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The Transiting Exoplanet Survey Satellite (TESS) uses four identical CCD cameras to methodically search nearly the entire sky for exoplanets circling bright, nearby stars. Its data are released to the public with no proprietary period, opening up the field of exoplanet discovery to anyone with an internet connection. NASA'S GODDARD SPACE FLIGHT CENTER

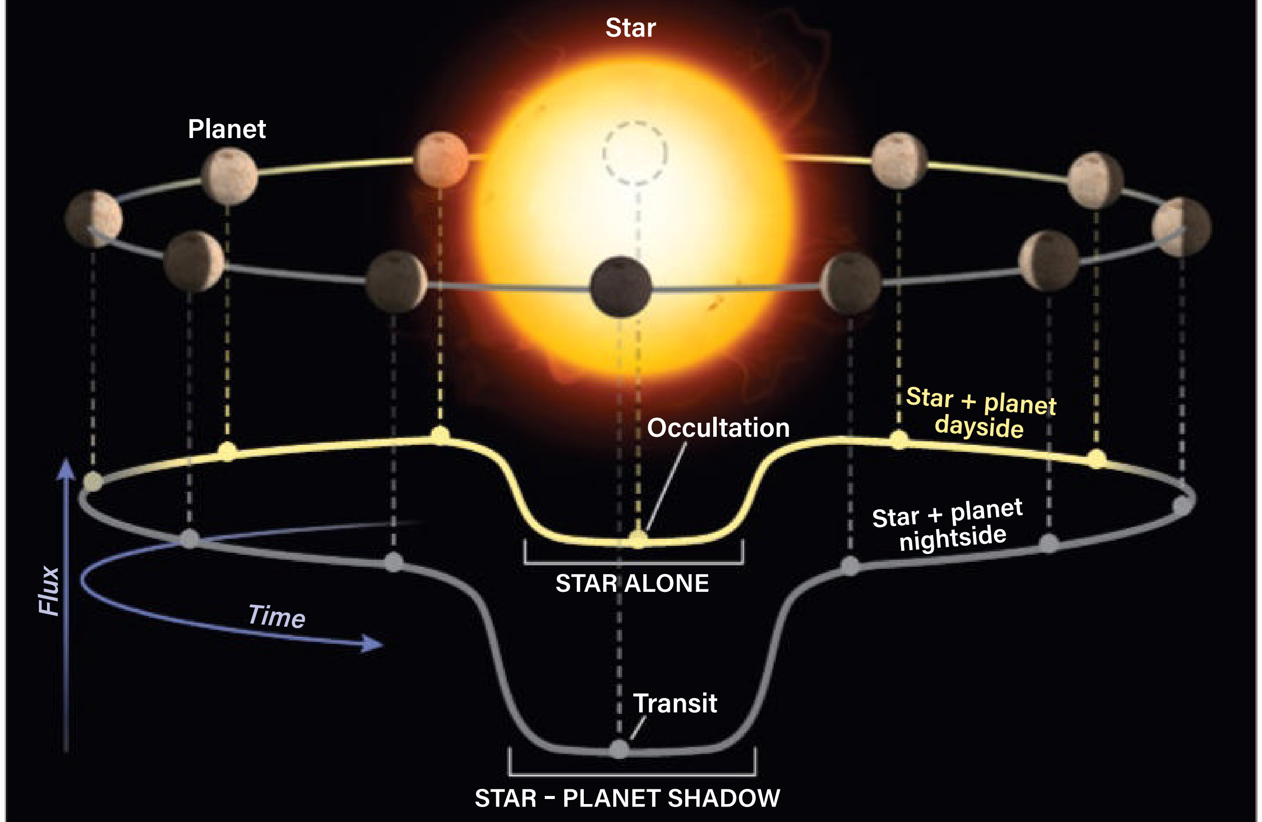
Inside the hunt for the NEAREST EXOPLANETS

TESS is revolutionizing our understanding of planets in the solar neighborhood. But finding new worlds is only the beginning.

BY GEORGE R. RICKER

IN 1995, astronomers discovered the first extrasolar planet orbiting a Sun-like star. Ten years later, exoplanet research remained in its infancy. Researchers still weren't sure whether planets circling other stars were plentiful or rare. So, members of my small satellite research group at MIT's Kavli Institute for Astrophysics and Space Research opened discussions with our neighbors at the Harvard-Smithsonian Center for Astrophysics (CfA). We pondered how we might repurpose the High Energy Transient Explorer-2 (HETE-2), which we had launched in 2000, to search for signals from extrasolar planets as they passed in front of their host stars.

WATCHING A PLANET TRANSIT



TESS identifies extrasolar planets by watching for dimming events associated with transits, which occur when a planet crosses the face of its host star as seen from Earth. The satellite is also sensitive enough to see occultations — when an orbiting planet passes behind its host star, slightly dimming the total light we receive. *ASTRONOMY*: ROEN KELLY

We knew that our MIT-built star trackers were capable of detecting changes of as little as 0.1 percent in a star's brightness. This level of precision would allow us to spot transits of close-in Jupiter-sized planets — so-called hot Jupiters — orbiting solar-type stars. So, in 2005, we proposed to NASA that HETE-2 be assigned a new task and a new name. Rechristened the Hot Exoplanet Transit Experiment-Survey (HETE-S), it would carry out a nearly all-sky survey for transiting hot Jupiters at low cost (approximately $2 million per year) for five years. Unfortunately, NASA declined our proposal, noting that the considerably more capable Kepler Space Telescope — a much larger, $600 million mission dedicated to finding exoplanets by watching them transit their host stars — would soon launch.

So, HETE-S never came to be. But from its conception was born the Transiting Exoplanet Survey Satellite (TESS). This mission is the result of more than a decade-long effort, with the primary goal of discovering transiting exoplanets in our solar neighborhood that are ripe for follow-up with the next generation of telescopes.

NASA EXPLORERS MISSIONS

NASA Explorer-class missions cover a range of scientific goals. Each class is characterized by a budget cap for total cost (in USD) to NASA that includes mission definition, development, operations, and data analysis.

Medium-Class Explorers (MIDEX)
MIDEX missions have a budget cap of $180 million to $200 million.

Small Explorers (SMEX)
SMEX missions are capped at a total cost of $120 million.

University-Class Explorers (UNEX)
UNEX missions are launched via low-cost methods and capped at a total cost of $15 million.

Missions of Opportunity (MO)
These are part of non-NASA space missions and capped at a total cost of less than $55 million to NASA. —*Alison Klesman*

TESS is born

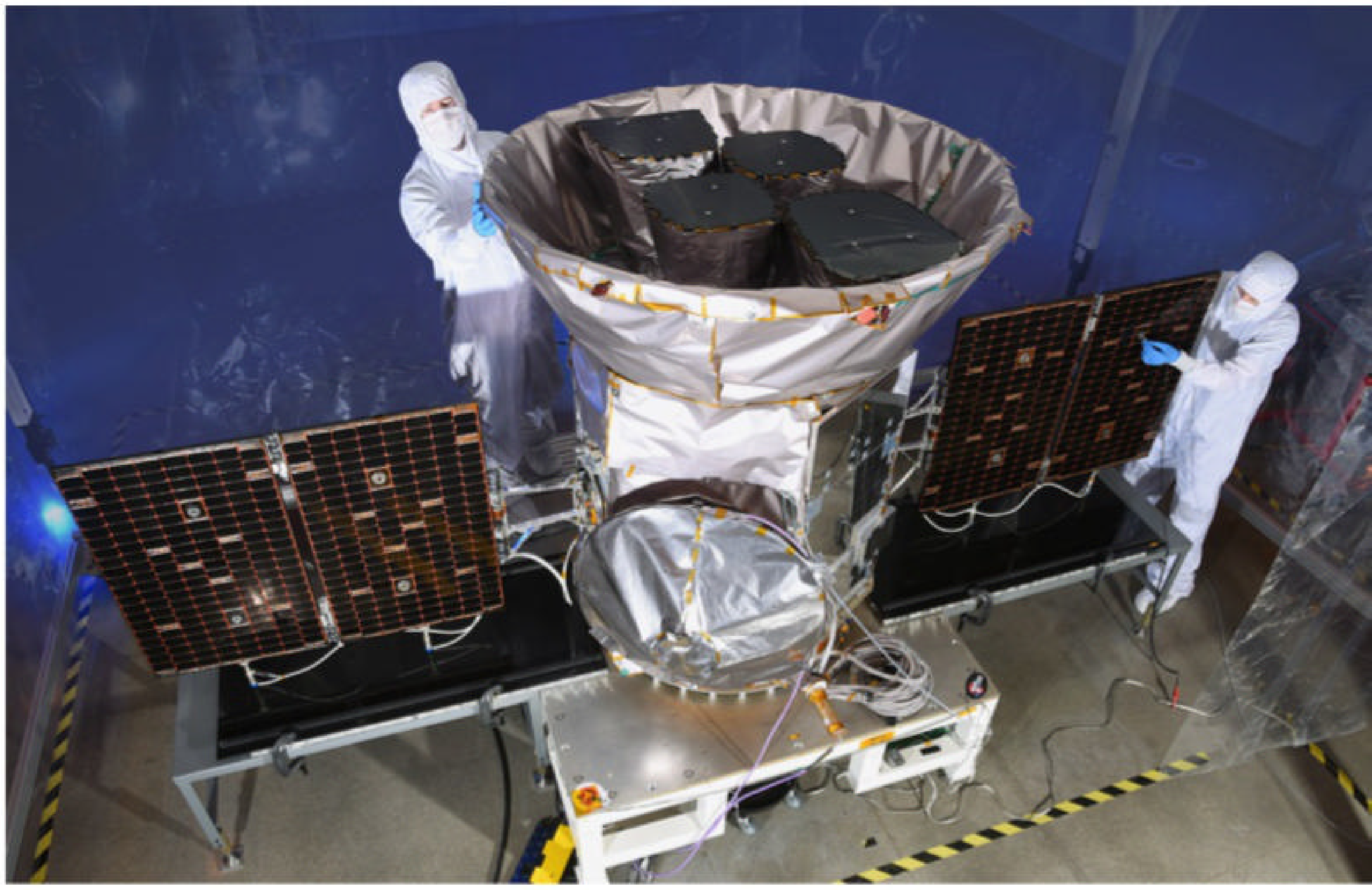
Although NASA rejected our proposal for HETE-S, we realized that a small satellite based upon HETE-2 and equipped with newer cameras could come in at a low enough cost for private funding. This new satellite, which we referred to as TESS-P (P for private), could carry out a shallow wide-field survey of the entire sky, complementing Kepler's 100-square-degree deep narrow-field search by covering a field 400 times greater.

During 2006 and 2007, the Kavli Foundation, the Smithsonian Astrophysical Observatory, Google, and a group of MIT departmental and private donors sought funding for TESS. Unfortunately, the Great Recession intervened and the majority of our prospective donors could no longer fund our plan.

Thus, when NASA announced an Astrophysics Small Explorer (SMEX) mission solicitation in 2008, we commenced work on our concept as a SMEX mission with only two months to go before the December proposal deadline. TESS survived as one of three mission proposals selected for a detailed Phase A study; unfortunately, it was not selected for flight following Phase A completion in 2009.

We immediately began planning for the next NASA solicitation, for which proposals were due in 2011. Yet again, NASA selected TESS for a year-long Phase A study, this time as a Medium-Class Explorer (MIDEX) mission. We were met with success: TESS was selected and funded as the MIDEX winner in April 2013!

A SpaceX Falcon 9 rocket carries TESS aloft from Cape Canaveral Air Force Station in Florida at 6:51 P.M. EDT on April 18, 2018. NASA/KSC



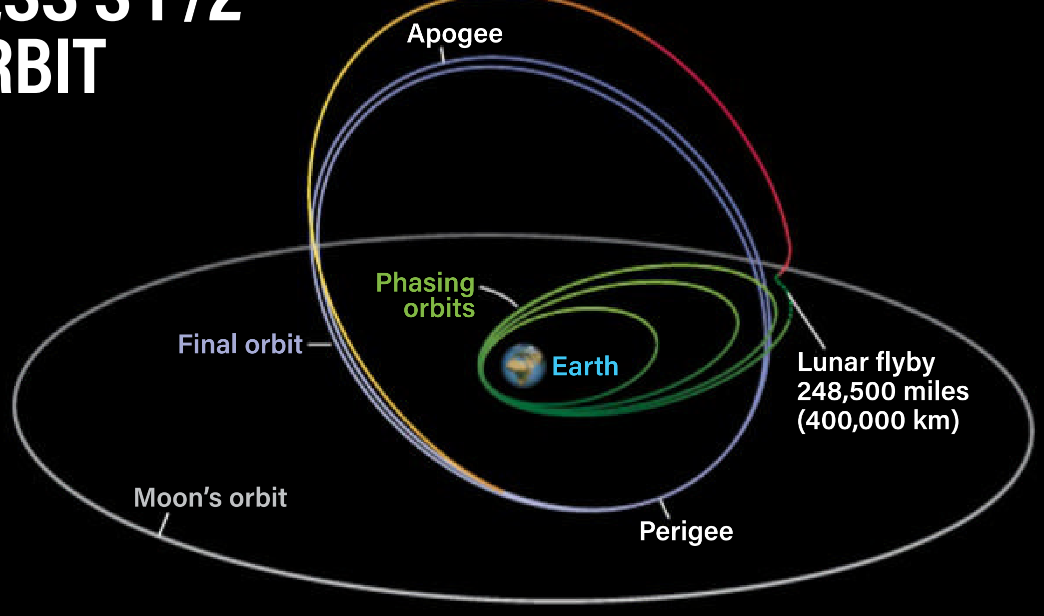
Each of TESS's CCD cameras, visible here as four cones with black covers at the top of the spacecraft, has a 24° by 24° field of view and functions as 64 million tiny light meters. Each pixel is 15 micrometers square. ORBITAL ATK

During the next five years, we assembled a highly skilled and dedicated team to design, build, fly, and extract scientific data from TESS. That team, which ultimately devoted more than a million hours to the effort, included members from MIT's Kavli Institute for Astrophysics and Space Research, MIT's Lincoln Laboratory, the Harvard-Smithsonian CfA, NASA's Goddard Space Flight Center and Ames Research Center, Orbital ATK (now part of Northrop Grumman), The Aerospace Corporation, Space Telescope Science Institute, and SpaceX. In addition, a science team comprising astronomers from more than a dozen universities worldwide collaborated to assemble the TESS observation program.

Getting a good view

TESS entered development in 2014 with the primary science goal of searching the entire sky for the best 1,000 small exoplanets within 200 light-years — i.e., the solar neighborhood. "Best" in this case means exoplanets with measurable masses, as well as atmospheres that can be studied with the upcoming James Webb Space Telescope (JWST). Essentially, TESS would be a finder scope for Webb, scouting for Earth-sized exoplanets orbiting the brightest Sun-like and smaller M-dwarf stars within about 200 light-years of our solar system. TESS would also serve as a bridge from the (now-defunct) Kepler mission to Webb, as well as other large exoplanet imaging space missions with launch dates in the 2030s and beyond.

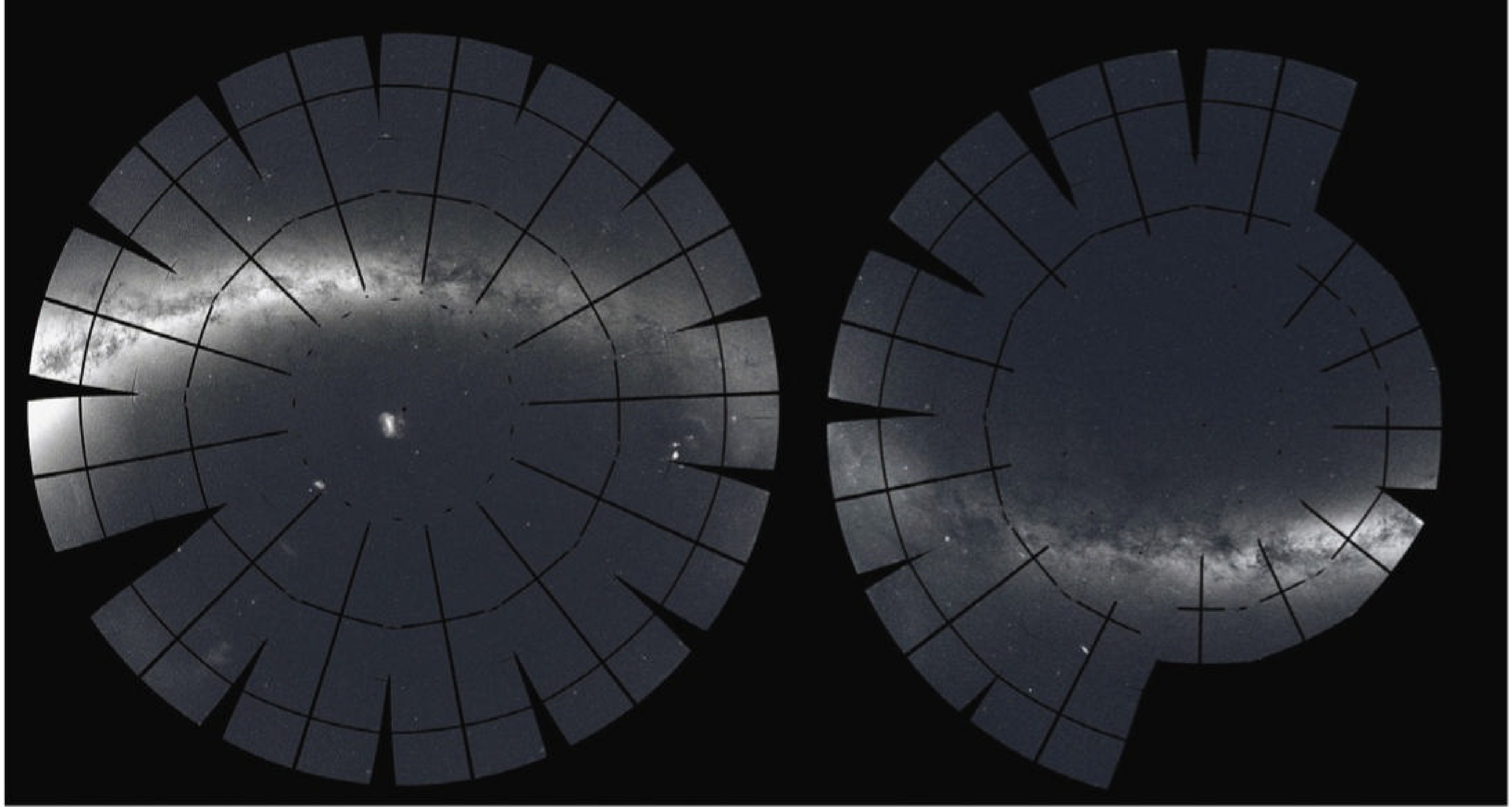
TESS'S P/2 ORBIT



TESS's unique 13.7-day orbit around Earth puts the satellite in a 2:1 resonance with the Moon, meaning the spacecraft completes two orbits for every one orbit of our Moon. During that time, TESS comes as close to Earth as 67,000 miles (107,800 km) at perigee and swings as far away as 232,000 miles (373,400 km) at apogee. To reach this orbit, TESS underwent a series of three transfer orbits and a lunar flyby, ultimately arriving in its final P/2 orbit 42 days after launch. *ASTRONOMY*: ROEN KELLY, AFTER RICKER ET AL. (2014)

The most critical bit of mission planning was selecting an orbit for TESS that would provide a view free of obstacles — namely, Earth. TESS needed to continuously monitor a huge field of view (more than 2,000 square degrees) for weeks at a time. In order to find planets, it would need to see at least two or three transits — and a transit of a small planet might only last one or two hours every couple of weeks. Based on this data collection rate, TESS would also need to downlink enormous numbers of images for ground-based observers to search.

Orbits very distant from Earth — like Kepler's 6.2 million-mile (10 million kilometers) heliocentric orbit or JWST's planned 900,000-mile (1.5 million km) orbit around the Earth-Sun Lagrange 2 point — seemed desirable. But

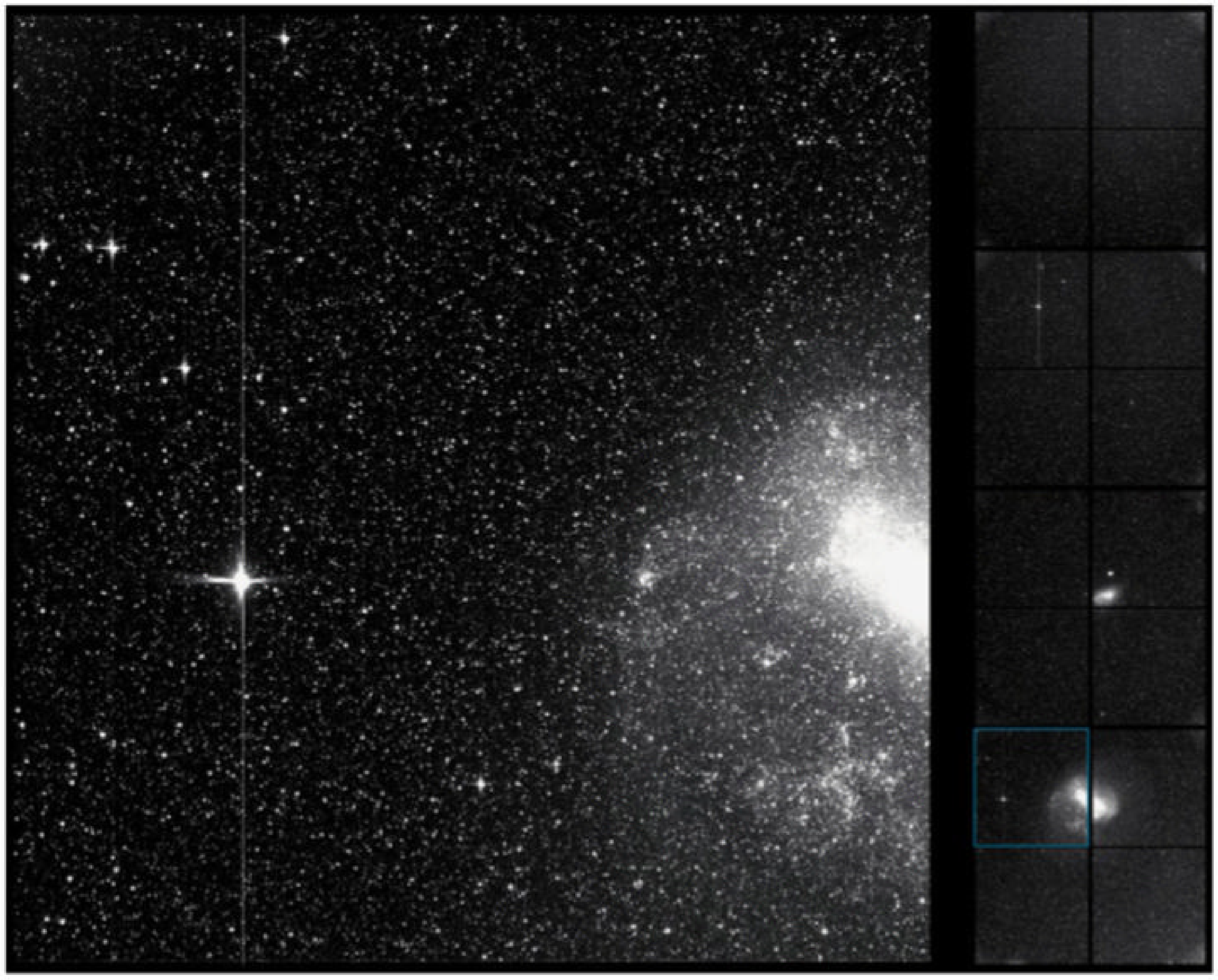


At the completion of its primary mission, TESS had mapped about 75 percent of the sky. Here, its complete view of the Southern Hemisphere appears at left and the Northern Hemisphere at right. The regions missing from the Northern Hemisphere map are areas TESS did not observe, to avoid picking up stray light from Earth or the Moon. NASA'S GODDARD SPACE FLIGHT CENTER

communicating from those distances would exceed any reasonable budget of antenna time a small mission could expect from NASA's Deep Space Network.

The solution turned out to be a new kind of elliptical orbit, in which the satellite spends part of its time close to Earth for data downlink but most of its time at a distance comparable to the Moon's distance from Earth. Generally, such orbits are notoriously unstable and can result in a spacecraft crashing into either the Moon or Earth within a couple of years. Our unique solution turned out to be an almost magical orbit in a favorable 2:1 resonance with the Moon's orbit around Earth. Since this specific so-called P/2 orbit had never been used previously in a space mission, our team spent an enormous amount of time analyzing how to establish and maintain it.

To be sure of our results, we had two different groups — one at The Aerospace Corporation and one at NASA Goddard — work independently on the calculations. In the end, our P/2 orbit was both elegant and practical. It even offered several major advantages, some of which surprised us — especially the excellent thermal stability of our cameras and the low radiation levels experienced by the spacecraft. Other advantages included high downlink rates and low stray background light.

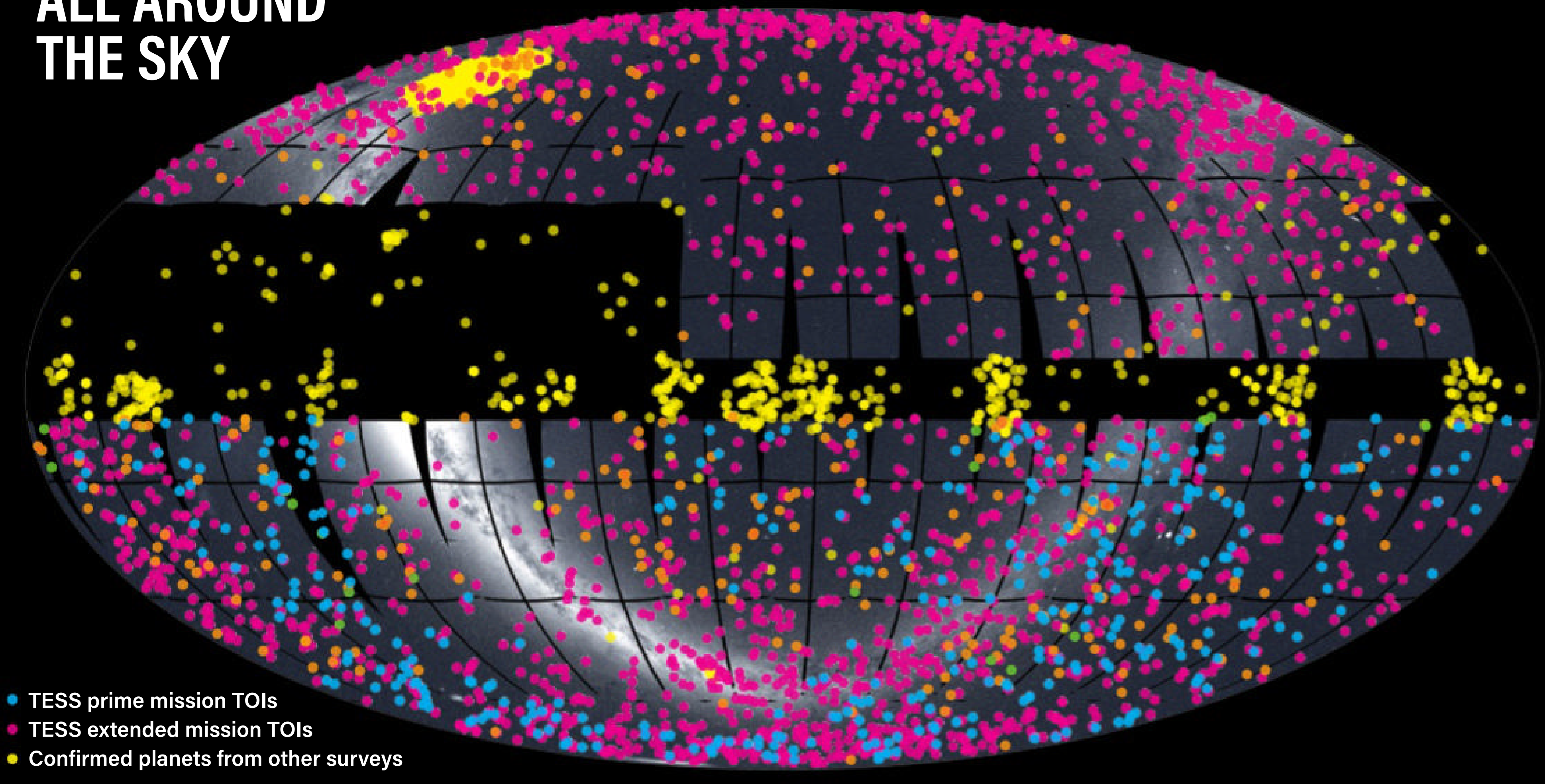


The precision of TESS's cameras allows the mission to detect exoplanets with diameters half that of Earth orbiting solar-type stars. At the same time, the field of view of a single TESS camera dwarfs that of any currently operating or planned wide-field systems, either on the ground or in space. This full-frame shot of the sky near the South Ecliptic Pole shows clearly the Large Magellanic Cloud and the bright star R Doradus. It was taken as part of the spacecraft's first-light science images in August 2018. NASA/MIT/TESS

Primary mission success

On April 18, 2018, a SpaceX Falcon 9 rocket carrying TESS roared into space. TESS arrived in its final P/2 orbit 42 days later, and our primary mission's first survey observation began July 8. Over the next two years, TESS's four wide-field CCD cameras systematically stepped across the sky. During the first year, TESS observed 13 Southern Hemisphere "sectors" 24° by 96° in size for 27.4 days each. In its second year, TESS switched

ALL AROUND THE SKY



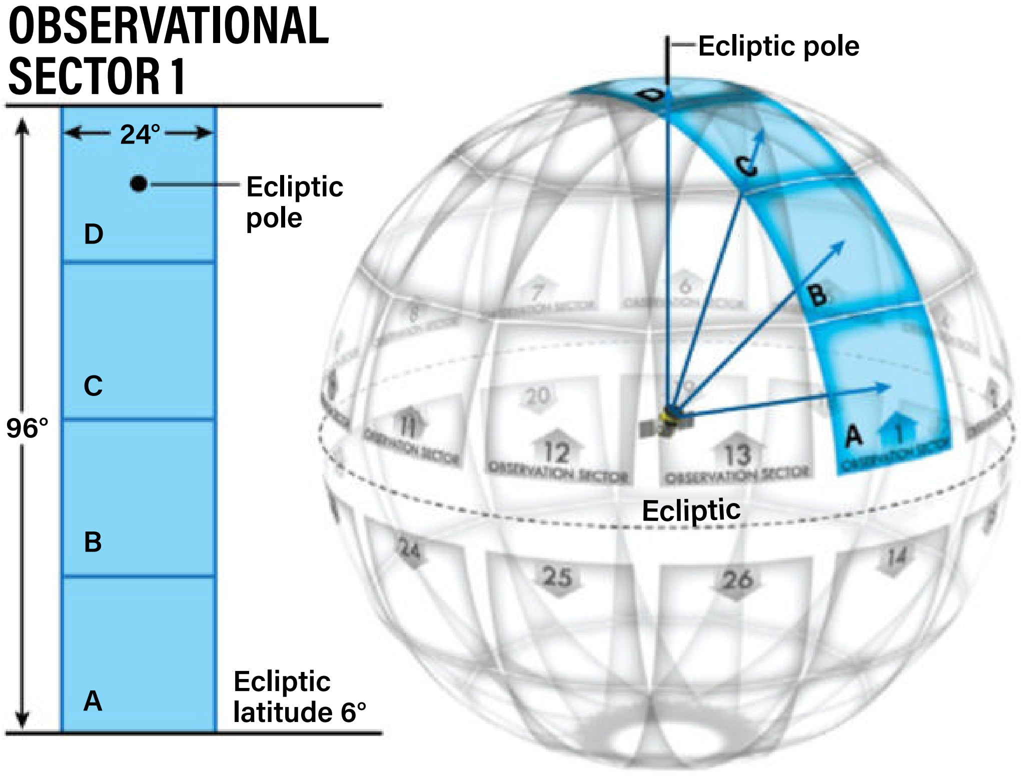
The nearly 3,000 TESS Objects of Interest (red and blue), or TOIs, are spread across the entire sky. By contrast, confirmed planets from other planet-hunting missions (yellow) are concentrated in only specific regions of the sky — an artifact of the search methods employed by those missions. *ASTRONOMY*: ROEN KELLY, AFTER NASA/MIT/TESS, ETHAN KRUSE (USRA), GREGGY BAZILE, NATALIA GUERRER

to observing 13 equally sized sectors in the northern sky.

The firehose of data from TESS's first three years has yielded thousands of new planet candidates spread over the entire sky. And the task of identifying the host stars for these candidates has fallen largely upon a small, dedicated group of analysts. Comprising primarily students and postdocs at MIT and the Harvard-Smithsonian CfA, this group — the TESS Objects of Interest (TOI) team — has been working for the past three years, examining light curves for more than 10 million stars brighter than 13th magnitude.

Their thousands of hours of effort have yielded approximately 3,000 new exoplanet candidates. We estimate that by the middle of this decade, this massive detective effort — which will be assisted by novel artificial intelligence methods currently under development — will have turned up as many as 10,000 new planet candidates. This immense collection should comprise essentially all of the best exoplanet candidates in the solar neighborhood for detailed follow-up and atmospheric characterization.

OBSERVATIONAL SECTOR 1



TESS divides each hemisphere of the sky into 13 distinct observational sectors measuring 24° by 96° each, observing a total of 26 sections between both hemispheres. The satellite views each sector for two orbits — a total of 27.4 days — before moving on to the next. *ASTRONOMY*: ROEN KELLY, AFTER RICKER ET AL. (2014)

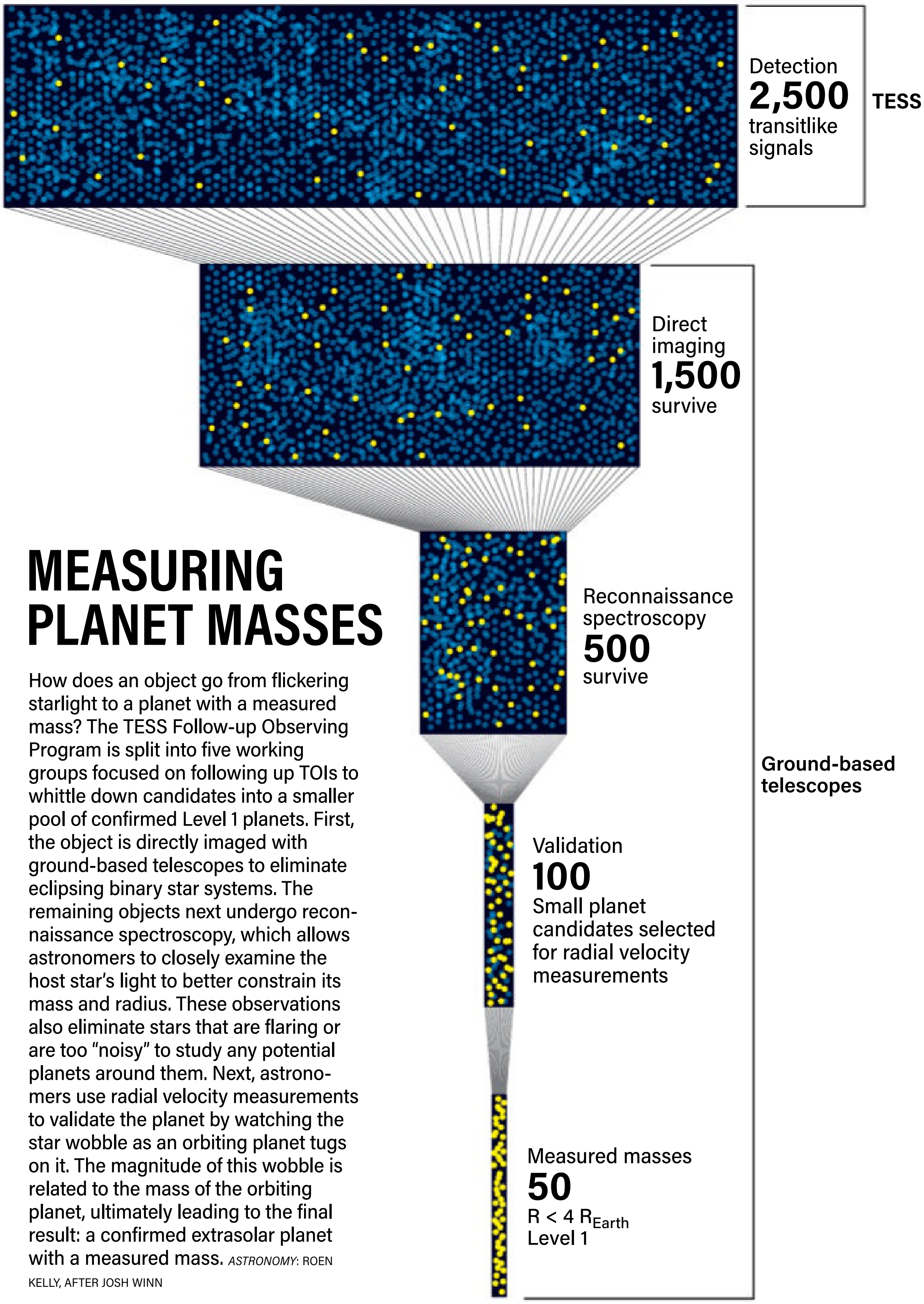
The TESS Follow-up Observing Program (TFOP), coordinated by our colleagues at the Smithsonian Astrophysical Observatory, is a worldwide effort of more than 550 astronomers at 100 institutions. These researchers sort through and follow up on this rich trove of TOIs using roughly 250 telescopes. TFOP astronomers have whittled down the 3,000 or so TOIs to about 100 so-called Level 1 confirmed TESS exoplanets. These Level 1 planets are all small, with radii less than four times that of Earth. Combined with the masses measured by the TFOP teams, we have confirmed that these small planets are indeed super-Earths and their slightly larger cousins with thicker atmospheres,

TESS IS FOR EVERYONE

From the start, we strongly advocated for TESS as a "people's telescope." As TESS scans the entire sky — including all the bright naked-eye objects — its perspective resembles someone contemplating a dark, cloudless night sky. Constellations are even readily recognizable in TESS images. (Of course, each 10-minute exposure goes 10,000 times deeper than the human eye!) Since launch, TESS has taken nearly 500,000 full-frame sky images, each with more than 10 million stars.

The TESS Guest Investigator (GI) Office solicits and selects proposals by astronomers worldwide to choose targets for science observations, and NASA can provide funding for U.S. astronomers. TESS's data are made accessible quickly with no proprietary period — not even for targets selected by individual astronomers or TESS science team members. In 2018, while the TESS team was developing and debugging its pipeline, the delay from receipt of raw data to production and release of calibrated images and light curves was about two to four months. By early 2020, the time required to deliver calibrated data had dropped to about one month. Now, in 2021, the delivery time is just a few days.

Today, the full TESS datasets are hosted as they arrive from space, orbit by orbit and sector by sector, with the help of the TESS GI Office at NASA's Goddard Space Flight Center and a public TESS archive at MAST. Their assistance has made the TESS data available for immediate downloading by anyone on Earth with access to an internet browser, at https://archive.stsci.edu/missions-and-data/tess. — *G.R.R.*



MEASURING PLANET MASSES

How does an object go from flickering starlight to a planet with a measured mass? The TESS Follow-up Observing Program is split into five working groups focused on following up TOIs to whittle down candidates into a smaller pool of confirmed Level 1 planets. First, the object is directly imaged with ground-based telescopes to eliminate eclipsing binary star systems. The remaining objects next undergo reconnaissance spectroscopy, which allows astronomers to closely examine the host star's light to better constrain its mass and radius. These observations also eliminate stars that are flaring or are too "noisy" to study any potential planets around them. Next, astronomers use radial velocity measurements to validate the planet by watching the star wobble as an orbiting planet tugs on it. The magnitude of this wobble is related to the mass of the orbiting planet, ultimately leading to the final result: a confirmed extrasolar planet with a measured mass. *ASTRONOMY*: ROEN KELLY, AFTER JOSH WINN

sub-Neptunes. Furthermore, an important subgroup of these Level 1 planets is Earth-like in both size and mass.

There are many other planets of varying sizes among the TESS planet candidates. And about 25 percent of TOIs are not planets at all, but distant eclipsing binary stars, whose eclipses can mimic exoplanet transits. Ongoing observations with higher-angular resolution telescopes, such as the Gaia space mission, will allow astronomers to separate these systems from real transiting planets.

TESS is also revolutionizing the study of multiplanet systems, especially those with six or more worlds co-orbiting their host star. Such systems were initially discovered by Kepler and the TRAnsiting Planets and PlanetesImals Small Telescope–South (TRAPPIST) survey telescopes. Unfortunately, these early discoveries orbit relatively faint stars — typically 14th magnitude — making them difficult to study.

As of early 2021, TESS has found more than 80 new multiplanet systems. Four recent discoveries, each with four or more planets, are much closer to Earth than the Kepler and TRAPPIST systems and thus have stellar hosts that appear 30 to 50 times brighter. These are much easier for follow-up observers to study. Brighter host stars also make it easier for JWST and the next generation of giant 30-meter class ground-based telescopes to investigate these planetary atmospheres via spectroscopy. This is because brighter stars mean shorter observations can still detect any potentially biologically interesting signatures in a planet's atmosphere as light from the host star filters through it.

Extended mission

After completing its initial planned two-year survey in July 2020, TESS embarked on a 26-month extended mission. Approved by NASA, this extension allows TESS to search for planets around

NASA'S GODDARD SPACE FLIGHT CENTER/CHRIS SMITH (USRA/GESTAR)

NOT ALL PLANETS

TESS was designed, funded, and built to identify transiting planets. But the very nature of its survey means it also catches plenty of so-called transient events that are *not* planetary transits. From eclipsing binary stars and supernovae to outbursts from nearby comets and far-flung supermassive black holes, TESS has seen it all. Although these events don't add to the catalog of known extrasolar planets, they still provide vital data for astronomers studying many other aspects of our universe.

TYC 7037-89-1: Located about 1,900 light-years away in the constellation Eridanus, TYC 7037-89-1 (also known as TIC 168789840) is a multiple-star system discovered within the TESS data. This unique six-star system is composed of three eclipsing binaries, meaning every star in the system undergoes eclipses as seen from Earth.

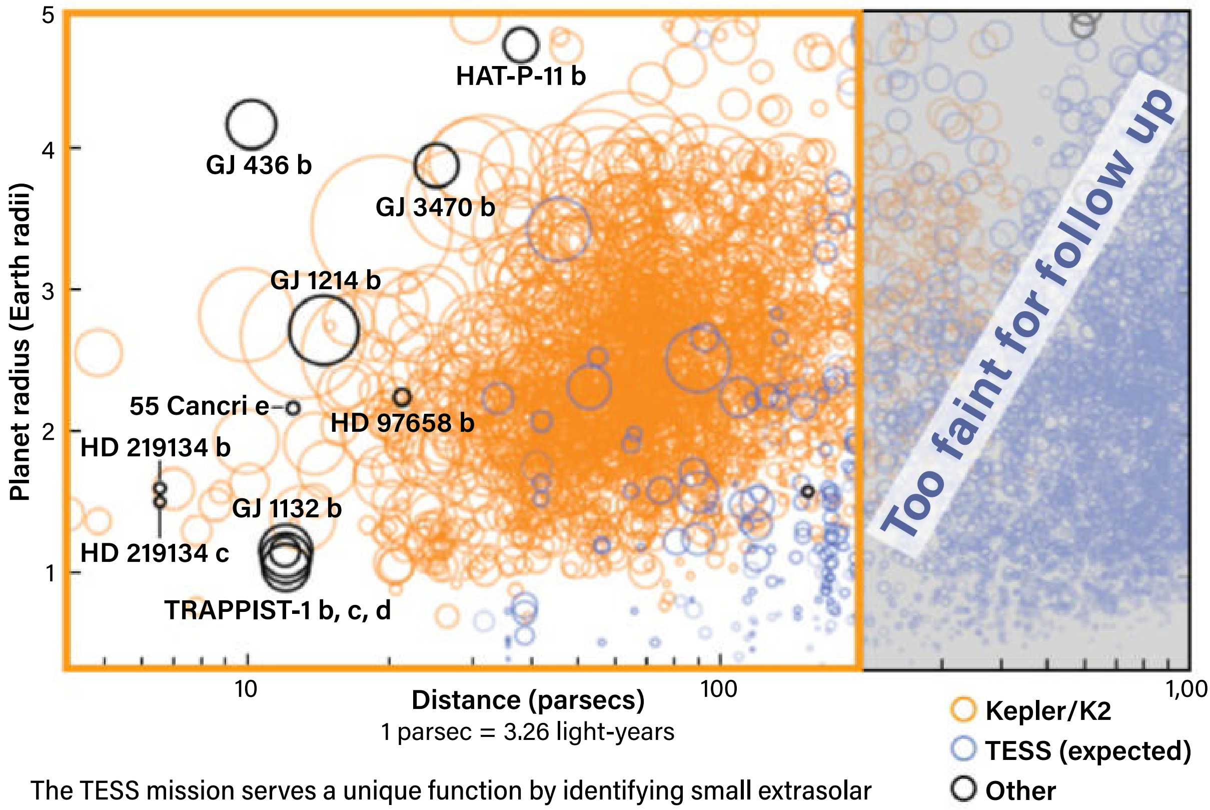
Nu (ν) Indi: TESS asteroseismology observations of this bright, naked-eye star have enabled astronomers to date the past merger of a satellite galaxy with the Milky Way to 11 billion years ago.

ASASSN-14ko: The galaxy ESO 253–3 contains an active supermassive black hole that belches out flares every 114 days (pictured at top in an artist's concept). TESS has been instrumental in helping researchers study these outbursts, which astronomers now believe occur as the black hole slowly nibbles away at an orbiting star during every closest approach.

Comet 46P/Wirtanen: When Comet 46P/Wirtanen swung near the Sun in late 2018, TESS was there to watch. The satellite observed an outburst of ice, dust, and gas from the comet as it was heated by the Sun — the most comprehensive picture of this type of event to date.

Supernovae: Within its first month of observation in 2018, TESS spotted six distant supernovae in other galaxies. That's the same number of supernovae the Kepler Space Telescope observed in four years — and it was only the start. Since then, TESS has caught nearly 200 such events popping off all over the sky. — *A.K.*

FILLING THE GAPS

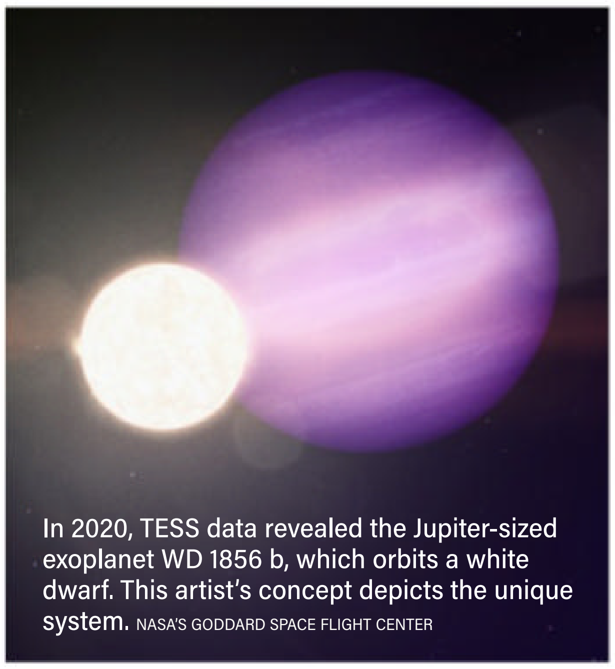


The TESS mission serves a unique function by identifying small extrasolar planets with radii just a few times that of Earth around bright, nearby stars. These particularly accessible host stars allow researchers to more easily and quickly follow up on newly discovered planets using ground- and space-based telescopes. ZACH BERTA-THOMPSON

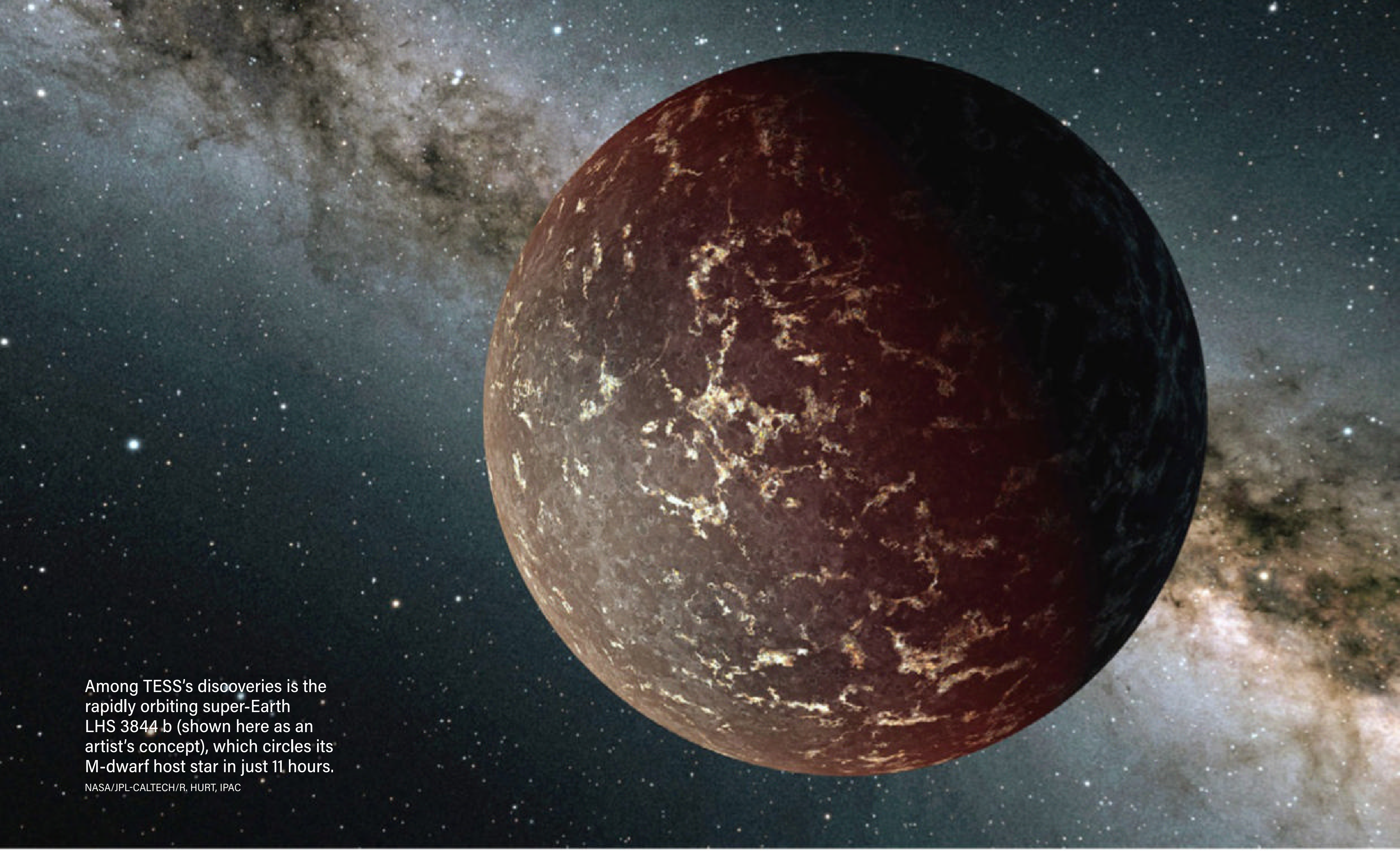
even more distant stars, as well as follow up on some of the most exciting discoveries from the primary mission.

This first extended mission consists of three major initiatives: First, TESS will survey the sky a second time, covering the Southern Hemisphere again in the first year and the Northern Hemisphere in the second year. Additionally, TESS will spend 135 days exploring a 12°-wide band along the Ecliptic Plane, which was not probed during the primary mission because we were focused on fully covering the continuous viewing zones for JWST that surround the north and south ecliptic poles. The Kepler Space Telescope's K2 mission surveyed the ecliptic plane from 2014 to 2018. But measurement uncertainties in transit times mean that some K2 planets could effectively be lost as their real transit periods drift away from the measured (uncertain) periods over the half decade since their discovery, like two clocks ticking out of sync. TESS should recover a large fraction of these more than 400 confirmed K2 planets.

Second, TESS now takes full-frame images every 10 minutes, down from the primary mission's 30-minute exposures. More frequent exposures should help catch short-duration exoplanet transits as brief as 40 minutes. This will reveal more Earth-sized planets in the habitable zone of M-dwarf stars, which comprise approximately 75 percent of the stars in our survey. Overall, this improvement could triple the number of planets we expect to find from 50 to 150 — or more. Additionally, a new 20-second exposure capability has been introduced, which improves TESS's ability to detect and accurately measure stellar flares. It will also help TESS search for exoplanets orbiting white dwarf stars. Such transits had long been predicted when our extended mission was written, but were not confirmed until TESS discovered the first one in 2020: a Jupiter-sized planet orbiting the white dwarf WD 1856.



In 2020, TESS data revealed the Jupiter-sized exoplanet WD 1856 b, which orbits a white dwarf. This artist's concept depicts the unique system. NASA'S GODDARD SPACE FLIGHT CENTER



Among TESS's discoveries is the rapidly orbiting super-Earth LHS 3844 b (shown here as an artist's concept), which circles its M-dwarf host star in just 11 hours. NASA/JPL-CALTECH/R. HURT, IPAC

Finally, guest investigators will get to choose at least 80 percent of the extended mission's two-minute cadence mode targets. This mode downloads a small "postage stamp" of pixels around a single star in TESS's field of view every two minutes. This faster-paced observing can catch the beginning or end phases of bright planet transits. The remaining 20 percent of the extended mission's two-minute cadence targets will consist of the most promising TOIs from the primary mission.

A revolutionary impact

Thanks to our open policy and high data quality, the number and volume of TESS images and light curves downloaded from the Barbara A. Mikulski Archive for Space Telescopes (MAST) has been extraordinary. During 2020, users downloaded a total of 680 terabytes of data — about seven times the amount downloaded from either the Hubble or Kepler missions during that same period. In December 2020 alone, there were nearly 5 million requests for a total of about 50 TB of data.

During its 2019 review, NASA commended the TESS mission for "having a revolutionary impact on the fields of exoplanets and stellar astrophysics," as well as for "providing a model of how to build and serve a broad user base to maximize science return." As of March 2021, TESS had observed a total of 34 sectors and identified 2,597 TOIs. Of those, 755 have radii less than four times that of Earth and 120 are confirmed — thus far — as planets. Dozens more are underway.

The mission's first planet, Pi Mensae c, is a super-Earth four times more massive and twice as large as Earth, circling the naked-eye Southern Hemisphere star Pi (π) Mensae every six days. But TESS has also discovered TOI-700 d — an Earth-sized planet orbiting in its red dwarf host star's habitable zone, where conditions are right for a planet to maintain liquid water on its surface. And there's also LHS 3844 b, a super-Earth so close to its star that one year lasts just 11 hours and daytime temperatures soar to 989 degrees Fahrenheit (531 degrees Celsius).

TESS's data has provided observations for more than 300 scientific papers written in 2020 alone. And while most of those papers focus on new exoplanet discoveries, others are studies of the way stars vary, oscillate, spin, and produce flares. Citizen scientists can easily engage with TESS data through the Planet Hunters TESS Zooniverse project. This has led to the discovery of numerous planets, including TOI 1338 b — TESS's first circumbinary planet with not one, but two suns at the center of its orbit.

Now engaged in its second complete survey of the full sky, this small but powerful satellite will continue to reveal the wide diversity of worlds — like and unlike our own — that share our solar neighborhood. Next, it will be up to missions like NASA's JWST and Nancy Grace Roman Space Telescope, and the European Space Agency's Atmospheric Remote-sensing Infrared Exoplanet Large-survey (ARIEL) satellite, to delve into this long list of nearby worlds in greater detail, studying their atmospheres and compositions to learn more about how exoplanets form and evolve. Perhaps one of these observatories will even hit the jackpot: discovering potential signs of life on a planet first identified by TESS.

George R. Ricker *is principal investigator for the TESS mission. He also serves as director of the Detector Laboratory and is a senior research scientist at the MIT Kavli Institute for Astrophysics and Space Research.*