ORBITING A RED DWARF, this imagined planet has its own moon. Both are bathed in a warm glow from the star and its flares.

PLANETARY SCIENCE

SHADOWS OF OTHER

Two telescopes due to launch this year should reveal a host of new exoplanets

By Joshua N. Winn

Illustrations by Ron Miller

WORLDS

IN BRIEF

The world's most prolific planet-hunting satellite, NASA's Kepler spacecraft, is preparing to shut down, but several new missions targeting exoplanets are due to launch this year.

The Transiting Exoplanet Survey Satellite (TESS) and the Characterising Exoplanet Satellite (CHEOPS) will both search for signs of other worlds crossing in front of their parent stars.

Scientists stand to add many more exoplanets to the growing tally, which should help them get closer to answering two questions: Are there other habitable worlds out there, and is there life beyond Earth in the universe?

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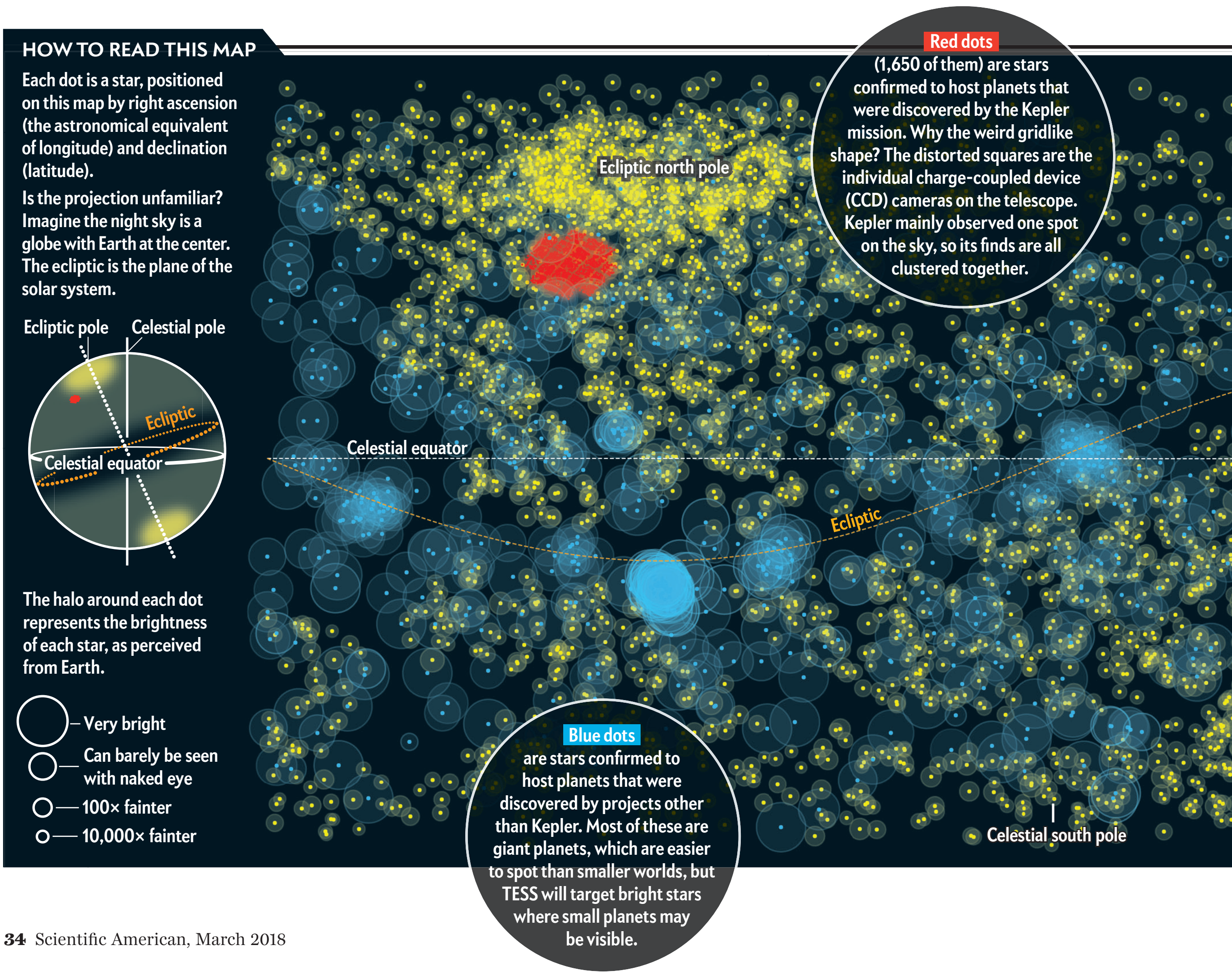
ON THE MORNING OF AUGUST 21, 2017, IN A GRASSY FIELD IN MIDVALE, IDAHO, MY FAMILY AND I WAITED WITH great anticipation. In a few minutes we would be enveloped by the moon's shadow. Along with millions of other people who had made their way to a narrow strip of land extending from Oregon to South Carolina, we were about to see a total eclipse of the sun.

Afterward I wondered how many budding young astronomers had been created at that moment, captivated by the eerie daytime twilight and the rare view of the sun's white-hot corona. Eclipses have been a source of inspiration and knowledge for centuries and still are. My own research relies not on solar eclipses but on a different type of eclipse entirely: the "transit" of an exoplanet. Although telescopes cannot actually watch a planet's silhouette move across the face of its star when that star is light-years away, the tiny dip in brightness that occurs when a planet is blocking a small portion of its star's light is enough to tell us that an alien world exists.

Astronomers detected the first exoplanetary transit in 1999. Within a decade the tally exceeded 100. Now we are up to nearly 4,000 transiting exoplanets, thanks mainly to a NASA mission called Kepler, which is due to end this year. Although the transit method is currently our most effective way of finding distant worlds, other planet-hunting techniques have turned up more than 700 exoplanets. All told, we have found a huge diversity of



worlds unanticipated by any planet-formation theories, and we suspect we are just skimming the surface of a vast ocean.

This year both NASA and the European Space Agency (ESA) are planning to launch new telescopes devoted to transiting planets. Meanwhile innovative telescopes at mountaintop observatories are extending the search to types of stars that the space missions will not explore. And all this will merely whet the appetite for the ultimate eclipse-detecting spacecraft that ESA intends to launch in 2026.

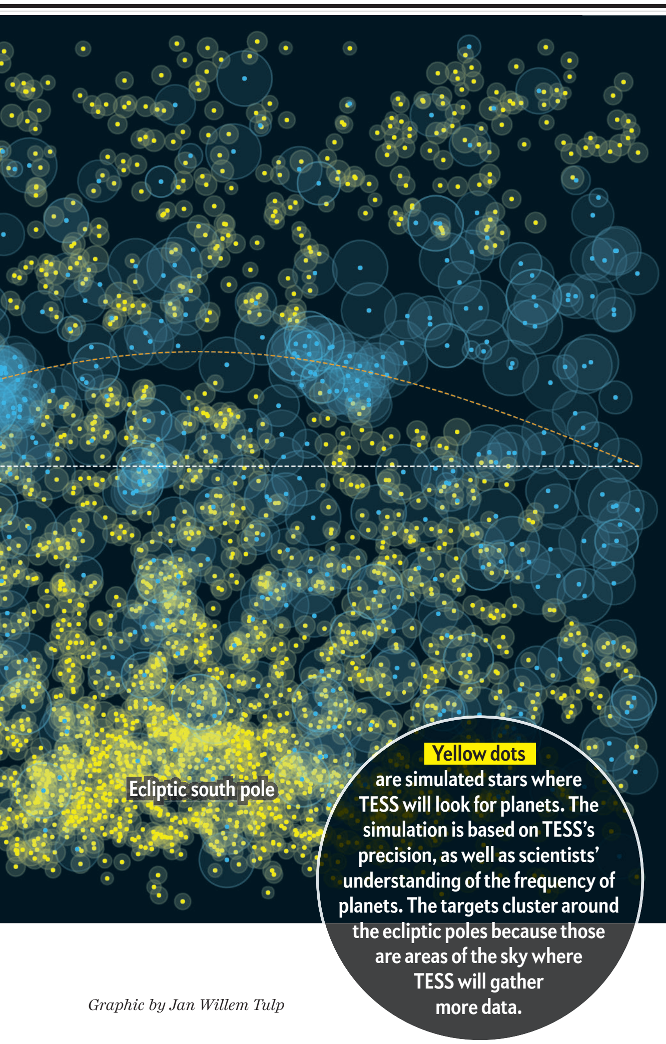
THE LANDSCAPE SO FAR

A LARGE FRACTION of what we now know about exoplanets comes from Kepler. After its launch in 2009, the telescope orbited the sun and stared unblinkingly at a patch of the sky straddling the constellations of Cygnus and Lyra, monitoring the brightness of about 150,000 stars. In 2013 the scope embarked on a modified plan following the failure of two of its reaction wheels, which keep the observatory pointed in the right direction, but amazingly it has been able to continue racking up planet finds.

This is despite the fact that eclipses are rare. Kepler found evidence for planetary eclipses in only a few percent of the stars it searched, in the form of brief and periodic decreases in brightness. Each sequence of dips betrays the existence of a planet whose orbit happens to be aligned nearly perfectly with our line of sight, causing a tiny partial eclipse each time it comes around. The fractional loss of light tells us the area of the planet's silhouette, relative to the star's cross section. Therefore, bigger bodies are much easier to detect: viewed from afar, for instance, Jupiter transiting the sun would produce a 1 percent dip, whereas the loss of light during an eclipse by Earth would be a mere 0.01 percent. No one has figured out how to measure such a minute signal with a telescope on Earth's surface; our atmosphere scrambles the starlight too much. Thus, we need space telescopes.

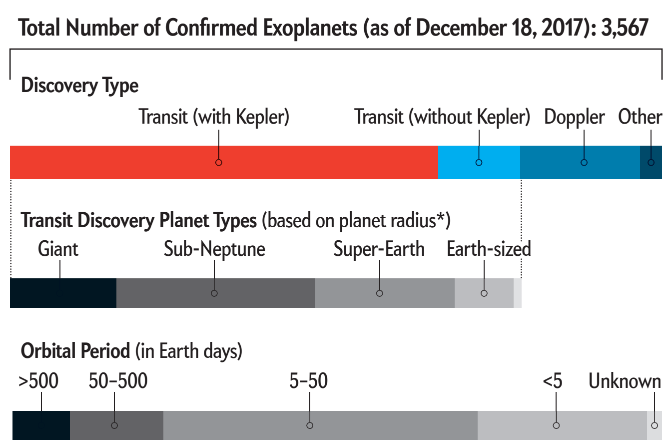
Kepler found nearly 5,000 candidate planets, with more than 3,500 of those so far confirmed through follow-up analysis as actual planets. Most of the Kepler planets fall into two categories: those roughly Earth-sized or a bit bigger ("super Earths") and those somewhat smaller than our eighth planet ("mini Neptunes"). The majority of planetary systems Kepler found have only one known planet, but hundreds of them have several planets, and one recently discovered system has eight, matching the solar system. These numbers reflect Kepler's own observational biases—its greater ability to more easily spot larger planets orbiting closer in to their stars—as well as the overall landscape of planets.

Some of Kepler's findings have been truly surprising. Its most far-reaching discovery, for instance, is in my view the existence of miniature solar systems. These have as many as six planets crowded around a star with orbits even smaller than Mercury's around the sun. What makes them so important is that they are common. If you point to a random sunlike star in the night sky, it turns out there is a 50 percent chance it has at least one plan-



Exoplanet Census

Exoplanet science began to take off in the mid-1990s; since then, astronomers have compiled a catalog that now includes more than 3,500 planets orbiting other stars. Yet these are just a small fraction of the planets likely to exist out there. Most of the discoveries so far have come from NASA's Kepler telescope, which will end its mission soon. Picking up the slack will be two new space observatories, NASA's Transiting Exoplanet Survey Satellite (TESS) and the European Characterising Exoplanet Satellite (CHEOPS), both due to launch in 2018.



*We show the planet categories adopted by the TESS mission, but these categories are somewhat arbitrary, and other groups use different definitions for each planet type.

Graphic by Jan Willem Tulp

NASA EXOPLANET ARCHIVE (*known host stars*); "PLANET DETECTION SIMULATIONS FOR SEVERAL POSSIBLE TESS EXTENDED MISSIONS," BY L. G. BOUMA ET AL. PREPRINT SUBMITTED TO ARXIV.ORG ON MAY 24, 2017 (*TESS targets*) et larger than Earth that orbits the star closer than Mercury orbits the sun. No one had foreseen that such planets would be common; in fact, some of the most detailed theories had predicted they would be especially rare. Something fundamental is missing from the standard theory of planet formation.

Kepler also found some rare and freakish planets that *had* been predicted—by science-fiction authors. One of my favorites is KOI 1843.03, an Earth-sized planet so close to its star that its dayside must be thousands of degrees. Its surface is probably covered by oceans of magma, not entirely unlike the imaginary *Star Wars* planet Mustafar, the site of Obi-Wan and Anakin's climactic lightsaber duel. The orbit of KOI 1843.03 is so tiny that it takes only 4.25 hours to make a full revolution, about the same time it takes to watch *Star Wars: Episode III* and all the bonus features. Meanwhile Kepler-16b resembles Luke Skywalker's home planet Tatooine: it has two suns in its sky. Its orbit surrounds a pair of binary stars that are themselves orbiting each other.

Then there is Kepler-36, where two planets share practically the same orbit, causing them to interact chaotically. Even if we knew the current positions of the planets to within one meter, we would not be able to predict their locations a few decades from now—it is a planetary version of the "butterfly effect." Here on Earth, the scientific revolution began with an understanding of planetary motion. Imagine how much harder that would be for any scientists in the Kepler-36 system!

Kepler was originally designed to answer the age-old question: How common, or rare, are Earth-like planets? By this term, most astronomers mean a planet of similar size and mass to Earth that could plausibly have oceans of liquid water. Such a planet must be located within the area around its star where the star's heat would be strong enough to melt water ice but not vaporize it. Scientists call this range of distances the "habitable zone" because they think that liquid water was essential for getting life started on Earth, and perhaps this is the case elsewhere.

Kepler found about a dozen potentially rocky planets in the habitable zone, bringing us right to the threshold of answering the question. Now all we need to do is divide by the number of stars that Kepler searched to calculate the percentage of stars with Earth-like planets, right? It sounds simple. In practice, the calculation is extraordinarily complex. It is not obvious how many stars that Kepler looked at were small, bright and stable enough for the telescope to have been capable of detecting Earth-like planets around them. Figuring this out will require another year or so to scrutinize the data and establish the properties of the stars.

A LARGER WINDOW

AS MUCH AS WE LOVE KEPLER, the mission had a major limitation. The telescope mainly pointed in one direction and viewed only 1/400th of the sky. As a result, Kepler had to look far away in that direction to monitor a large enough sample of stars to make the survey worthwhile. The typical Kepler star is at a distance of thousands of light-years.

Now, like any astronomer, I enjoy dazzling audiences with tales of distant objects, quadrillions of kilometers away. But from a practical perspective, far away is bad. Distant stars are faint and send only a trickle of photons to our telescopes. This faintness limits the precision of our data and renders some measurements impossible. For example, we cannot measure the masses of most of the Kepler planets. The transit signal tells us a planet's diameter but not its mass. This gap leaves us wondering what kind of planet we are dealing with. Is it dense and rocky, like Earth? Is it diffuse and gaseous, similar to Jupiter and Saturn? Or somewhere in between? Only with both the diameter and the mass can we tell.

The usual way to determine a planet's mass is to measure the star's acceleration in response to the planet's gravitational force: the more massive the planet, the more the star gets pulled around. We track the star's motion using the Doppler shift, the small shift in the wavelength of a star's light caused by its motion toward or away from us. (This method also sometimes lets us discover previously unknown planets because we can spot a star's telltale wobble even if the planet does not eclipse.) The technique requires high-resolution spectroscopy: we need to spread out the starlight into a rainbow and measure its intensity at a minimum of about 50,000 different wavelengths. For faint stars, though, there is not enough light to spread out so thinly.

NASA's next mission, the Transiting Exoplanet Survey Satellite (TESS), for which I am a co-investigator, aims to solve that problem. Onboard will be four telescopes, each 10 centimeters across, only a 10th the size of Kepler's telescope. This setup might seem strange—usually the direction of progress is toward larger telescopes, not smaller ones. But the advantage of a smaller telescope is a wider field of view; this reciprocal relation between collecting area and field of view is baked into the fundamental laws of optics. Each TESS camera sees nearly six times as much of the sky as Kepler did, and in addition TESS will rotate to peer in different celestial directions. Ultimately TESS should be able to observe many, many more bright stars than those few that happened to lie in Kepler's small field of view.

TESS is scheduled to launch between March and June of this year. For the next two years TESS will scan about 90 percent of the sky by dividing it up into 26 partially overlapping sectors and monitoring each sector for about one month. Like Kepler, we expect that TESS will discover thousands of planets, but they will be around stars that are typically 30 times brighter. This brightness will be a boon when we use ground-based telescopes to follow up on TESS discoveries—it will seem as if the light-collecting power of those telescopes had been boosted by a factor of 30 compared with their ability to follow up on Kepler finds.

And not far behind TESS is a European space mission, the Characterising Exoplanet Satellite (CHEOPS), scheduled for launch by the end of 2018. CHEOPS has a single telescope with a 32-centimeter diameter that will be used for a different and complementary mission. Whereas TESS will scan broad swaths of the sky in a methodical and predetermined pattern, CHEOPS will point at individual stars for which there is already some evidence for a planet and collect better data.

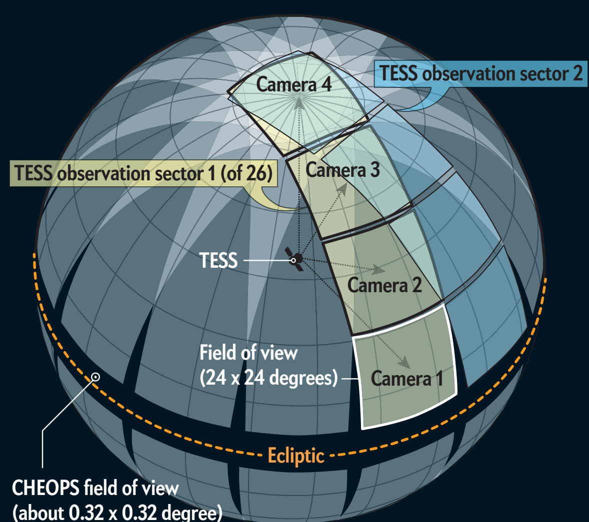
For example, TESS might find suggestive evidence for an interesting planet but with questionable statistical significance. In that case, I or one of my fellow TESS scientists will pick up the red phone hotline connecting us with the CHEOPS team to ask if they can get a better look. Or consider Proxima Centauri and Ross 128, two nearby stars for which the Doppler technique has provided evidence that Earth-mass planets are tugging them around. CHEOPS will be able to check for eclipses by these and other planets. The telescope will still require some good luck because the probability that we are viewing the orbit from the right direction is small; for Proxima Centauri, it is only 1.4 per-

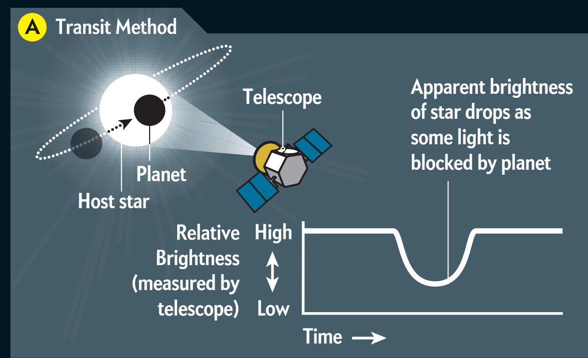
Searching for Planets

Astronomers' best tool for finding exoplanets around other stars—the Kepler Space Telescope—will soon be wrapping up its mission. In its place, two new observatories dedicated to planet hunting are due to launch in 2018: the Transiting Exoplanet Survey Satellite (TESS) and the Characterising Exoplanet Satellite (CHEOPS).

OBSERVING PLAN

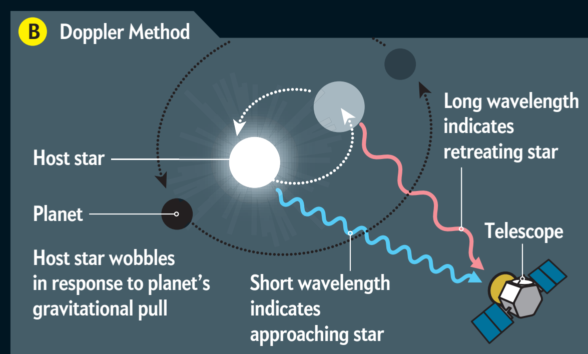
Although Kepler searches for planets in a small area of sky, TESS will be able to canvas about 90 percent of the celestial sphere. The telescope's four cameras will give it a large field of view covering 24 by 96 degrees. It will divide the sky up into 26 overlapping observation sectors and spend a month viewing each one. CHEOPS, in contrast, will study individual stars that astronomers already suspect harbor worlds to check for eclipses and to obtain better data.





HOW TO FIND PLANETS

The Kepler, TESS and CHEOPS telescopes use a technique called the transit method to identify worlds around other stars (A). When planets move in front of their star from Earth's perspective, they block a bit of starlight, causing the star to dim. Through this dimming, astronomers can identify planets that are too faint to see on their own. A second technique, the wobble method (B), looks for stars that sway instead of dim. If Doppler shifting shows that a star moves back and forth in a regular pattern, a planet's gravitational pull must be tugging the star in and out as it orbits around. This technique does not require the star and planet to be lined up from Earth's perspective, as the transit method does.



cent. But if we do hit the jackpot, we will be able to learn much more about those planets than we otherwise could.

LITTLE STARS

THESE NEW TOOLS will take us to the next frontier of planet hunting, but they still have their drawbacks. To be sure that a star's dimming is caused by a passing body, as opposed to an instrumental glitch, scientists like to see it repeat at least once and preferably many more times. TESS, however, will gaze at any given star for only one month—not nearly long enough to see multiple transits from planets such as Earth that take a year to orbit their stars. For a few percent of the sky, where all TESS's observing sectors overlap, it will look for as long as a year—but even that span is much shorter than Kepler's four-year staring contest.

As a result, TESS will largely be limited to finding planets that orbit very quickly, in a few weeks or less—not ideal. This short duration was the main compromise that scientists made to fit the mission into a $228-million budget. We decided it was a good concession because Kepler taught us that a huge variety of planets exist in short-period orbits: lava worlds, low-density "puffball" planets, chaotically interacting planets, and even planets that are apparently disintegrating in the ferocious heat of their stars. TESS will find the nearest and most easily studied examples of these types of exotic planets. A truly Earth-like planet around a sunlike star, however, will have to wait.

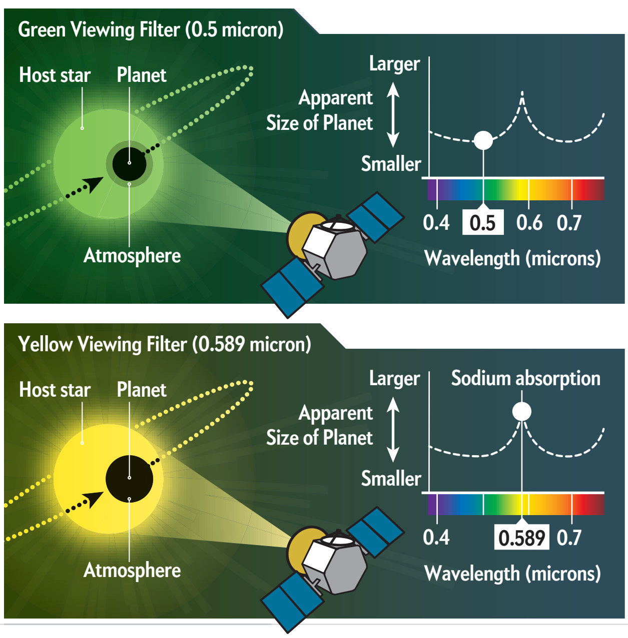
Nevertheless, TESS is an important part of the long-term quest for life on other planets. We predict that TESS will find about a dozen planets within the habitable zone, about as many as Kepler did. The trick is to stop being so insistent on a sunlike star. Astronomers like to refer to the sun as a completely ordinary star, just one of the hundreds of billions in the Milky Way galaxy. But this is a little white lie. Actually the sun is above average. Most stars in the galaxy are so-called red dwarfs, cooler and fainter stars with less than half the mass of the sun; if the sun were a spotlight on a Broadway stage, a red dwarf would be a candle.

You would need to stand awfully close to a candle to get the same warmth as you do from a spotlight. Consequently, the habitable zone of a red dwarf lies very close to the star, where the orbital periods are short. Conveniently short. For a red dwarf with a mass of a fifth that of the sun, any habitable zone planets

Illustration by Jen Christiansen

Peeking at Atmospheres

Beyond simply detecting the presence of exoplanets, transits sometimes tell scientists what their atmospheres are made of. When a planet eclipses its star, some starlight passes through the planet's atmosphere on its way to Earth. Every atom and molecule absorb and redirect specific wavelengths of light, depending on the energies of their electrons. By observing stars through colored filters and comparing which wavelengths come through when a planet is blocking the star and when it is off to the side, researchers can isolate the light signatures belonging to the planet.



would revolve around in just a few weeks, putting them within TESS's hunting ground.

Kepler looked at a few thousand red dwarfs and found that they are loaded with close-in planets, at an even higher rate than sunlike stars. Among the few hundred thousand TESS target stars are about 50,000 red dwarfs. Although they are dim, red dwarfs more than make up for it by being small, which allows planets to more easily block a large portion of their face when transiting, thereby delivering a noticeable dip in brightness to our telescopes. For instance, a planet would be equally detectable crossing in front of one star that was 16 times less bright as another star, as long as the first star had just half the radius of the second. In fact, planets in front of red dwarfs are so clear it is not even strictly necessary to use a space telescope to detect them.

For this reason, several projects are now under way at ground-based telescopes to hunt for planets around red dwarfs. Because these stars are faint, though, astronomers are using large telescopes, which will necessarily have a small field of view. They must monitor the stars one at a time, making this a low-efficiency, long-term enterprise. After years of searching, only three planetary systems have emerged from these efforts, but these three are among the most sensational discoveries in the field. One of them, TRAPPIST-1, was front-page news in early 2017. This minuscule planetary system has seven—yes, seven—Earth-sized planets packed tightly around an object of such low mass that it just barely qualifies as a star. At least two of the seven planets are in the star's habitable zone. (The name "TRAPPIST" is supposedly an acronym, but it is really one of the favorite beers of the Belgium-based principal investigator, Michaël Gillon, who has now christened a more ambitious project "SPECULOOS," after one of his favorite cookies.)

THE ROAD AHEAD

AFTER ALL THESE SPACE MISSIONS and ground-based projects, we will know the locations of thousands of transiting planets that have stars bright enough for detailed follow-up studies. We can look forward to measuring their masses, learning about planetary structure and getting more clues about the correct theory of planet formation. And if all goes well, we will have a growing collection of potentially habitable Earth-sized planets.

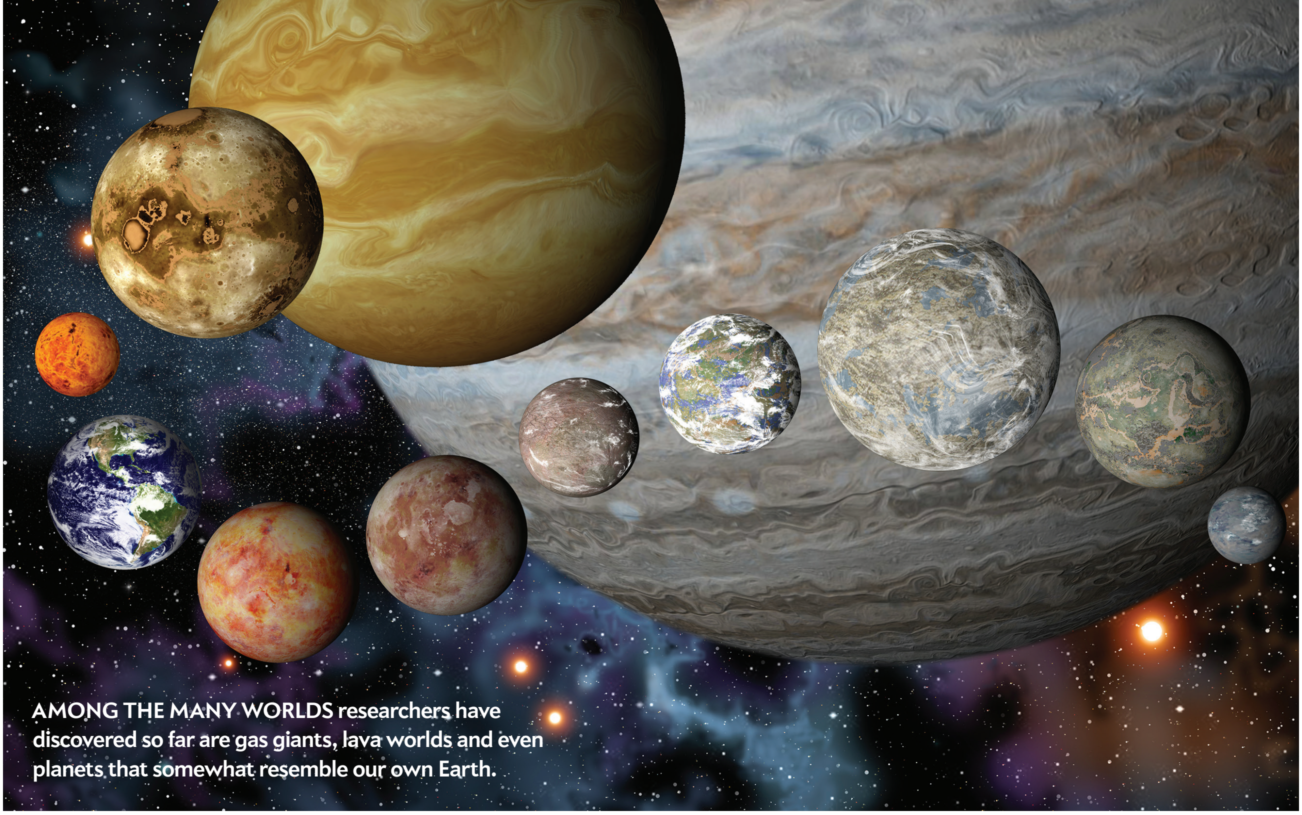
Then what? How can we take the next step and figure out if these potentially habitable planets are *inhabited?* The traditional approach, advocated since the 1950s, is to point a big radio telescope at the star and hope that we can tune in to the broadcast of any intelligent alien civilization. Though a valid plan, we have no idea if it will ever work.

Another approach is to analyze the planet's atmosphere for signs of life. We can do that by playing a transit trick. The outermost layers of a planet's atmosphere are translucent, so when the planet is in front of the star, a small portion of the starlight filters through the planet's atmosphere and makes it out the other side, where it continues on its way to our telescopes. We can then use the traditional technique of spectroscopy to probe the composition of the planet's atmosphere. Each atom or molecule has certain favorite wavelengths of light that it absorbs or deflects in other directions. This favoritism arises from the discrete set of energies that electrons have, according to quantum theory. Sodium, for instance, is fond of a particular shade of orange-yellow because the outer electron of a sodium atom can readily absorb light with a wavelength of 589 nanometers.

The trick, then, is to monitor the spectrum of the star before, during and after a transit. During the transit, the atoms and molecules in the planet's atmosphere remove starlight at their favorite wavelengths, slightly changing the observed spectrum of the star. Then after the transit is over, we see the ordinary, unaltered spectrum of the star once again. If we do this carefully enough, we can take the difference between the normal spectrum and the transit spectrum and isolate the tiny changes caused by the planet.

Astronomers have applied this technique to Jupiter-sized transiting planets and even a few Neptune- and Uranus-sized planets. It has turned up molecules such as methane, carbon monoxide and water in alien atmospheres. But we have never applied it to Earth-sized planets because their signals are so small, and the only stars we have found them around so far are too distant and faint. If we ever found oxygen in an exo-Earth atmosphere, that would get everyone's blood pumping. The reason Earth has so much oxygen in its atmosphere is because of

Illustration by Jen Christiansen



AMONG THE MANY WORLDS researchers have discovered so far are gas giants, lava worlds and even planets that somewhat resemble our own Earth.

life. If life on Earth suddenly disappeared, the rocks in Earth's crust would soak up all the oxygen to make oxides within a few million years. Thus, a planet with copious amounts of oxygen, the thinking goes, just might be home to Little Green Men—or at least some type of organism. The hope, then, is that the coming surveys will deliver Earth-sized planets around stars so bright that we will be able to interrogate their atmospheres.

In this sense, TESS, CHEOPS and SPECULOOS are acting as finderscopes for the next great observatory, the James Webb Space Telescope. This $10-billion spacecraft is scheduled to launch in 2019. Among many other things, this technological marvel will be by far the most powerful tool available for transit spectroscopy. But the Webb telescope has a planned lifetime of only five to 10 years before it runs out of the fuel it needs to maintain its orbit. This timetable creates some urgency to discover the best and brightest targets in the sky.

Because observing time on the Webb telescope will be in such high demand, some exoplanet astronomers have banded together to propose specialized space telescopes that will do nothing but transit spectroscopy. The American mission is called the Fast Infrared Exoplanet Spectroscopy Survey Explorer (FINESSE), and its European counterpart is the Atmospheric Remote-sensing Infrared Exoplanet Large-survey (ARIEL). The word "infrared" appears in both names because molecules such as water and carbon dioxide are easiest to spot at infrared wavelengths. In the next year or two we should know whether these missions are going forward.

Even further ahead are plans for a European spacecraft called PLATO, scheduled for launch in 2026. I think of PLATO as a super-TESS that will have 24 telescopes to scan the sky, instead of just four. PLATO should be able to search for planets with greater sensitivity and over a longer duration than telescopes before it.

And at least as important is that PLATO's data quality will be high enough to detect the brightness variations associated with a star's oscillations. It turns out that stars, like any fluid body, ripple with waves that are somewhat analogous to earthquakes, which is why their investigation goes by the name "asteroseismology." The frequencies and patterns of these oscillations depend on the internal structure of a star, such as its density and composition. When PLATO finds a planet, we will benefit from a deeper knowledge of the star's basic properties, including one that is currently hidden from us: its age. As time passes, oscillations reveal age because the nuclear furnace at the center of a star converts more and more hydrogen into helium, producing subtle changes in the frequencies of waves up at the surface. Through asteroseismology we can tell whether a star has just gotten started with fusion or has been at it for 10 billion years. We will be able to see how planetary systems evolve over cosmic time.

Between scientists' ongoing analysis of Kepler data and the forthcoming TESS, CHEOPS, Webb and PLATO missions, the planet-hunting agenda is full. We are poised to finally start diving into that limitless vat we have just begun to explore. And all those budding young astronomers who were dazzled by last summer's solar eclipse will have plenty of planetary eclipses to study when they grow up.

MORE TO EXPLORE

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