Astronomy magazine

OUR SEARCH FOR EXTRASOLAR PLANETS

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THE EXOPLANET NEXT DOOR


An artist's impression of the surface of Proxima Centauri b, drawn as if it has an atmosphere. Whether or not an atmosphere exists is not yet known. ESO/M. KORNMESSER

There's no star closer to us than Proxima Centauri — and now we know it has an Earth-mass planet in its habitable zone.

by John Wenz

THE HUNT FOR EXOPLANETS HAS, in some ways, been about the hunt for an Earth-like planet — something warm where water could exist. Headlines tout each discovery as "the most Earth-like planet yet." Many of those planets are far distant.

A new discovery published August 24 in *Nature* hits closer to home, though, with an Earth-mass planet in the habitable zone of its star. What's more, that star is Proxima Centauri, only 4.24 light-years away.

This is a landmark discovery: finding a planet orbiting the closest star to the Sun. And so far, this exoplanet shows some similarity to Earth, as it's roughly the mass of our planet and in just the right place where, if it has an atmosphere, liquid water could exist on the surface.

This is as in our backyard as it gets.

"I think it actually marks a transition," Jeffrey Coughlin, a SETI Institute scientist not involved in the study who assembles the Kepler catalog, says. "Twenty years ago, we were finding the first exoplanets, and it was totally exciting," he says. Then there was the Kepler space telescope, which found thousands of planets, including some in the habitable zone, and some within a few dozen light-years of us.


This artist's view shows how Proxima Centauri may look from just behind Centauri b. ESO/M. KORNMESSER

And now there's a planet named Proxima Centauri b of 1.3 Earth masses right next door, zipping around its star in 11.2 days. Its distance of around 4.3 million miles (7 million kilometers) from its star may seem tiny, at less than one-fifth the distance between Mercury and the Sun, but Proxima Centauri is the runt of the litter in the Alpha Centauri system. At a diameter of around 125,000 miles (200,000km), it's only 1.43 times the diameter of Jupiter.

So how was there a planet hiding around the closest star to us, just waiting to be discovered? The simple answer: Finding a planet is really hard. Kepler found thousands of planets by staring at 145,000 stars in a minute region of the sky at the tail end of Cygnus, waiting for the 1 percent chance a planet would pass directly in front of a star and cause a dip in its light, in a method known as transiting.

The problem with Proxima Centauri b is that it doesn't transit — at least not from our vantage point. In order to witness a transit, the orbital plane of a planet must be at or near our line of vision, but not all solar systems have the same orientation. A star might have all of its planets aligned at a 90-degree angle from us, with the planets orbiting in such a way that they never pass in front of their star, enabling our telescopes to detect them. Some planets have been found by direct imaging (that is, a planet appearing in a photo along with its star). In order for instruments to directly image them, planets must be very young and still glowing, or else very large — not possible with the 5-billlion-year-old Proxima b.

How to find a planet (that doesn't want to be found)

That's why the Pale Red Dot project, tasked with finding a planet around our nearest neighbor, had to turn to indirect — but reliable — methods of detection. The researchers chose radial velocity, a process that looks for shifts in a star's light due to the tug of a planet, sometimes called the Doppler method. Gravity induces subtle movements that cause the light of a star to move toward the blue end of the light spectrum, which means it's moving toward us, or the red end of the spectrum, which means it's moving away. Based on those changes, researchers can calculate a mass estimate, and the frequency gives an idea of the orbit.

The planet itself was found over a series of nights from January 19 to March 31, 2016, during which Proxima was monitored closely for subtle variations on the European Southern Observatory's HARPS instrument, a spectroscope that measures tiny wobbles in a star's light.

"Instead of applying for a few nights over a semester and repeating the same thing over the years, what we did here is try to convince ESO it was worth doing intensive campaigns to monitor the star 60 days in a row, only 20 minutes per night," principal investigator Guillem Anglada-Escudé said in a press conference.

The end result is a planet as close to us as any could be, outside of a similar discovery in the same system.

The project team, however, has been cautious every step of the way. They ignored weak evidence of the planet's existence stretching back to 2013 in favor of stronger observations over the subsequent three years, factoring in other studies of the star stretching back 16 years. Though fairly convinced it's a planet (above 99 percent certain, in fact) based on their data, the researchers still refer to the planet as a candidate. A possible second planet in the system with a 60-day or longer orbit only gets a passing mention in the paper, ignored in favor of the solid, concrete evidence.

The researchers also were tight-lipped about their findings, awaiting the end of the peer review process. But as their intended press conference approached, an anonymous ESO astronomer leaked the story to the German press, sending Pale Red Dot into damage control, with the team keeping a tighter lid on its findings as rumors swirled in the astronomy community. *Nature* was forced to address the rumors in its materials to the press before the official announcement.

Going back to the 2013 detection: the evidence was initially weak. Subsequent observations bolstered the planet's case, but it wasn't until the most recent observation campaign that proof for a planet and not some other phenomenon solidified. Given this history, the team has been methodical every step of the way.

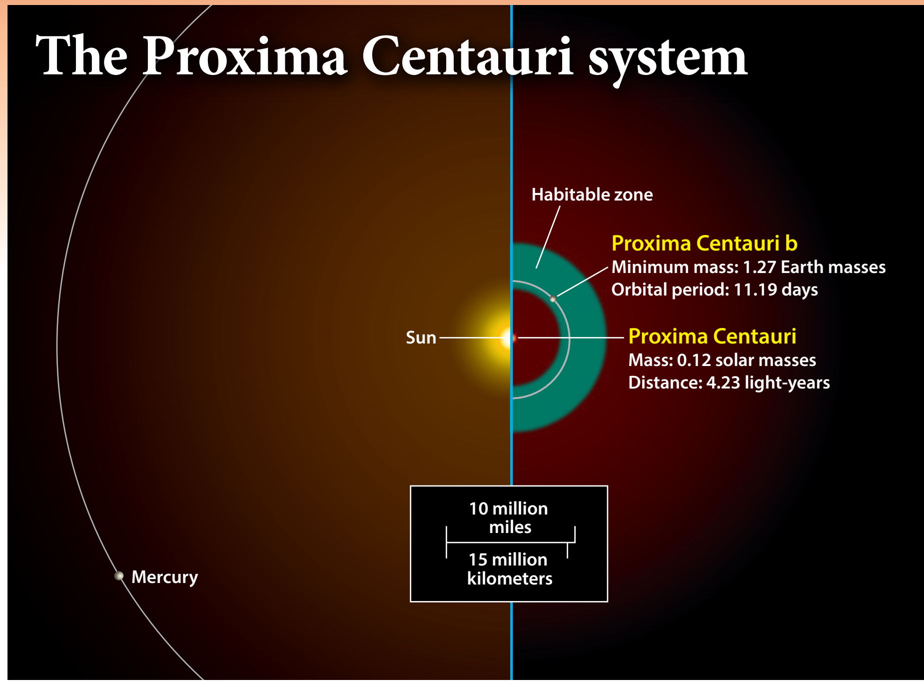
"The authors do a great job in their analysis. They follow all protocol and all standard techniques," Sara Seager, an MIT exoplanet researcher and astrobiologist, says. "And they do say that they looked at all the different types of stellar activity and other things that could generate a spurious Doppler signal at 11 days, but after looking at all that, they concluded the variability in the data is best explained by the presence of a planet."

Part of the caginess may arise from a 2012 detection of a planet around another star in the system, Alpha Centauri B. That planet, aptly named Alpha Centauri Bb, was too hot to sustain life, but instantly became the closest planet to us by default.

Or it would have, if it actually existed.

The detection was riddled with problems, drawn out from spurious data, and ignored a low signal-to-noise ratio in search of a sensational new planet, the kind science fiction has long dreamed of. Instead of becoming an Earth-shattering revelation, serious doubts were cast on the detection, which also used radial velocity.

"[Pale Red Dot] actually just said the most likely explanation is the presence of a planet," Seager says. "If you remember Alpha Centauri Bb … I just think there's a concern in the community that every retraction looks bad, even though that one wasn't officially retracted."



This diagram compares the size of the Proxima Centauri system with our own solar system. The star is smaller than our Sun, while the planet orbits within just a fraction of Mercury's orbit. However, because the star is smaller and cooler than the Sun, Proxima Centauri b falls in the habitable zone, even that close in. ESO/M. KORNMESSER/G. COLEMAN

Thus, the team was rigorous — and transparent — every step of the way. After all, they couldn't repeat the mistakes of Bb. The end result? A solid detection of an Earth-size planet in a place called the "Goldilocks zone," because it's neither too hot nor too cold for liquid water to exist — even if the researchers do use the word "candidate" to describe a detection with Kepler-catalog-like certainty.

"Because there have been previous claims of other planets (in the system), we had to verify as much as possible that [something else] was not causing this candidate signal," Anglada-Escude said.

But is it habitable?

Potential habitability and a lush world of liquid bodies of water and a thick atmosphere are two very different things. In our own solar system, three planets are technically in the habitable zone. Venus is on the inner edge, while Mars is in the outer. (Hint: The third is Earth.)

Mars and Venus likely had bodies of water at some point in their history. But solar winds and other stellar events ripped away layers of lighter elements and evaporated lakes, oceans, and streams. As the water boiled away, the hydrogen escaped into space while the oxygen descended and bonded with carbon atoms.

For volcanic Venus, this meant a series of heavy elements and molecules created a permanent smog that ensured the planet remained a dry hellscape free of all but the slightest traces of water vapor. For Mars, this meant a thin carbon dioxide atmosphere with what little water remained trapped in frozen lakebed glaciers buried under oxidized iron-rich soil, or in seasonal floes of brine mixed with trace amounts of water.

In either case, these planets didn't last long as habitable worlds, at least for any life-form beyond a microbe.

One of the big culprits is the lack of a present-day magnetic field on either planet, which, like the energy shields in *Star Trek*, deflects the worst the Sun and the universe can throw at Earth.

Even if Proxima Centauri b is in the habitable zone, it could have had an early atmosphere ripped away by the first billion years of violent stellar activity common with red dwarfs. This means that, even if the planet is in the right place for liquid water, a lack of atmosphere could have evaporated that water long ago, leaving a cold, barren planet of –40° F (–40° C).

"The planets are a lot closer to the star [than ours is to the Sun], so they're closer to these big energetic events — you're just potentially getting bombarded with more of that for potentially habitable planets around M-dwarfs," Elisabeth Newton, a postdoctoral fellow at MIT who studies red dwarf systems (also called M-dwarfs), says.

This could be especially compounded by the planet's tidal locking to its parent star. Because of the small separation in the system — the distance between Centauri b and its star is just 5 percent the distance of between Earth and the Sun — the same side of the planet faces Proxima Centauri at all times, much as the same side of the Moon faces Earth at all times.

However, if Centauri b still has an atmosphere, it could reach temperatures up to 86° F (30° C) on its sunlit side, and –22° F (–30° C) on its darker side, bringing it into quite Earth-like temperature ranges.

The key to preserving an atmosphere is a magnetic field. Researchers have gone back and forth about if tidally locked planets could generate magnetic fields, which are a consequence of molten materials in the planets' core stirring with its rotation. Since red dwarf planets are in lockstep with their star, some believe the cores would be inert.

Mercedes Lopez-Morales, an astronomer at the Harvard-Smithsonian Center for Astrophysics, has modeled the possibilities of magnetic fields around red dwarf planets, and a picture is gradually emerging: The planets likely form in the outer parts of their solar systems and migrate in. This means they start out life rotating, and possibly generating a magnetic field if they have the right materials in their core.

"On Earth, we're only here because we have a magnetic field that shields us from any solar wind," she says. "Any solar storm could wipe us out otherwise."

Once these planets migrate in, their star strips off the early atmosphere of lighter elements. But heavier elements — like oxygen — could be left behind. The magnetic field shields the planet from the worst excesses of its star, which then settles into a state of relative dormancy it can stay in for trillions of years.

Volcanism and other mechanisms could replenish the atmosphere. With the star less active, that atmosphere could stick around. Lopez-Morales also says that the magnetic field could stay active for billions of years, even after a planet becomes tidally locked.

In other words, the hope for life can stay alive, even after the brutal first eon of the planet's life.

"There's no reason why a planet like this could not keep a magnetic field long enough for life to develop itself," Lopez-Morales says.

That means it could hold on to liquid water. But does it?

In transit

The Pale Red Dot team found a planet. It seems to be the right mass and the right distance from its star to put something somewhat similar to Earth in our cosmic backyard. But reality is way more complicated than that, as seen by the aforementioned histories of Venus and Mars.

Astronomers need to observe the planet in greater detail in order to further characterize it. The problem is that Centauri b was detected indirectly, and there's very little to draw out of the data besides its orbit and size.

"The planets are so small, the signals are so weak, it takes a huge amount of resources to make a detection at all," Seager says. "If you want to do better, it almost needs its own dedicated telescope just to hammer away at it and do better and better."

The easiest way to study a planet's atmosphere — and *easy* is a very, very relative term here — is to watch the planet pass in front of its star and to watch the spectra of any gases that distort the star's light. The problem with this method is that thus far, no transits have been detected around Proxima Centauri, though it hasn't been ruled out as a possibility.

But to Newton, "it's basically the best target for future efforts to look for biosignatures in the atmospheres of other planets." You just need to know how and where to look.

Currently, no instrument in space or on the ground is sensitive enough to pick up reflected light from older and smaller planets. But the James Webb Space Telescope might be, as will other mega-telescope projects currently under construction.

Catching these glimmers of light, however faint, could indicate whether there's an atmosphere, and even what it's made of.

"You find the spectrum of the planet, and from that you can detect molecules in the atmosphere of the planet," Newton says.

Seager mentions the possibility of using stellar suppression techniques in the future, a process in which blocking the light of the star from the vantage point of a telescope allows the instrument to gather more light from the planet or planets around that star.

One of the other possibilities is viewing in infrared. Cullen Blake, a University of Pennsylvania researcher who studies low-mass stars and their planets, says in visible light, "you definitely have a pretty severe limit to the distance to which you can see these measurements."

Infrared eliminates some of those hurdles. This could show the planet's own glow, without the need for starlight. Because of atmospheric distortion, virtually all infrared astronomy has to be performed by space-based telescopes or high-altitude flying observatories like NASA's Stratospheric Observatory for Infrared Astronomy, a telescope mounted to a Boeing 747SP.

Future space observatories like Webb or Hubble-like telescopes built for infrared with apertures of around 3 meters could also aid in the hunt.

"We can look at the light from the star that gets reflected on the atmosphere of the planet, or we can look at the light in the infrared coming directly from the planet," Lopez-Morales says.

In this image of the Alpha Centauri system, the yellow circle shows the location of distant, tiny Proxima Centauri. In the system, Alpha Centauri A and Alpha Centauri B, slightly larger and slightly smaller than the Sun, respectively, orbit each other while Proxima orbits both at a distance. SKATEBIKER/WIKIMEDIA COMMONS

Looking to the future

Now we know — or know with only a sliver of a percent of doubt — that there's a planet slightly more massive than Earth the next star over. It's a banner accomplishment, one that has the scientific community salivating at the possibilities.

"To find one around the nearest, best-studied star … maybe we're just really lucky, or maybe there really are just billions of M-dwarf planets out there waiting for us to find them," Newton says.

Low-mass stars are the most plentiful in the galaxy. Of the 10 closest star systems to Earth, only one does not contain a low-mass star (the Sirius system consists of a blue giant and an ultra-compact white dwarf, the remnant of a Sun-like star). Beyond those two, only Proxima Centauri's bigger brothers Alpha Centauri A and B are larger stars.

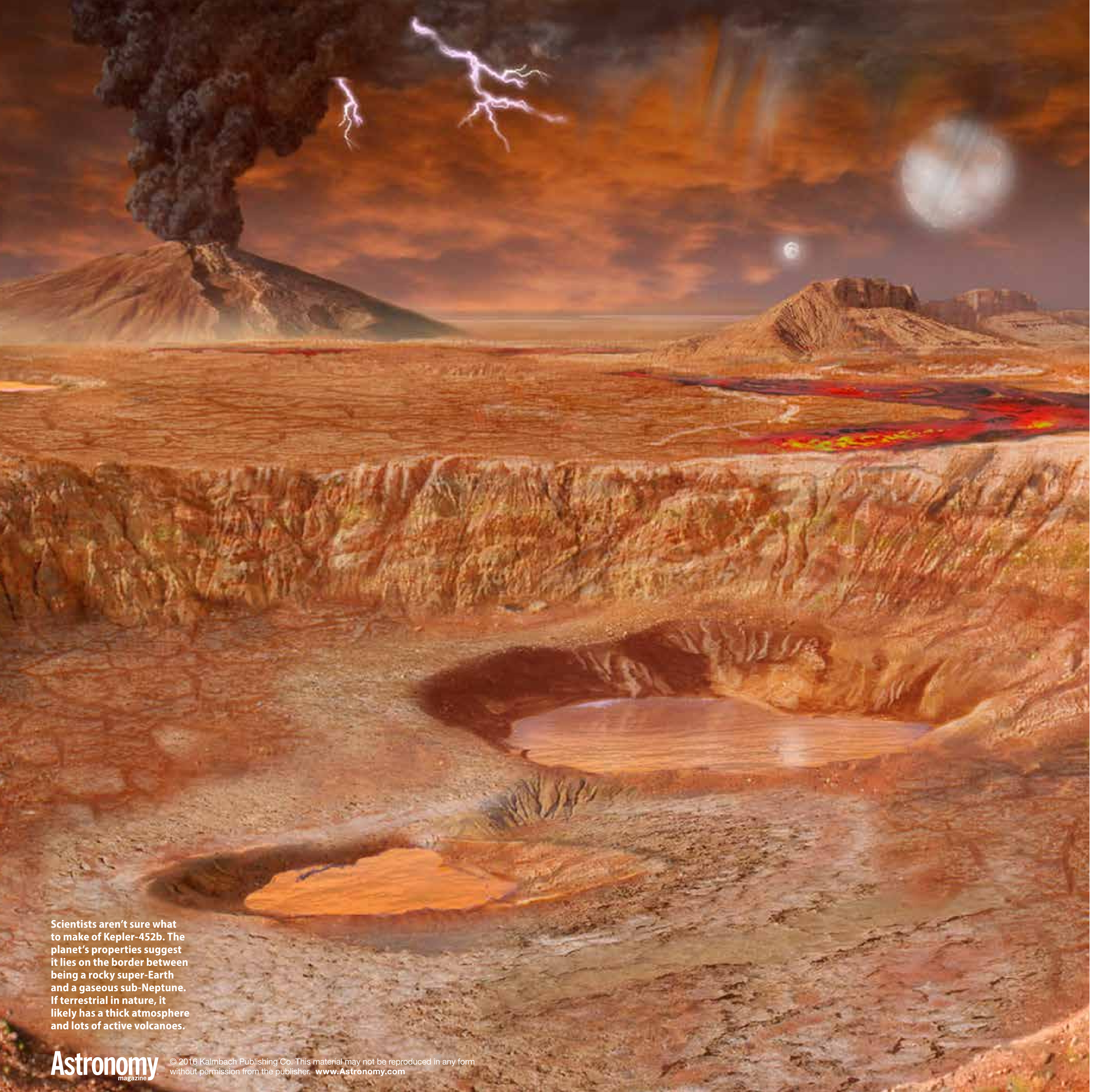
Nearly every star is suspected to have a planet. Some of those could be habitable. If it ends up that Proxima Centauri b is barren, then perhaps we'll have better luck looking at the next star over, Barnard's Star, where planetary detection has remained elusive. It could be that, like Proxima Centauri, we haven't been looking for the right kind of planet with the right kind of dedication.

Or maybe the real solution is at Wolf 359, 7.7 light-years away. Or Lalande 21185, 8.2 light-years away. Or any number of other targets less than a dozen light-years away.

"If you just make a list of the closest stars to the Sun, there's a handful there that would make good targets for these kinds of observations," Blake says.

We may not need to go clear out to Wolf 1061 at 13.8 light-years away to find the next closest potentially habitable planet. All we need to do is stretch our instruments to the limits and take a dedicated look for the next pale red dot.

John Wenz *is the associate editor of* Astronomy *magazine.*



Scientists aren't sure what to make of Kepler-452b. The planet's properties suggest it lies on the border between being a rocky super-Earth and a gaseous sub-Neptune. If terrestrial in nature, it likely has a thick atmosphere and lots of active volcanoes.

The hunt for Earth's BIGGER COUSINS

Larger than Earth but smaller than Neptune, these in-between worlds harbor some surprisingly terrestrial environments.

Text and illustrations by Michael Carroll

Somewhere between the gas giants and the terrestrial Earth-like worlds that populate our galaxy lies a twilight zone, a region where planets defy easy classification. It is a dimension between gaseous and rocky, a territory where planet size straddles Earth and Neptune.

Several of these recently discovered hybrid planets offer the most exciting possibilities for Earth-like conditions on other worlds. And wherever such environments exist, the chance that life might gain a foothold can't be ruled out.

In search of Earth 2.0

Finding exoplanets isn't easy. It's exceedingly difficult to directly image a planet at interstellar distances because it gets lost in the glow of its host star. But astronomers are adept at teasing out planets by closely examining the light from distant suns. When a world passes directly in front of its star from our perspective (a transit), the star dims, and the amount of dimming depends on the planet's physical size. The Kepler planet-hunting spacecraft used this technique to find thousands of exoworlds.

A second method, called radial velocity, measures a star's movement as an orbiting body pulls on it. The planet's gravity causes its sun to wobble. When the planet tugs the star away from us, the light becomes redder; on the opposite side of the orbit, the star gets yanked toward us, and its light becomes bluer. Astronomers can detect this so-called Doppler shift in a star's light. And the bigger the shift, the more massive the planet must be.

By combining these two techniques, scientists gain insights into the nature of exoplanets. If a planet has twice the mass of Earth but the same volume, for example, it must be very dense and thus rocky. But if a planet with Earth's mass has 10 times our planet's volume, it must be a low-density, fluffy world like a small gas or ice giant.

Astronomers have charted a wide range of planets orbiting in their host star's habitable zone — the region where liquid water could exist on a world's surface — from small terrestrials akin to Mercury to rocky or gaseous worlds the size of Neptune. Of the worlds with sizes comparable to our home planet, our galaxy may hold upward of 10 billion. Among the exoplanets

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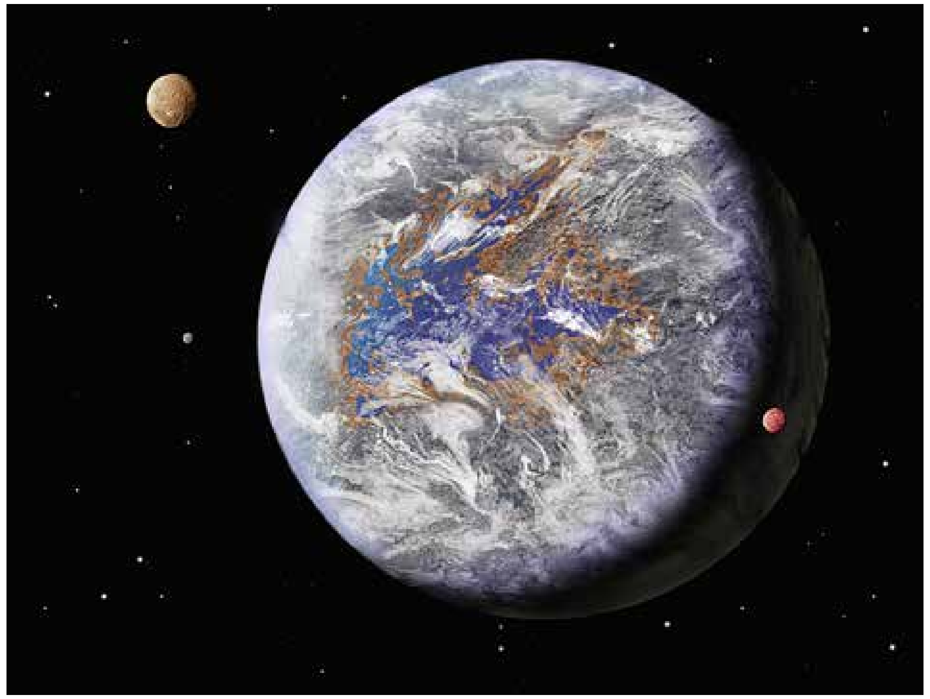
Frequent contributor **Michael Carroll** *is a science writer and astronomical artist. His latest book is* Earths of Distant Suns *(Springer, 2017).*



Gliese 581g could be one of the more Earth-like worlds in our galaxy. Its tightly wound orbit around a red dwarf sun places the exoplanet within the star's habitable zone. Models indicate that under the right conditions, a large ocean would spread across this super-Earth's star-facing hemisphere.

discovered so far, however, the Neptune- and sub-Neptune-sized worlds are the most common. Many of these relatively small giants qualify as super-Earths.

Super-Earths and sub-Neptunes

Broadly speaking, the term *super-Earth* applies to planets that are larger than Earth but still have a rocky surface and a thin atmosphere. The term *sub-Neptune* refers to a small gaseous giant. But uncertainties in the data mean that the boundary between these two classes is more blurry than clear-cut.

Super-Earths seem to be the most common type of exoplanet. Roughly three out of every 10 worlds now known fall into this category. These worlds have no analog in our solar system. Scientists classify super-Earths strictly by mass without considering their composition, nature, or distance from their host star. Most of those discovered so far orbit close to their suns — simply because those that orbit close to their suns are the easiest to detect. The masses of these worlds range from a low of about 1.5 to 2 Earth masses up to a high of 10 Earths.

Astronomers sort super-Earths into four categories. Low-density planets contain large amounts of hydrogen and helium and are referred to as dwarf or sub-Neptunes. Medium-density super-Earths probably are ocean worlds where water is a major component. A third type has a denser core than a sub-Neptune but still possesses a sub-Neptune's extended atmosphere. The extent of that atmosphere depends on the planet's distance from its star — the farther away it orbits, the cooler it will be, and the more atmosphere it will retain. Finally, larger, high-density super-Earths, sometimes called mega-Earths, probably include major components of rock and/or metal.

Not quite like Neptune

The ubiquitous sub-Neptunes join the exoplanet menagerie with masses ranging up to slightly less than our system's Uranus and Neptune. (Uranus contains 14.5 Earth masses; Neptune holds 17.1.) These worlds likely come with a wide variety of personalities.

Research scientist Mark Marley models exoplanet atmospheres at NASA's Ames Research Center in Moffett Field, California. He believes that sub-Neptunes may turn out to be the most varied of any size worlds. "You get bigger than a Saturn or so, and [planets] all tend to be about the same size because they are dominated by their hydrogen-helium atmospheres. When you get down closer to 1 Earth mass, they're probably all rocky worlds with a little bit of atmosphere. But [in this region between Neptune and Earth], there's probably a huge range of what these planets could be like. Every one is going to be unique," he says. Their natures depend on a host of factors, including their mass, the amount of water they possess, and the size of their core.

Like Neptune, most sub-Neptunes are gaseous. Unlike Neptune, however, many of these worlds orbit near their primary star. This provides astronomers with a mystery: How did sub-Neptunes end up close to their star when they had to form in the outer regions of their planetary system? Such worlds can be born only beyond the so-called snow line, where cool temperatures enable them to collect large quantities of ices and gases.

Planets, it seems, are slippery things, capable of forming in one place and shuffling off to another. Our solar system's arrangement of gas and ice giants outside of smaller terrestrial worlds apparently is not the norm across the galaxy. Astronomers developed the Grand Tack model to explain the solar system's early evolution. The theory proposes that Jupiter and Saturn marched toward the Sun, but Saturn was able to pull

Kepler-22b likely is a rocky planet with a radius about 2.4 times that of Earth. It orbits its host star near the inner edge of the habitable zone, so it may resemble Venus more closely than Earth.

Jupiter back from the brink of death. Similar migrations may be common in other systems, where sub-Neptunes could form at a large distance and drift starward later. An Earth-like world that develops close to its sun would have a much higher density because it lacks the water content of a planet originating in a system's cooler outer region.

Elisa Quintana of NASA's Ames Research Center has been working with a team trying to figure out when a planet transitions from being Earth-like to being a gaseous sub-Neptune. "Before we knew of any exoplanets, we had a basic mass-radius relationship based on our solar system. Now, we've had to throw that away," she says. "Theoretical models tell us that the transition from rocky super-Earth to gaseous sub-Neptune is about 1.5 or 1.6 Earth radii. Once a planet reaches 2 Earth radii, it will be more like a sub-Neptune." Researchers hope to pin down the transition point as they study more super-Earths.

How much like home?

Although the discovery of planets with terrestrial dimensions is exciting, it takes more than size to make an Earth. Even among worlds close to Earth's size and mass, the "Earth-like" pickings appear to be slim. Most orbit outside the host star's habitable zone.

Typical of these is the nasty Earth-sized planet circling the star Gliese 1132. Astronomers calculate that Gliese 1132b spans 1.2 times the radius of Earth and has a mass about 1.6 times as large as our planet, putting it on the border between being rocky or sub-Neptunian. As Earth-like planets go, so far, so good. But scientists estimate that its surface broils at the temperature of an oven, around 460° F (225° C).

Just how Earth-like is a super-Earth? Features that contribute to our own world's uniqueness offer a good yardstick. First, Earth orbits in the Sun's habitable zone. Although some super-Earths orbit within the habitable zone of their own star, studies show this may not be enough to beget Earth-like environments. Plate tectonics is another critical attribute of our home world because it recirculates the minerals that wash into the seas and recycles elements of the atmosphere that have been chemically locked into rocks.

But recent models contend that super-Earths may not enjoy the benefits of plate tectonics. First, it takes the right mineral smorgasbord to create the planetary jigsaw pattern of shifting plates. On Earth, as one plate slides under another, increasing pressure rearranges the atoms within it, making the rock denser. Without this alteration, plates would stall out and cease sliding past each other. The change in density depends on the plate's makeup. Planets with mineralogically different crusts may not be able to maintain a conveyor belt of plates.

Second, a super-Earth's crust may be too thick to carry on tectonics. Simulations of the pressures within giant Earths reveal that thick crusts likely surround most of these worlds, putting up a physical barrier to plate tectonics. Still, some researchers suggest that the increased heat within a super-Earth might be enough to drive plate tectonics.

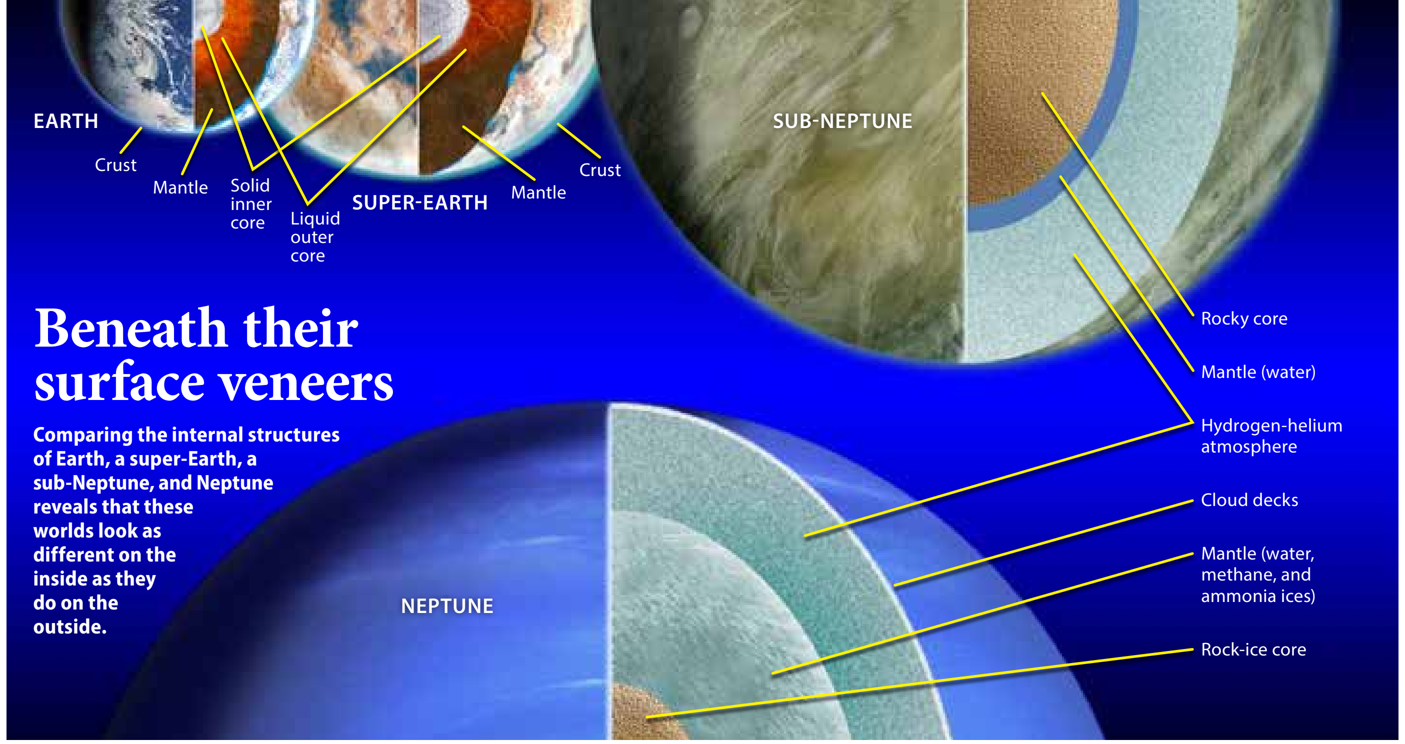
Another factor that would contribute to a super-Earth's earthiness is a magnetic field. Earth's rotating molten core generates a field that protects us from energetic charged particles. To be Earth-like, a super-Earth needs to have such a field.

A survey of super-Earths

Out of the thousands of exoplanets known, astronomers have found only a few super-Earths with the right characteristics to be potentially Earth-like. One of the closest matches appears to be Kepler-452b.

The first roughly Earth-sized planet found in the habitable zone of a star similar

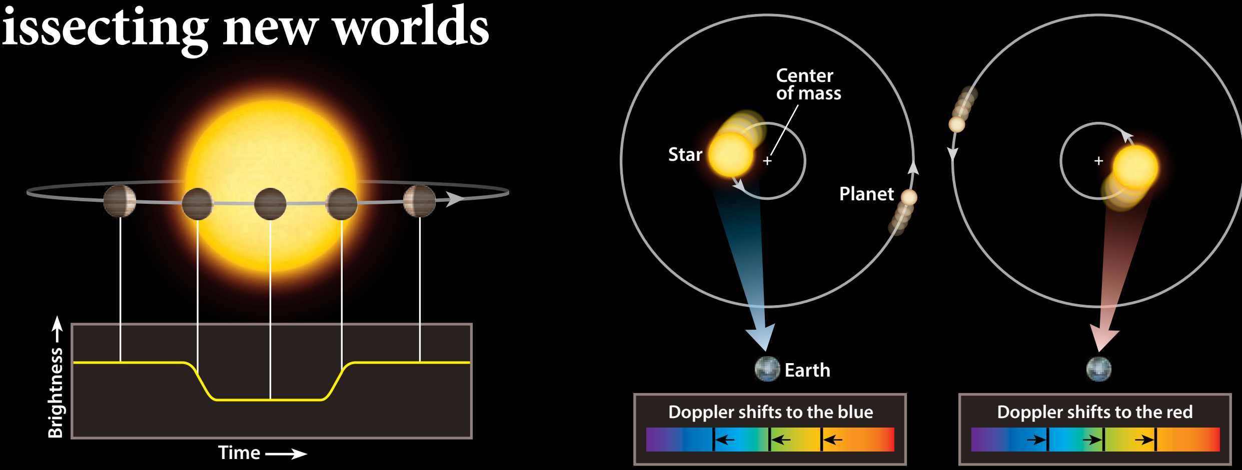
Two super-Earths orbit Kepler-62. Both worlds likely have deep oceans of water, though Kepler-62f (bottom) orbits farther from its star than Kepler-62e (top) and thus may be covered with ice.



Beneath their surface veneers

Comparing the internal structures of Earth, a super-Earth, a sub-Neptune, and Neptune reveals that these worlds look as different on the inside as they do on the outside.

Dissecting new worlds



Astronomers know the most about exoplanets observed with both the transit and radial velocity methods. When a planet passes in front of (transits) its parent star (left), it causes a slight dip in the star's light. The wobbles induced by a planet's gravity alter the host star's radial velocity and show up as shifts in the stellar spectrum (right). In the rare cases when scientists can view a planet with both methods, they get valuable information on the world's size, mass, and density. ASTRONOMY: ROEN KELLY

to the Sun, Kepler-452b is roughly 1.5 times larger than Earth. Although it lies slightly farther from its star than Earth does from the Sun, its star (Kepler-452) shines slightly brighter than ours, so the planet gets just a bit more energy than Earth does. Any terrestrial vegetation transported there likely would thrive in similar lighting conditions and temperatures.

That is, *if* Kepler-452b has a solid surface. The planet's size hovers right on the edge between a rocky super-Earth and a gaseous sub-Neptune. Columbia University astronomers Jingjing Chen and David Kipping published a study in *The Astrophysical Journal* in late 2016 that gives the planet only a 13 percent chance of being terrestrial rather than gaseous. Models suggest that if Kepler-452b is rocky, it probably has a thicker atmosphere than Earth's and likely would be volcanically active.

Kepler-452b takes 385 days to orbit its sun, a year quite similar to Earth's. But all may not be well on this world. Its star is 1.5 billion years older than the Sun and radiates more light and heat than it used to. The planet once was in the center of the habitable zone, but as the aging parent star has warmed, its habitable zone has migrated outward, stranding the planet on the inner edge. Any oceans it once had likely are evaporating into a thick atmosphere.

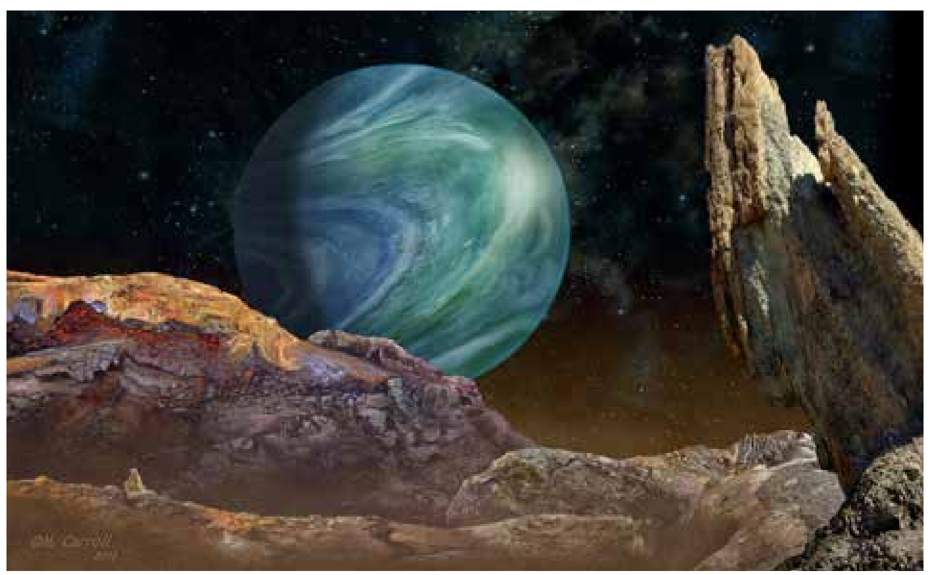
Other possible matches may circle Gliese 581, a red dwarf star that lies 20 light-years from Earth. Up to five planets may orbit this star, and three of them may be super-Earths in the star's habitable zone. Gliese 581c orbits near the zone's inner edge. It may circle close enough to the star that it suffers from a runaway greenhouse effect like that found on Venus.

The other two planets — Gliese 581d and Gliese 581g — may be more Earth-like, but astronomers aren't even sure they exist. Both worlds have been detected by multiple teams, but other researchers have failed to confirm them. If real, they would be on the shortlist for most Earth-like planets.

Gliese 581g appears to orbit just 0.13 astronomical unit (AU; 1 AU is the average Earth-Sun distance) from the star. But because the red dwarf is dim, the planet receives roughly the same amount of energy as Earth does from the Sun. Its mass may be no larger than 2.2 Earths, barely qualifying it for super-Earth status. The planet orbits close enough to its sun that it should be tidally locked, always keeping the same face toward the star. Depending on its atmospheric composition and surface, it might be a barren, Venus-like world, or one with an abundance of water.

If it has an atmospheric pressure similar to Earth's, the globe might be blanketed in a thick ice crust. But if the air contains enough greenhouse gases like carbon dioxide, temperatures could be substantially warmer. The tidally locked world could develop a permanent ocean on the hemisphere facing the star, where temperatures would be similar to those in Earth's tropics.

Another possible world in this system, Gliese 581d, appears to be much heavier, perhaps as much as 7 Earth masses. This purported planet's size caused astronomers to add a new class to exoplanets: the mega-Earth. The world apparently orbits its star with a period of 67 days, placing it near the outer edge of the habitable zone.



Seen from the surface of a hypothetical nearby moon, super-Earth Gliese 667Cc may be a sub-Neptune, with windy cloudscapes rather than rocky vistas. The planet lies so close to its red dwarf host that it probably is tidally locked, a situation that may wreak havoc with its banded cloud formations.

Kepler's reign of glory

At a distance of 620 light-years, the Sun-like star Kepler-22 hosts Kepler-22b. The planet has the distinction of being the first habitable-zone world discovered by the Kepler spacecraft.

With a diameter about 2.4 times that of Earth, it has a density similar to rock, which means that it may be terrestrial. Kepler-22b also might have a fairly dense atmosphere and, because it orbits in the inner region of its star's habitable zone, the climate may resemble Venus more closely than Earth. But the planet's rotation and cloud cover could moderate conditions there. Some recent models point to a surface temperature hovering around a comfortable 72° F (22° C).

Farther out in the galaxy, at a distance of about 1,200 light-years, Kepler-62 boasts five confirmed planets. Two of these reside in the habitable zone of the host orange dwarf star. Both are roughly 1.5 times larger than Earth, putting them at the border between Earth-like and super-Earth.

Studies indicate that water likely covers Kepler-62e in a deep global ocean. And although sibling Kepler-62f also may have a large component of water, it lies far enough out in the habitable zone that the surface might be frozen, at least at the poles. The latter world may have an atmosphere denser than Earth's, perhaps similar to — but cooler than — that of Venus.

Some 22 light-years from Earth lies the triple-star system Gliese 667. Two of the members are K-type orange dwarfs somewhat cooler than the Sun, while the third is an even cooler red dwarf. The two K-type stars orbit each other; the red dwarf, Gliese 667C, circles them both at a distant 230 AU. Gliese 667C appears to have at least three planets in the vicinity of its habitable zone.

Perhaps the most intriguing of these is Gliese 667Cc, which has a mass less than four times that of Earth. This alien planet may be a rocky terrestrial, though some researchers think it may be a sub-Neptune. The world circles its sun at breakneck speed, completing a circuit in just 28 days. But because Gliese 667C is a red dwarf, the world lies far enough out that liquid water could exist on its surface. Gliese 667Cc collects about 90 percent of the light that Earth receives from the Sun. And as with any large planet in a habitable zone, it may have moons with quite Earth-like environments.

One of the most Earth-like planets yet discovered is a world with a radius 12 percent larger than our own. Kepler-438b orbits within the habitable zone of a red dwarf, making a circuit every 35 days. If Kepler-438b is terrestrial in nature, its mass would be about 1.4 times Earth's. Surface temperatures on this world likely would range from 32° to 140° F (0° to 60° C). The planet suffers from the disadvantage of orbiting close enough to its parent star to feel the fallout from the stellar flares common to red dwarfs. In fact, observers have seen Kepler-438 unleashing radiation and plasma every few hundred days. But if Kepler-438b has a strong magnetic field, its surface still might be hospitable.

A red dwarf sets behind clouds on Kepler-438b. The planet lies close enough to its active star to be exposed to massive stellar flares. If it does not have a magnetic field, the world likely experiences deadly levels of radiation.

Astronomers have discovered a variety of exoplanets within their host star's habitable zone. The field seems ripe for the discovery of worlds with thriving biomes beyond our own. The search for life-forms on Earths of distant suns will be a difficult one, but the detection of a living world would forever change our views of biology, planetary development, and the frequency of life in the universe.

The search for alien Earths is heating up. But there's still no place like home.

Why we haven't found another Earth. Yet.

by Nola Taylor Redd

AS LONG AS HUMANS HAVE STUDIED PLANETS, they have sought signs of life beyond Earth. Venus and Mars both provided early hopes, but one proved too hot and the other too dry. Today, scientists look beyond the solar system, with the hope of finding Earth 2.0.

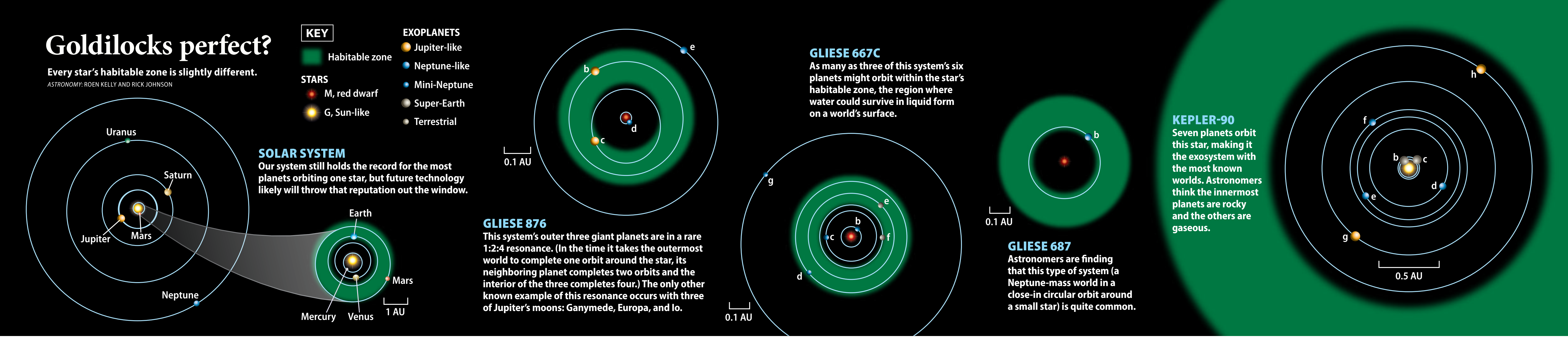
To narrow their search, scientists have identified a region around stars where rocky planets could hold surface liquid water. This area is known as the habitable zone.

For nearly 50 years, the phrase was confined to scientific jargon. With no known exoplanets, the public wasn't exposed to the term. Yet after the explosion of planetary candidates identified by NASA's Kepler spacecraft in 2010, "habitable zone" sprung out of scientific journals and into the public consciousness.

The transition has not necessarily been a smooth one. Habitable zone conjures up a region ripe for life to evolve, though this is not the image the scientific community intended to evoke. Phrases such as "habitable planet," "Earth twin," and "Earth 2.0" have added to the confusion, blurring the line between what scientists meant to say and what the general public imagines.

Defining the habitable zone

The field of exoplanet discovery is fairly young, but the term habitable zone itself has existed since at least the 1950s. At that time, it characterized the region around a star in which life-supporting planets can exist. But in the 1990s, not long after scientists discovered the



first planet beyond the solar system, a new paper established the present-day definition.

"The conservative definition since 1993 of the habitable zone is the range of distances from a star at which a rocky planet can maintain liquid water on the surface," says Jim Kasting, professor at Pennsylvania State University and lead author on that pivotal paper.

Because the habitable zone depends on the sun it surrounds, its location varies with a star's age and temperature. The habitable zone of a cooler, dimmer M star, for instance, lies closer in than it would around a Sun-like star.

It has sometimes been called the "Goldilocks zone" because when it comes to water, it's neither too hot nor too cold. However, just because liquid water could flow across the plains of a planet does not mean that it does — a major distinction.

"There's a lot of planets in the habitable zone that are likely not to be habitable, or at least not be able to have large extended regions of water on the surface," says Cornell University planetary scientist Ramses Ramirez, a co-founder of the Institute for the Pale Blue Dots.

Ramirez pointed to a planet in our own solar system that meets the criteria — Mars. The Red Planet lies within the defined habitable zone, whose edge stretches to almost 1.7 times the average Earth-Sun distance, or astronomical unit (AU). At 1.5 AU, Mars lies near the outer edge, yet lacks standing liquid water on its surface.

Since the 1990s, scientists have tried to establish firm boundaries. But there is still no hard-and-fast method, as the planet's characteristics impact whether or not water survives at the surface.

For instance, Kasting points to the changing definition of a rocky planet. In 1993, he says, that meant a planet with a radius up to approximately twice Earth's, and with no more than 10 times its mass.

> "When you talk about the habitable zone, a person very naturally thinks you are talking about a zone in which everything is habitable."
> Stephen Kane

Today, Kasting says an Earth-like planet tends to be classified with no more than 1.5 times Earth's radius. Larger bodies are now known as sub-Neptunes — extremely gaseous worlds with rocky cores.

The presence or absence of an atmosphere, as well as its composition, also helps determine if a planet keeps liquid water at its surface. If the atmosphere differs from Earth-like levels of carbon dioxide and water, a planet might hold onto liquid water at greater distances from its star. The result, Kasting says, is that different authors have different definitions for what qualifies as the Goldilocks zone.

"We need to get systematic about the choices we make," Kasting says.

Searching for signs of life

With today's instruments, scientists can only detect if a planet lies within the habitable zone, and if it has a size similar to Earth. These two factors do not necessarily mean that a planet could sustain life. However, a rocky planet orbiting inside the habitable zone of its star will likely encourage scientists to take a second, more in-depth look.

"The habitable zone is defined in such a way that we can try to find the type of life that would leave atmospheric biosignatures," Ramirez says.

That means surface life that changes the very air it breathes in a detectable way.

Scientists are already studying alien atmospheres, but the techniques are still in their early phases. NASA's Hubble Space Telescope — launched only a few years before any exoplanets had been found — was the first to study these atmospheres.

Hubble studies an exoplanet's atmosphere as it passes in front of its host star. Light from the star illuminates the atmosphere, allowing scientists to detect the components.

What would make a planet habitable? "It at least has the conditions suitable for life to take hold," Ramirez says.

For now, scientists are after Earth-sized planets with carbon dioxide and water as their primary greenhouse gases. A magnetic field is also thought to be important due to its ability to help the planet retain its atmosphere.

Another key ingredient is the presence of plate tectonics, according to Vlada Stamenkovic, a post-doctoral candidate at the Massachusetts Institute of Technology's department of Earth, Atmospheric, and Planetary Sciences. On Earth, geological activity helps the planet regulate the atmospheric carbon dioxide levels. Too much of this gas results in a runaway greenhouse effect; too little creates an icy snowball planet where the water is frozen over.

"If you really want to understand habitability, you really have to understand how the interior of the planet functions," Stamenkovic says. "Plate tectonics are key to allowing you to open the door to the interior."

Self examination

If all of this sounds familiar, it is. The goal is to find another planet similar to Earth, because at the present, Earth is the only planet known to have the conditions right for life to evolve.

But in the search for habitable worlds, some think that exoplanets may not be our best bet.

"I strongly feel that we need to learn more about our own solar system in order to understand exoplanets," Ramirez says.

He pointed to Saturn's moon Titan, with its lakes of liquid methane that could act as a solvent, taking over the role water plays on Earth. Another solar system world with the potential for life to evolve is Jupiter's moon Europa, an icy body thought likely to house a subsurface ocean. NASA plans to launch a mission to study the frozen world in the mid-2020s. The evolution of life on these bodies, originating completely independently from Earth-life, could help us to understand life on planets beyond the solar system, Ramirez says. And it would probably change our definition of the habitable zone to something less Earth-centric.

"It's possible that planets orbiting outside what we think of as the habitable zone can somehow be inhabited," says Aleksander Wolszczan of Pennsylvania State University. He was on the first team to find an exoplanet.

Of course, finding a Europa analog several light-years away would not play a strong role in the search for extraterrestrial life, because signs wouldn't be visible to today's instruments.

"We can only see the atmosphere," Ramirez says. "If you just have an ice layer that's sealing everything off, the life is not going to cut through that ice. You're probably not going to see anything with our measurements."

Earth's long-lost twin

While potentially habitable worlds may exist beyond the habitable zone, a planet classified as Earth-like would lie within that "just right" region.

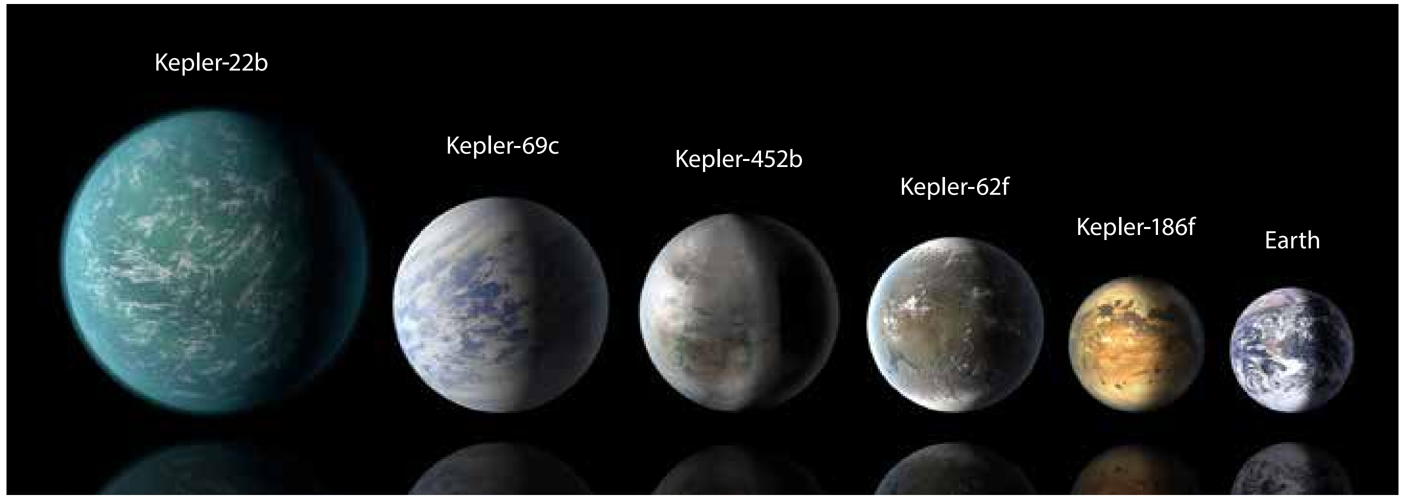
Recently, NASA announced the discovery of Kepler-452b, a rocky planet in the habitable zone of a Sun-like star that many have dubbed Earth's closest twin. But when an astronomer deems a world an Earth twin, they are only referring to a few key features.

NASA

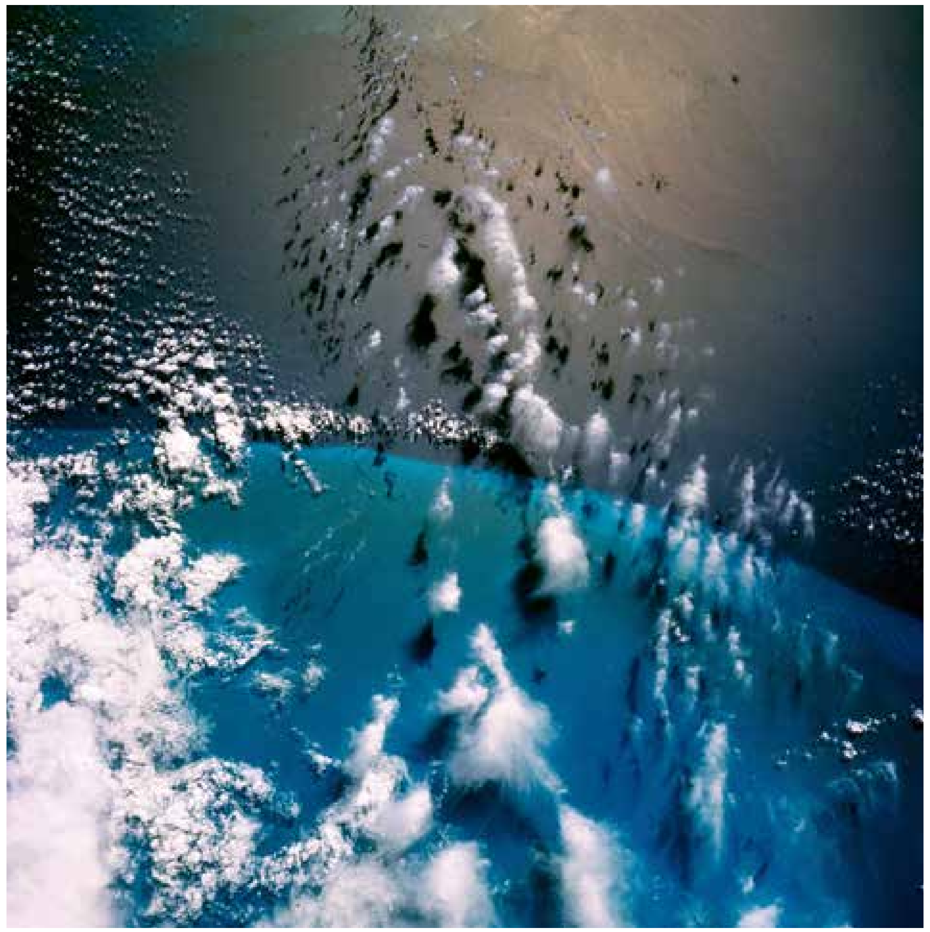
From nearby, there are many signs that Earth is inhabited. Astronaut Reid Wiseman snapped this shot from the International Space Station looking north past Cuba toward the Southeastern United States.

NASA (EARTH ON PAGE 24)

Freelance writer **Nola Taylor Redd** *combined an astrophysics degree with a creative writing degree to write about her favorite topic — anything astronomical. You can follow her on Twitter at @NolaTRedd*



When you stack up the most promising recent exoplanet finds, as illustrated here, it becomes clear none is Earth's true twin. NASA/AMES/JPL-CALTECH



Gemini IV astronauts Jim McDivitt and Ed White took this picture with a Hasselblad camera and a 70mm lens as they passed over the Florida Straights in June 1965 following White's historic first American spacewalk. NASA

"When scientists say 'Earth-like planet in the habitable zone,' it means they're talking about an Earth-sized planet in the habitable zone where liquid water can be sustained," Stamenkovic says.

That's it — the size and orbit. But the phrase "Earth twin" or "Earth-like" conjures an identical twin — a world with oceans, continents, and clouds. "There's a lot more than knowing the radius to determine if something is Earth 2.0," Ramirez says. "I wouldn't call anything an Earth twin or Earth 2.0 until we can verify if the planet is at least orbiting a star like the Sun, confirm that it has an ocean, an atmosphere, and that we've found bona fide biosignatures."

Spotting vegetation covering the land would be another strong suggestion for life, according to Abel Mendez, director of the Planetary Habitability Laboratory. He says that scientists could detect chlorophyll on exoplanets within the next 20 to 30 years, which would suggest the presence of vegetation. He cautioned that such signs could also be confusing. And, if they didn't correspond with the atmospheric clues that life evolved, they could raise even more questions.

According to Mendez, finding chlorophyll would stretch the limits of human technology.

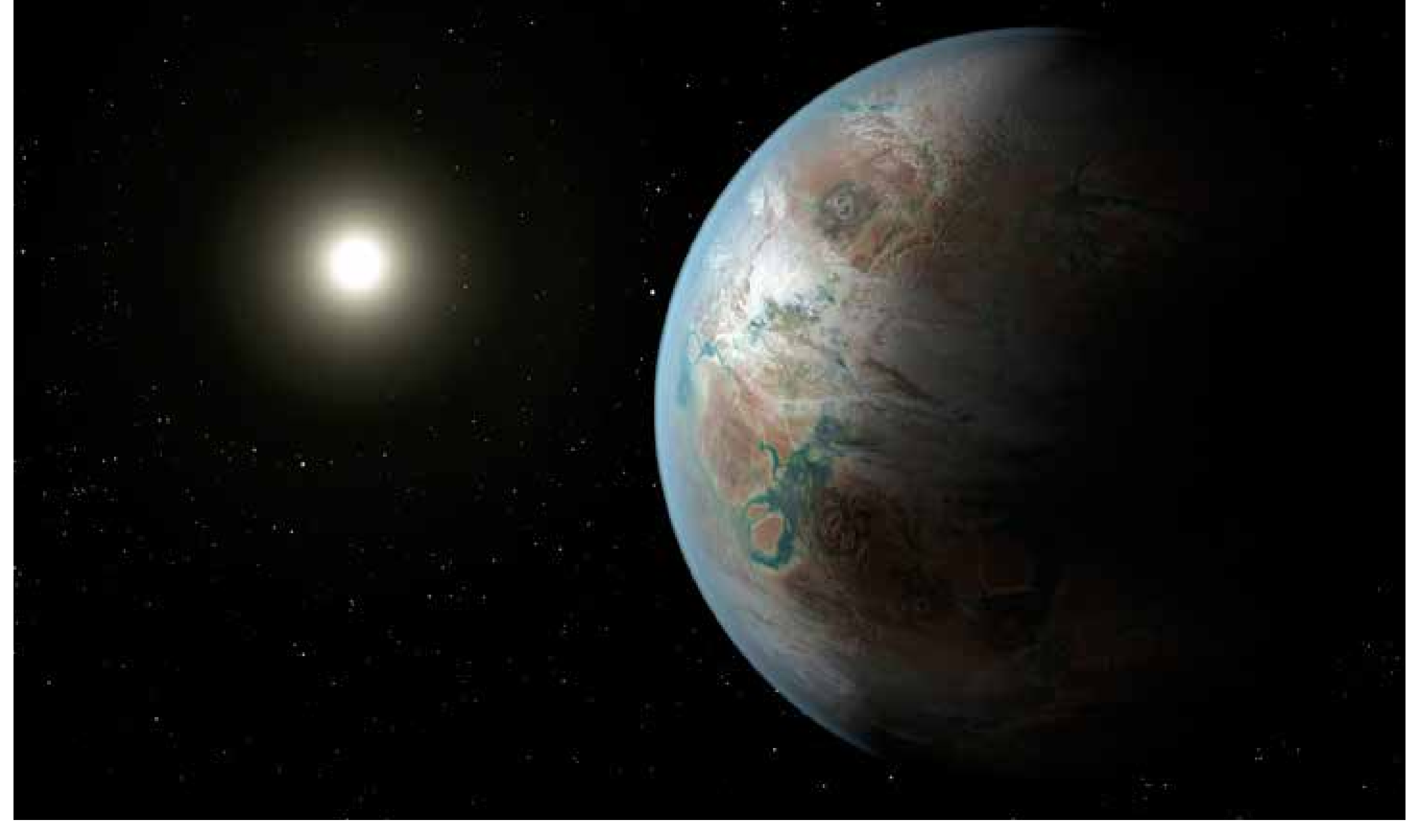
"After that point, we have to come to a stop," he says.

Scientists could continue to determine whether distant worlds were potentially habitable, but it would be hundreds or even thousands of years before we could gather direct evidence that life existed on planets beyond the solar system.

NASA's Kepler telescope has already helped to identify more than 4,000 new planets and planetary candidates, providing plenty of fresh targets for study. But while one of the primary goals of Kepler was to find the frequency of Earth-sized planets, it wasn't intended to classify them as Earth-like or Earth twins, according to Stephen Kane of San Francisco State University. Kane also serves as chair of NASA's Kepler Telescope Habitable Zone working group, which culls the data from Kepler to determine which potentially habitable planets should be studied in depth.

"It was never meant to be a characterizing mission," Kane says.

Other instruments will help to discover Earth-like planets. NASA's Transiting Exoplanet Survey Satellite and the European Space Agency's CHaracterising ExOPlanet Satellite, or CHEOPS, will both help astronomers find new planets around brighter stars. The James Webb Space Telescope will zoom in on the best candidates from these surveys and seek to classify their atmospheres, revealing more information about the distant worlds. It also will directly image the planets, providing further insight into understanding them. ESA's PLAnetary Transits and Oscillations of stars mission, or PLATO, will predominantly study terrestrial planets in the habitable zones of Sun-like stars.



In 2015, the latest batch of exoplanets from NASA's Kepler spacecraft were released. This rocky world, Kepler-452b, is thought to be much larger than Earth and orbiting a much older Sun-like star. NASA/JPL-CALTECH/T. PYLE

Each of these missions will help astronomers to understand more about the worlds beyond our solar system. With their help, Kane estimates identifying a true Earth analog by the late 2020s or 2030s.

Have we been there, done that?

If scientists can't identify more than the size and location of a planet, then why are phrases such as Earth twin and Earth-like so often heard? One reason has to do with the name itself, which could be considered misrepresentative.

"When you talk about the habitable zone, a person very naturally thinks you are talking about a zone in which everything is habitable," Kane says.

But this isn't the case, thanks to the numerous ingredients that factor into making a planet habitable. Some of those also can be misleading.

"We shouldn't say Earth-like," Kasting says. "We should say, 'a probable rocky planet in the habitable zone.'"

American astronomer Harlow Shapley originally called the region the "liquid water belt," possibly a more apt name, in 1938. Even that could be misunderstood as a region where liquid water definitely exists, instead of having the potential to. And many astronomers agree that changing the name would be unlikely to solve the problem. "The issue of communication is to be solved by educating people," Mendez says. "Many terms are confusing at the beginning."

In their impatience, people look only toward that distant answer, and miss what could be learned with what we have today.

But Kane feels the issue goes even deeper than that. The explosion of new planets in the last two decades has led to what some have termed exoplanet fatigue. New exoplanets excite little interest unless they are dramatic. As a result, scientists and the media may sometimes feel the need to stress unusual potential characteristics over what is actually known.

The field of exoplanets is young compared to astronomy as a whole, and continues to grow.

"People want to know the final question," Kane says.

They want to know if worlds beyond Earth could house life, if planets beyond the solar system could nourish civilizations. In their impatience, people look only toward that distant answer, and miss what could be learned with what we have today.

"It's better to understand that is the final question, and along the way to answer many others," Kane says.

Each new exoplanet offers the opportunity to learn more about how planets — including Earth — form, or how solar systems work.

By focusing primarily on the habitability of a planet, Kane says they're "trying to scoop the real discovery that will be made at least 10 years from now."

"One day, we will measure the atmosphere of a terrestrial planet that models will show is unambiguously habitable," Kane says. "I hate that the reaction will be, 'didn't we already do that 10 years ago?'"