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THE ESSENTIAL GUIDE TO ASTRONOMY

MAY 2023

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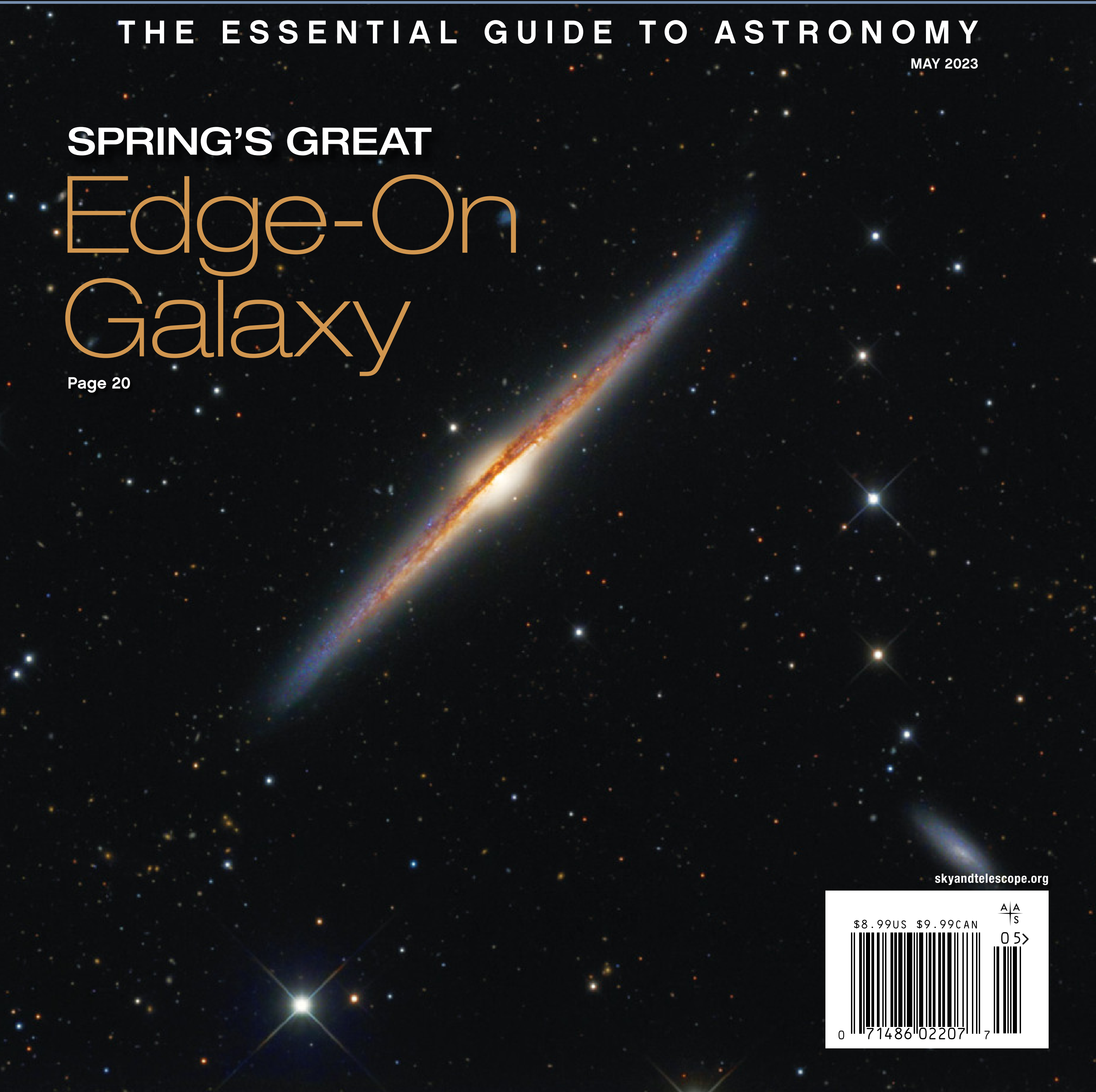

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 by Knicole Colón

Exoplanets EVERYWHERE

AWASH IN EXOPLANETS
The Southern Hemisphere sky, with candidate (orange) and confirmed (blue) exoplanet systems found by TESS, as of late 2022

NASA / MIT / TESS AND ETHAN KRUSE (UNIVERSITY OF MARYLAND, COLLEGE PARK)

The TESS space telescope is expanding our knowledge of exoplanets, helping us focus on those orbiting stars that are the smallest and closest to Earth.

Over the past few decades, there has been an exoplanet revolution. Thirty years ago, we only knew of a handful of planets outside our solar system. Today, we know of more than 5,000 of these distant worlds, with some similar in size to Earth and some orbiting stars like the Sun. A major player in this exoplanet revolution was NASA's Kepler space telescope, which was retired in 2018. More than 50% of all exoplanets discovered to date have come from searching through Kepler data.

But our planet-hunting days are far from over. NASA's Transiting Exoplanet Survey Satellite (TESS) launched in 2018 and quickly picked up where Kepler left off (*S&T:* Mar. 2018, p. 22). Its mission: to search the entire sky for the nearest exoplanets.

One of Kepler's main goals was to determine how common exoplanets are in our galaxy, the Milky Way. Kepler surveyed a single part of the sky for several years to search for exoplanets via the *transit method*, in which periodic dips in a star's brightness reveal a planet passing in front of that star. The exquisite data Kepler collected during this initial mission, which lasted from 2009 to 2013, showed us that exoplanets are indeed abundant in our galaxy. We can now say with confidence that there are more planets than stars in the galaxy and so, on average, every single star in the galaxy hosts at least one planet. Of course, this does not mean every star actually hosts a planet. Rather, some stars host no planets and some stars host multiple planets.

However, there is more to the story than simply counting how many exoplanets there are. We want to know what exoplanets are made of and what their atmospheres are like. To find that out, we need to take a close look at these worlds. But the systems Kepler surveyed predominantly orbit faint, distant stars — poor targets for detailed study.

This is where TESS comes in. TESS is the only space observatory capable of surveying the entire sky to discover many of the closest, most accessible exoplanets in the Milky Way. Because TESS discoveries are predominantly around small, bright, nearby stars, astronomers can readily use other observatories to follow up and determine the exoplanets' masses and the composition of their atmospheres. With its discoveries, TESS is thus moving us further along in our journey to determine what exoplanets are made of and whether there is any other planet out there like Earth.

The Story Behind TESS

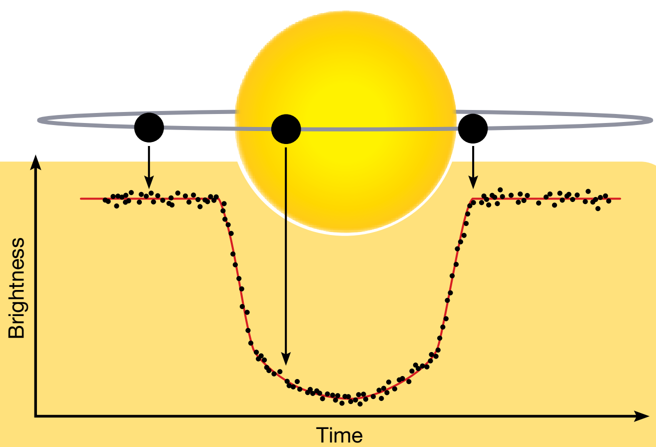
While TESS and Kepler both use the transit method to discover exoplanets in our galaxy, they differ in a few key ways. Kepler was a 0.95-meter telescope with a field of view about 12° wide, capable of detecting the change in brightness caused by an Earth-sized planet passing in front of a faint, distant, Sun-like star. In its primary mission, Kepler surveyed just one region of the sky for about four years. For another four and a half years after that, it stared at a series of patches of sky along the ecliptic plane as part of its "K2" mission.

TESS, on the other hand, has four CCD cameras each with 10.5-cm apertures that together cover an area of 24° by 96° on the sky — more than 20 times greater than Kepler's field of view. TESS's observations step around the sky every 27 days or so to produce a nearly all-sky survey over the course of two years. With these characteristics and approach, TESS is capable of detecting the change in brightness caused by Earth-size planets passing in front of bright, nearby stars similar in size to the Sun or smaller.

While TESS has relatively small camera apertures compared to Kepler's large mirror, it is very efficient. It observes millions of stars in order to find the kinds of systems we're looking for. TESS focuses on relatively small planets and small, bright, nearby stars for a few reasons. First, such

CANDIDATE VS. CONFIRMED

The process of discovering and confirming bona fide exoplanets is quite involved, which is why there are so many more candidate exoplanets compared with confirmed exoplanets. The confirmation of an exoplanet requires astronomers to determine with extremely high confidence that the only object that could be causing the tiny periodic dip in starlight is a planet. The alternatives include a binary star system, where one star eclipses another star periodically, or a false alarm, in which the "transit signal" is actually due to something like starspots or instrumental artifacts mucking up the data.



▲ **TRANSIT METHOD** When a planet passes in front of its star from our perspective, it blocks a small fraction of the star's light, which appears as a dip in starlight. The graph of how the star's brightness changes with time is called a light curve.

LEAH TISCIONE / *S&T*, SOURCE: NASA

planets and stars are common. Planets smaller than 4 Earth radii are the most common type of planet in our galaxy. Red dwarf stars — typically at most 60% the size and temperature of the Sun — are similarly the most abundant. Red dwarfs (also known as *M* dwarf stars) make up most of the nearest neighbors to our solar system (*S&T:* Jan. 2019, p. 34).

Second, it is generally easier to detect and study small planets around small stars with the transit method than around large stars, because what astronomers measure is the ratio of the size of the planet (and its atmosphere) relative to the size of the star. Correspondingly, it's more difficult to detect a small planet around a Sun-like star than it is around a red dwarf.

While Kepler has provided us with a bounty of small planets, the mission focused on Sun-like stars, and they for the most part lie far away from Earth. In fact, less than 1% of Kepler planetary systems are located within 200 light-years, a distance range well-suited for further follow-up.

WHAT'S IN A NAME?

TESS exoplanets have a variety of names, simply because there is no strict naming scheme employed by the mission team. TESS exoplanets typically receive a name that follows from an established star catalog, particularly for bright stars, e.g., Pi Mensae c. Otherwise, TESS targets are normally named as TOI-<insert number here>, where TOI stands for "TESS Object of Interest." This indicates the mission team flagged the object (star and planet) as a viable planetary system and assigned it a TOI number, e.g., TOI-257.01. Once a planet candidate is confirmed as a bona fide planet, we often change the number into a letter, in this case TOI-257b.

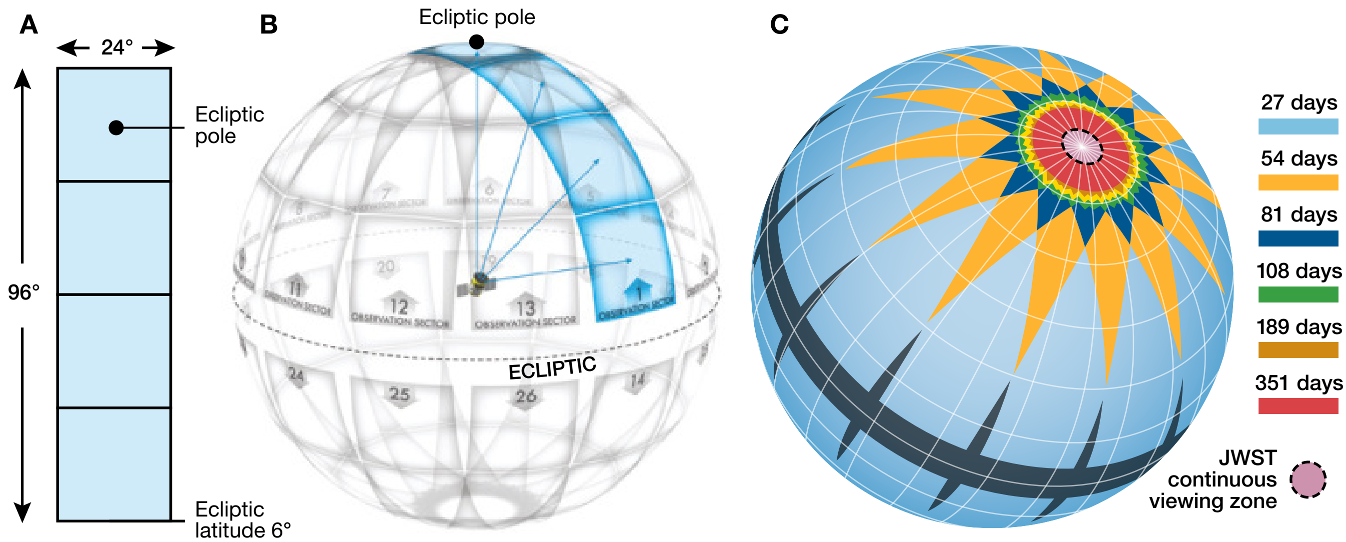
Small Exoplanets Close to Home

TESS has brought our focus closer to home. We've discovered 285 confirmed exoplanets to date, with more than 4,000 additional candidate exoplanets awaiting confirmation (see tipbox, page 35). At first glance, TESS's discoveries so far match the expectations that we had before launch. TESS was specifically designed to discover 50 planets with radii smaller than 4 times that of Earth whose masses we could then measure with ground-based observatories. We've far exceeded this goal, with 174 small planets discovered to date, 116 of which have measured masses.

Mass measurements are possible for so many TESS exoplanets because the worlds orbit relatively bright stars, in whose starlight we can more easily detect the tiny wobble caused by the planet's gravitational tug on the star. More than 70% of all TESS exoplanets are found around stars brighter than a visible magnitude of 12. In Kepler's case, just 8% of discoveries are around such bright stars. TESS planetary systems are also located relatively close to home, with 40% found within 200 light-years of Earth. And more than 20% of TESS exoplanets orbit red dwarfs, compared to just a few percent of Kepler exoplanets.

One of the first planets TESS discovered, Pi Mensae c, orbits a star bright enough that it can be seen with the naked eye — at least if you find yourself in a location with an extremely dark sky and you have pretty good vision to boot. While you can see the star Pi Mensae with your own eyes on a clear night, it is not possible to see the planet with the naked eye because it is only about twice the size of Earth and it orbits very close to its star, with a period of just over 6 days.

▼ **OBSERVING SECTORS** The combined field of view of TESS's four cameras spans a long, 24° × 96° strip of sky (A). Every 27 days or so, the spacecraft will observe a different strip of sky (B), slicing the celestial sphere into 26 sectors (13 per hemisphere). These sectors overlap near the ecliptic pole (C). The dashed circle around the pole shows the region that JWST can observe uninterrupted.



LEAH TISCIONE / *S&T*, SECTORS SOURCE: C. BEALS / MIT, COVERAGE MAP SOURCE: D. DEMING / TESS TEAM

Another planet, a gas giant on a much longer orbit discovered before TESS observed the system, also exists around this star.

The discovery of Pi Mensae c really opened the floodgates of what was to come from TESS. And flood it did! TESS has mostly discovered small planets that are within a few times the size of Earth, with around 50% of TESS exoplanets landing in a "super-Earth" or "mini-Neptune" category — a fraction roughly similar to previous discoveries, and contrary to what we see in the solar system. Super-Earth planets that are within about 80% of Earth's size are large enough that we cannot declare them to have rocky surfaces; instead, they may have a variety of compositions (*S&T:* Feb. 2022, p. 21). One of the expected compositions is that of a water world, which is just what TOI-1452b may be. This planet is approximately 70% larger and has about five times more mass than Earth. From the size and mass, astronomers can calculate the planet's density, which suggests it may have a very deep ocean.

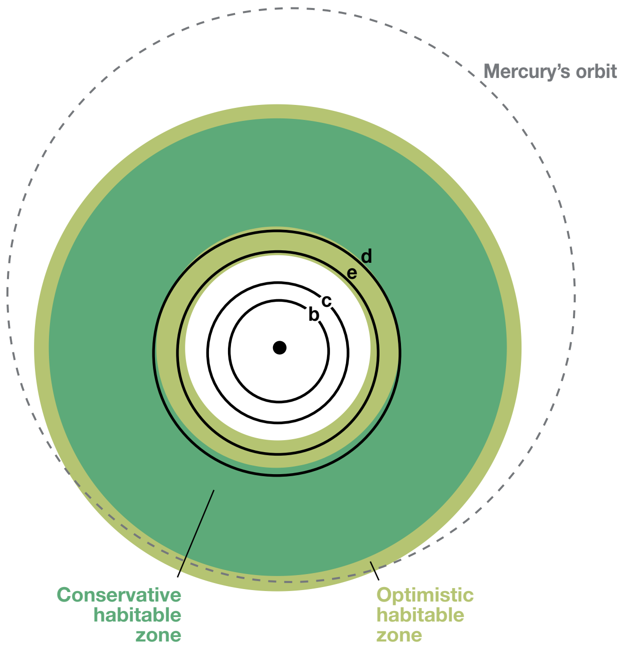
TESS is also making great strides in finding presumably rocky planets as small as (or smaller than!) Earth, with 11 such planets discovered so far. These include HD 21749c and L 98-59b. Both of these planets are quite a bit warmer than Earth, rendering them uninhabitable to life as we know it. However, TESS has found a few planets at the right distance from their stars such that, given the right atmosphere, the worlds might have temperatures similar to Earth and be able to sustain liquid water on their surfaces. TOI-700 d is a prime example of a TESS-discovered exoplanet found in the habitable zone of its star. The planet is also just 20% larger than Earth, making it more likely to have a rocky surface.

That said, even if TOI-700 d were just like Earth in size and temperature, that would not make it precisely Earth-like. One of the key differences is that TOI-700 d orbits a red dwarf — TOI-700 is approximately 40% of the Sun's size and about half as hot. In fact, the planet actually orbits around this cool star every 37 days, but it still has a temperature similar to Earth because the star is so much cooler than the Sun. Because red dwarfs are also typically more active than the Sun, planets like TOI-700 d on relatively short orbits will suffer from higher levels of radiation over their lifetime. Such radiation surely impacts the formation and evolution of life in ways we have not been able to fully explore yet (*S&T:* Dec. 2022, p. 34).

As exciting as it is to think about the prospects of finding potentially habitable planets, TESS was not designed to find perfectly Earth-like planets. And that is okay. TESS has clearly been enormously productive in its own right, finding plenty of small planets around small, bright, nearby stars.

Revealing New Secrets of Exoplanets

TESS is going well beyond its original mission goals and is making unexpected discoveries, too. We already knew from Kepler that the average exoplanet in the galaxy is around 2 to 3 times the size of Earth, and TESS has confirmed this trend extends to the worlds around cooler stars. However, a real



▲ **NOT QUITE EARTH-LIKE** The star TOI-700 has two planets in its habitable zone: d and a newly discovered planet, e (announced in January 2023). But because the star is a red dwarf, the habitable zone lies closer to the star than Mercury does to the Sun.

BEATRIZ INGLESSIS / *S&T*, SOURCE: NASA EXOPLANET CATALOG

surprise is that TESS has found more of these planets in tight orbits than predicted. This close-in region, where a planet only takes a few days to circle its star, is known as the "hot-Neptune" desert, because Kepler's discoveries had indicated that Neptune-size or smaller planets on close-in orbits were exceedingly rare.

Another surprise is that TESS is finding more giant planets than might be expected. Giant planets make up just 4% of the discoveries from Kepler. Yet, around 27% of TESS discoveries are roughly Jupiter-size or larger. Giant planets are common enough that astronomers discovered them with ground-based all-sky surveys long before Kepler launched, so it is not necessarily surprising that TESS's space-based all-sky survey would reveal additional giant planets as well as small planets. It does come as a surprise, however, that ground-based surveys did not already discover all the giant planets around bright stars in their scans of the sky. Notably, TESS is finding a population of giant planets around small stars (like TOI-1899b). We thought such a configuration would be rare, because it's difficult for the cloud that forms a small star to have enough material left over to make a big planet.

Together, these discoveries are further evidence that our solar system apparently has a rare architecture. Other ongoing searches for exoplanets around Sun-like stars will give us even more insight into just how unique our solar system is.

Clearly, by surveying the entire sky and observing millions of stars of all different types (from red dwarf to Sun-like to evolved stars), TESS is proving capable of discovering all kinds of planetary systems. A key example is its discovery of the Jupi-

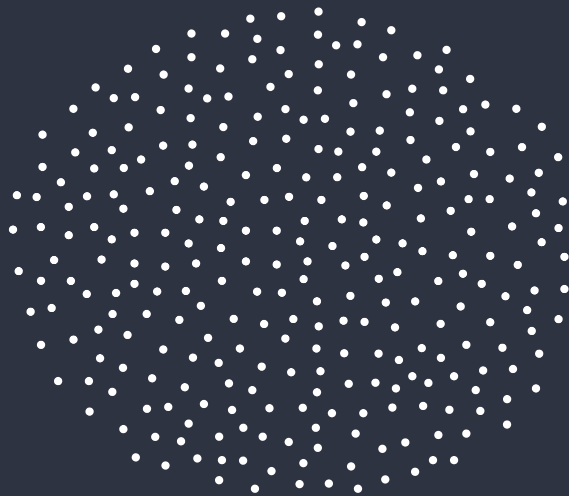
(continued on page 40)

TESS'S EXOPLANETS

Using TESS, astronomers have discovered 5% of all confirmed exoplanets. But for nearby terrestrial planets and planets around the smallest stars, its impact is much larger. (These numbers are for January 1, 2023.)

TESS
Total Number of Exoplanets Discovered

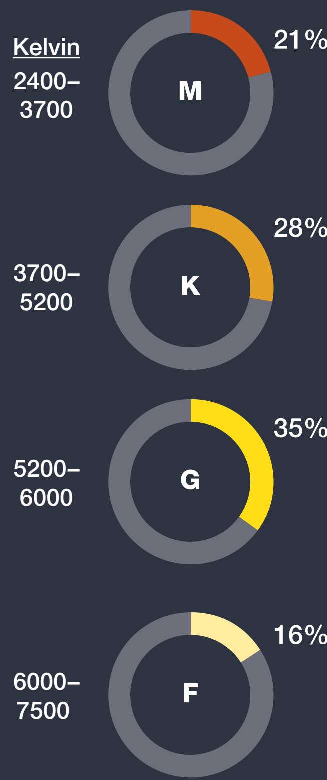
285



50%

Fraction of all known terrestrial planets within 200 light-years of Earth that were discovered by TESS

TESS STELLAR HOSTS BY TYPE*



*some stars have no published temperature

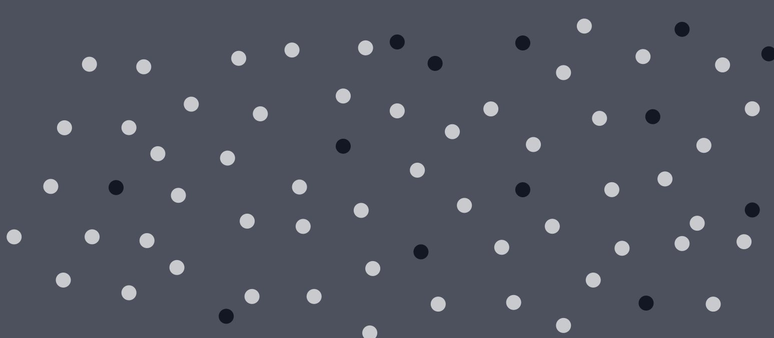
TESS PLANETS BY SIZE*

R_e = Earth radii
*some planets have no published radius

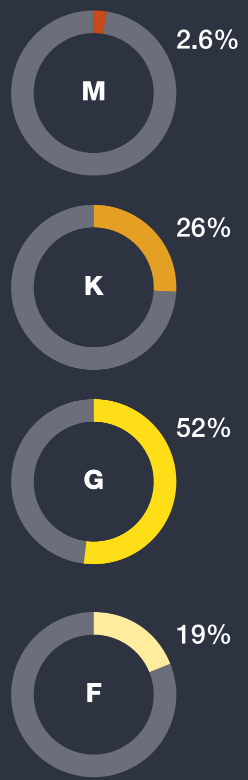
Mars 0.3–0.7 R_e
Earth 0.7–1.2 R_e
Super-Earth 1.2–1.9 R_e
Sub-Neptune 1.9–3.1 R_e

PLANETS DISCOVERED WITHIN 200 LIGHT-YEARS OF EARTH

TESS
Kepler



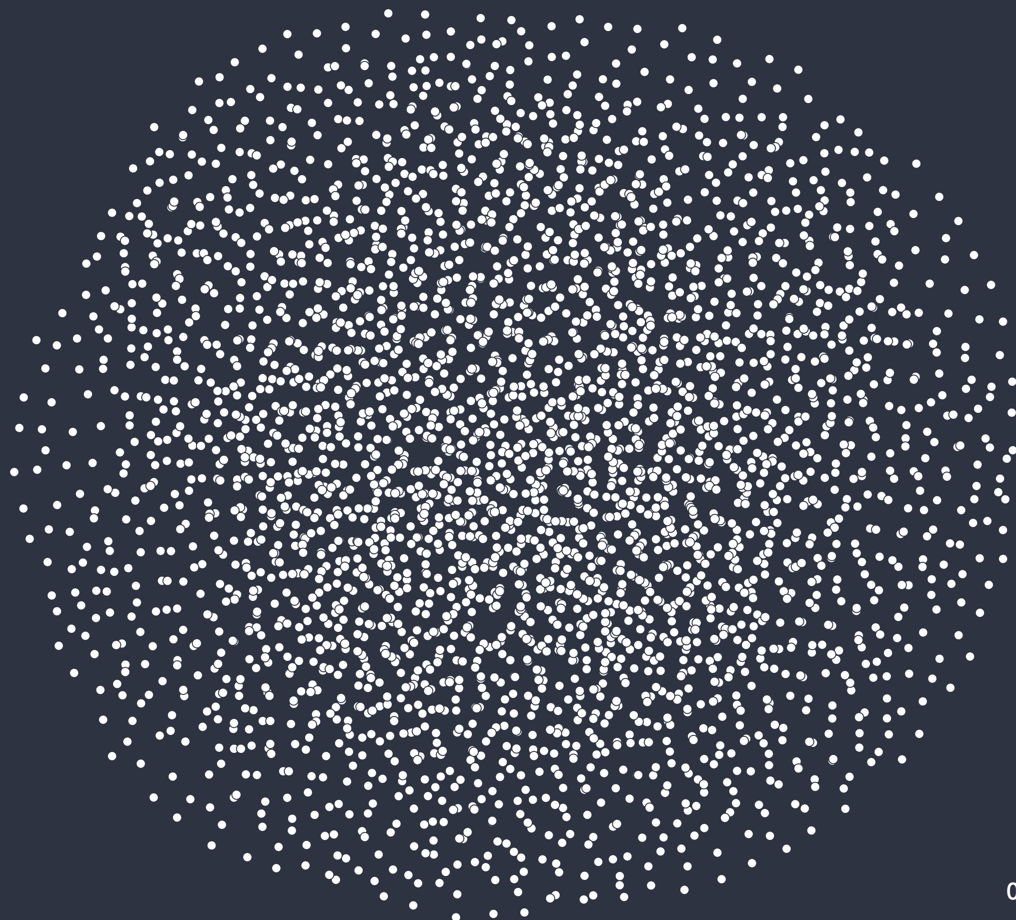
KEPLER STELLAR HOSTS BY TYPE



Kepler

Total Number of Exoplanets Discovered

3,253



KEPLER PLANETS BY SIZE

Neptune 3.1–5.1 R_e

Sub-Jupiter 5.1–8.3 R_e

Jupiter 8.3–13.7 R_e

Super-Jupiter 13.7–23.5 R_e

112
TESS

29
Kepler

INFOGRAPHIC: TERRI DUBÉ / S&T; EARTH ICON: MARTIN VANCO FROM NOUN PROJECT

(continued from page 37)
ter-size planet WD 1856+534b, found in orbit around a white dwarf star. This is the first intact exoplanet known to orbit a stellar remnant. Worlds are often destroyed once a Sun-like host star evolves to the red giant phase and sheds its outer layers, eventually leaving behind a dense white dwarf (*S&T:* Jan. 2023, p. 14). Finding an intact exoplanet that evidently survived this stage of stellar evolution requires us to revisit what we know about the life and death of planetary systems.

On the flip side, TESS is also finding newly formed planets around young stars like AU Microscopii. AU Mic is a nearby red dwarf that is only around 25 million years old (compared to the Sun's more mature 4.6 billion years). AU Mic has been an excellent laboratory for astronomers for years, since it is young enough that it still has a disk of gas and dust around it left over from its formation. Astronomers expected that young exoplanets would exist in this disk, given the presence of a gap between the inner disk and the central star. So far, TESS has found not one but two planets in this gap, a pleasant but not wholly unexpected surprise. Establishing the presence of exoplanets around young stars like AU Mic is critical for understanding the time scale over which planets can form around different types of stars.

But wait, there's more! TESS is finding planets on ultra-short-period orbits — like GJ 367b with an 8-hour orbit — and planets that orbit multiple stars, like TOI-1338b (*S&T:* July 2022, p. 34). These worlds highlight the intriguing diversity of exoplanet systems, greatly complementing results from other surveys. All of the individual and collective discoveries that TESS is making serve to fill gaps in our knowledge of exoplanets and how they form, evolve, and die.

What's Next for TESS?

The TESS prime mission formally ended in July 2020, at which point its extended mission began. With operations now continuing until at least 2025, TESS is continuing to survey the sky and observe as many stars as possible, covering a longer stretch of time that will enable us to discover additional exoplanets, particularly those with longer orbital periods.

A key goal for the TESS mission continues to be discovering exoplanets orbiting stars bright enough to enable the measurement of planetary masses and atmospheric compositions using other telescopes. Observers have measured masses with ground-based telescopes for nearly 80% of TESS exoplanets so far, compared to just 11% of Kepler exoplanets.

TESS discoveries are already making themselves known in the realm of atmospheric observations. Because many TESS exoplanets orbit small, bright, nearby stars, we have a vastly improved ability to detect the tiny amount of starlight that filters through these planets' atmospheres to reveal their compositions. TESS worlds make up nearly 37% of the transiting exoplanets that the James Webb Space Telescope (JWST) is observing in its first year of science operations. With JWST, we will search for evidence of water, carbon dioxide, methane, and other molecules in these planets' atmospheres.

CITIZEN SCIENTISTS

TESS discoveries are made possible largely thanks to the work of professional astronomers, but citizen scientists play a key role as well. Citizen scientists work on projects like Planet Hunters TESS (https://is.gd/zooniverse_tess), Exoplanet Watch (https://is.gd/exoplanetwatch), and UNITE (science.unistellaroptics.com) to find new signals that automated search algorithms cannot easily find in the data, and also to vet candidate exoplanet signals to verify their planetary nature. These programs take advantage of the fact that all TESS data are publicly available, enabling citizen scientists to contribute to the discovery of hundreds of TESS candidate exoplanets so far.

What we learn about the compositions will add another piece to the puzzle of how exoplanets form and evolve.

It was only a few decades ago that we had to rely on the imagination of astronomers and authors and filmmakers alike to picture what types of exoplanets might exist (if any). Now here we are today, knowing that exoplanets outnumber stars in our galaxy and, by extrapolation, in our universe. And thanks to TESS, science fiction keeps turning into fact with the variety of extrasolar worlds that we are discovering close to home. TESS is continuing to uncover new surprises along the way that reveal just how vast the exoplanet landscape is. With every discovery, we're changing our understanding of how planets form and evolve — and getting closer to answering the ultimate questions of what our place in the universe is and how we got here.

■ **KNICOLE COLÓN** is the TESS Project Scientist at NASA's Goddard Space Flight Center. She also has roles on JWST and the Pandora SmallSat and studies extreme exoplanets in her spare time.

FOUR EYES Artist's concept of TESS in space, showing its solar panels and four cameras

NASA GODDARD SPACE FLIGHT CENTER