. This spectrometer captured data of specific energy ranges that our planet's atmosphere absorbed from the Sun, which tells scientists the composition of Earth's atmosphere — like water, ozone, and carbon dioxide. Astronomers plan to analyze atmospheres of exoplanets the same way with the James Webb Space Telescope.** *ASTRONOMY*: ROEN KELLY, AFTER SARA SEAGER

## In the neighborhood




**Astronomers estimate that the Transiting Exoplanet Survey Satellite (TESS) will find some 300 super-Earth-sized and Earth-sized worlds. The telescope will focus on stars that are nearby and cooler than the Sun, which have habitable zones closer in than our star does.** *ASTRONOMY*: ROEN KELLY, AFTER GEORGE RICKER




**When a planet crosses in front of its star (in a transit or primary eclipse), scientists can measure the size of the world and see how its atmosphere affects its sun's radiation. When the planet passes behind its star (in a secondary eclipse), researchers can learn what portion of the detected light from the transit is actually from the star and how much is from the world.**

### Sniff the air

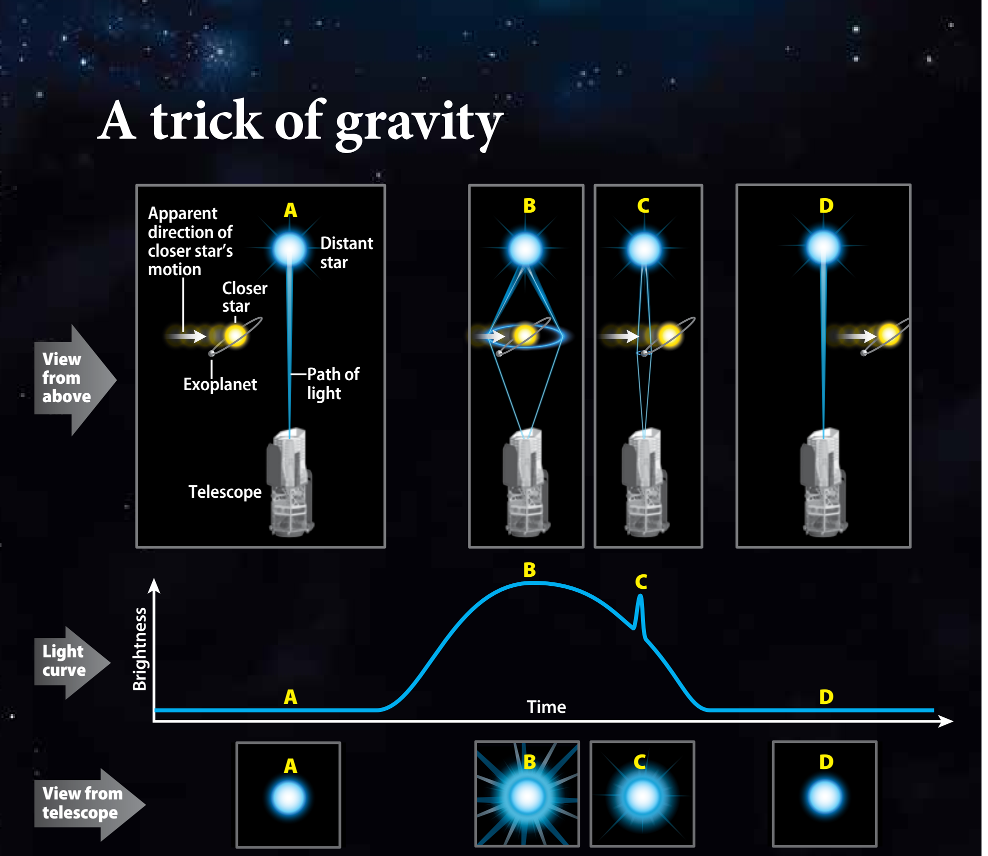
While the solid body of a planet that crosses in front of its star blocks light, its surrounding atmosphere — if it has one — alters that light. When the planet passes behind the star (an event called a secondary eclipse), the overall amount of light detected from the system will drop. Using that change, scientists can figure out how much radiation comes from the star alone and how much comes from the planet. Then they can study the world's spectrum, which tells them what materials make up its atmosphere.

Different materials in the atmosphere absorb radiation at certain wavelengths, so the spectrum will show these wavelengths as "missing." Scientists know what colors correspond to different gases from laboratory experiments on Earth. Ozone ($O_3$), for example, absorbs light at 9.6 micrometers; carbon dioxide ($CO_2$) absorbs radiation at 15 micrometers.

To search for life, astronomers look for gases that "don't belong" according to chemistry and physics models. Oxygen, for example, doesn't live long, so if there are large amounts of it, something must be replenishing it — like life. But it's not just oxygen or ozone that scientists look for. "On Earth, there's untold number of gases produced by life, probably thousands," says Seager. "The reality is we're just going to have to keep an open mind and look for gases that simply don't belong by many orders of magnitude."

"TESS will find good candidates for sniffing the atmospheres of lower-mass planets around lower-mass stars," says Scott Gaudi of Ohio State University in Columbus. Astronomers will then study those suns with the Webb telescope. "That's our next big tool to characterizing and learning about the personalities of these planets."

Each transit lasts a few dozen minutes to a couple hours, and Webb will need to detect at least 10 of them — and likely a few times that many. Seager compares the length of observing needed for one exoplanet to the Hubble Deep Field, a focused 1-million-second-long image. Because Webb is a large-scale mission that will be used for a



In gravitational lensing, a nearby star's gravity acts as a lens that warps and brightens the light from a background star. If the nearby star also has an orbiting planet that crosses in the line of sight, it too will increase the brightness of the background star. Astronomers have discovered a handful of stars using this technique, but they expect to find many more. *ASTRONOMY*: ROEN KELLY, AFTER LAS CUMBRES OBSERVATORY; NASA (WFIRST)

## KEPLER'S SECOND CHANCE

After the Kepler spacecraft's second stabilizing wheel died in May 2013, astronomers thought the planet-hunting mission was over. (The first wheel stopped working in July 2012.) The probe needed at least three of its four gyroscope wheels to stabilize it in three dimensions and detect the tiny 30-parts-per-million (ppm) brightness fluctuations that result from small transiting worlds. Its telescope was still operable, though, so scientists and engineers figured out a way to continue using the hardware.

If they position Kepler so that it lies parallel to its orbit around the Sun and has our star at its back, the Sun's radiation pressure can maintain balance in one plane. Then, the two remaining working wheels can ensure that the spacecraft points in a particular direction. Scientists will reposition the craft before sunlight enters the telescope — this will range from 40 to 85 days depending on the field of view.

Scientists have dubbed this new proposed mission "K2." It won't monitor the same stars that Kepler did, but it will be able to see different fields and thus provide information about planet demographics in other regions. K2 could detect signals only as small as about 300 ppm, so it would be less sensitive.

The mission team hopes to demonstrate how the reworked stabilization performs over about 80 days in March through May. — *L. K.*

variety of astrophysics topics, scientists will need to limit Webb's time spent on exoplanet research and pick just a few dozen worlds.

The Exoplanet Characterization Observatory (EChO) is a candidate ESA mission that also will study exoworld atmospheres. It's a much smaller-scale satellite than Webb — about 1 meter wide compared to 6.5 meters — but EChO would be devoted to researching the chemical composition, weather, and structure of atmospheres of about 100 exoplanets. If approved, the spacecraft would launch in 2024.

Atmospheric studies from both Webb and EChO would tell scientists about the planets' surface temperatures, cloud cover, and general weather patterns. And, of course, they would search for the signatures of life.

## The importance of chance

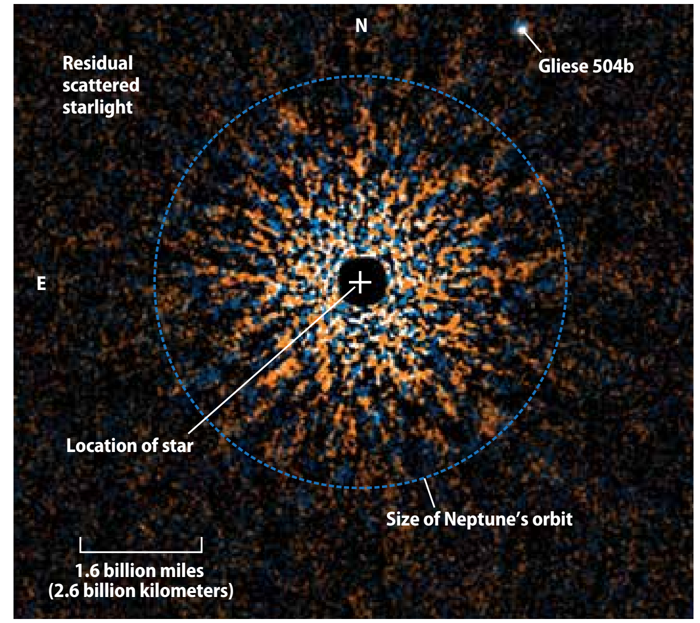
Transit and radial velocity searches, while the two most common exoplanet-hunting techniques, are certainly not the only ones. Another method, called microlensing, uses a trick of gravity. Any body with mass bends spacetime, and the light from a background object will follow that warping. If a star crosses along the line of sight between Earth and a distant sun, the "gravity of the foreground star bends the light of the background star and focuses it," says Gaudi. "The background star gets first brighter and then fainter as the alignment gets better and then worse as the star moves along its merry way." On average, it takes about 100,000 years of staring at a single star to see this happen once.

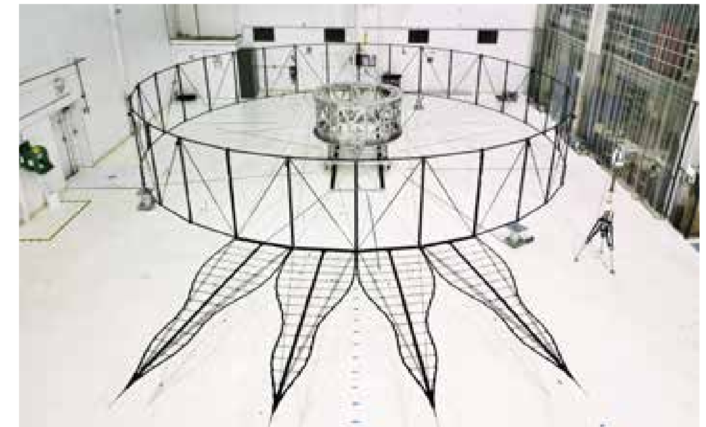
If that foreground star happens to have a planet, it could also cross the line of sight and create a similar magnification effect, but on a smaller scale. "Microlensing is a powerful technique because you can get very large signals for very small planets," says Gaudi. "You can get like tens-of-percent signals from Mars-mass planets. In principle, you can find planets down to the mass a few times that of Moon." He compares the reasoning behind the intense brightening to an effect seen in a glass of water on a sunny day: "Occasionally, you get these super-bright spots where the sunlight is being focused by this water. That water is taking the light from the Sun that's coming from many different directions and focusing it all into one direction."

**Scientists won't just find the planets; they also would be able to study the light spectrum of an imaged world directly.**

Astronomers have used microlensing to find evidence of a few worlds unattached to any star, and they hope to use sky surveys to monitor larger swaths of sky — and thus millions of stars — looking for more planets with this method. The proposed Wide Field Infrared Space Telescope (WFIRST) is one such project. If NASA approves it, WFIRST will monitor hundreds of millions of stars more or less continuously for 170 days out of the year. Astronomers will use the collected data to search for exoplanets as well as study galaxy structure across cosmic time, look for bright exploding stars, and try to answer some of the biggest questions about how the universe has evolved.

WFIRST topped the National Academy of Sciences Decadal Survey for Astronomy as the priority for a large space mission, and NASA is putting considerable developmental effort into the project.



▲ Researchers are working on a prototype starshade. This 34-meter-wide instrument would block the light from a distant sun, allowing the orbiting planet's reflected light — about 10 billionth the brightness — to be visible. JPL

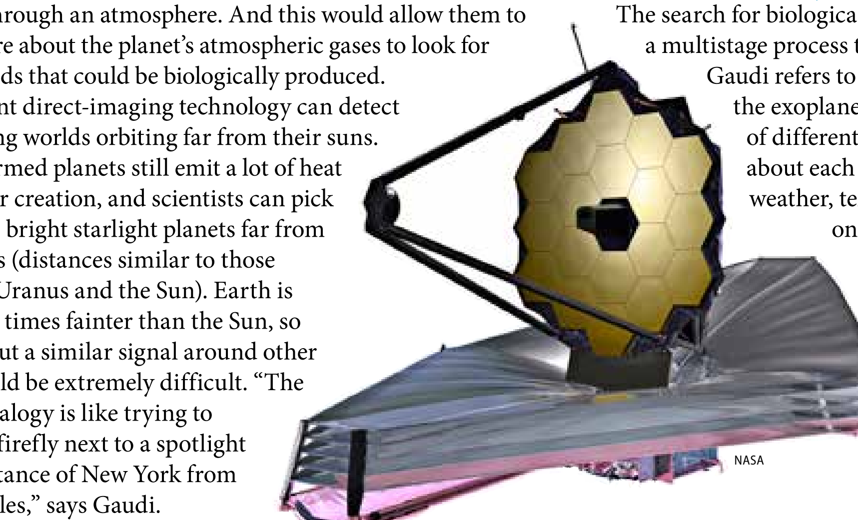
◄ Current technology limits the size and brightness of exoplanets that scientists can directly image. Gliese 504b is the lowest-mass world so far photographed around another star. It weighs about 4 Jupiter masses and orbits its Sun-like star from about 44 times the Earth-Sun distance. NASA'S GSFC/NOAJ

If Webb launches and begins operations on time, WFIRST will likely be NASA's next big mission, slated for a 2023 launch.

## What is a picture worth?

The methods described so far in this article all use indirect ways to find and study worlds around other stars, but "eventually what we want to do is direct imaging," says Gaudi. Scientists won't just find the planets; they also would be able to study the light spectrum of an imaged world directly instead of just seeing its star's radiation filtered through an atmosphere. And this would allow them to learn more about the planet's atmospheric gases to look for compounds that could be biologically produced.

Current direct-imaging technology can detect only young worlds orbiting far from their suns. Newly formed planets still emit a lot of heat from their creation, and scientists can pick out of the bright starlight planets far from their stars (distances similar to those between Uranus and the Sun). Earth is 10 billion times fainter than the Sun, so picking out a similar signal around other stars would be extremely difficult. "The classic analogy is like trying to resolve a firefly next to a spotlight at the distance of New York from Los Angeles," says Gaudi.



NASA's James Webb Space Telescope is an infrared observatory set to launch in 2018. Its 6.5-meter-wide mirror will provide observations of the compositions of a few dozen exoplanets' atmospheres.

In November 2013, the newest direct-imaging instrument saw first light. The Gemini Planet Finder, attached to the 8-meter Gemini South Telescope in Chile, will observe infrared radiation from about 600 large young exoplanets over two years. Astronomers expect these worlds to orbit their stars from distances between five and 40 times Earth's separation from the Sun.

Some scientists are working on a way to include on WFIRST an instrument called a coronagraph to block a star's light and look for its orbiting planets. Seager and colleagues are investigating something similar: a starshade and telescope system. The two parts would launch together. Once in space, the starshade would unfold and the two instruments would separate by tens of kilometers. To work properly to block the bright star from view, they would need to be aligned within a meter of the line of sight to a chosen observational target. Such a system is still many years away, but Seager's team is beginning to test the technology with a prototype starshade.

## It takes many steps

The search for biologically produced gases on Earth-like worlds is a multistage process that involves many avenues of exploration. Gaudi refers to three distinct steps: First, determine what the exoplanet demographics are (how common worlds of different sizes and orbits are). Next, learn indirectly about each planet's characteristics, like mass, radius, weather, temperature, and atmosphere. Third, focus on a few Earth-like worlds around nearby stars and study those in greater detail to determine if they do host life. "All of these are necessary steps that we have to take, but they're part of the overall goal of basically trying to find a 'pale blue dot' and characterize its atmosphere," says Gaudi.

Each phase to get to that objective tells scientists a great deal about the worlds around us. It also teaches them how the solar system formed and evolved. So far, they've found none that look just like our home system — but that does not necessarily mean it is unique, rather that the current tools can't yet detect and characterize other systems in enough detail.

Only after analyzing and cataloging many similar systems can astronomers determine how many worlds just like ours, and inhabited by living beings, exist. The next few decades hold immense promise for answering the age-old question of whether we're alone.

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