The ongoing search for habitable exoplanets

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Eric Ford is director of Penn State's Center for Exoplanets and Habitable Worlds, which celebrates its 10th anniversary this year. Credit: NASA/Michelle Bixby

A balmy Florida evening, and my family and I stood on Cocoa Beach, looking northward toward the Cape Canaveral Air Force Station. We were part of a seaside crowd gathered to witness the launch of NASA's

Kepler Space Telescope. As the fireball appeared and slowly began to rise in the distance, we cheered with our fellow observers. About 30 seconds later, we felt the ground rumble and heard the deep roar, watching the Delta II rocket climb into the night sky and accelerate as it headed out over the ocean.

Kepler went on to spend nine years in deep space searching for galactic neighbors like us: Earth-sized planets orbiting Sun-like stars. Kepler watched a patch of the Milky Way galaxy that included millions of stars. It beamed back data on nearly 200,000 of them and found more than 2,300 exoplanets—planets outside our solar system.

"With data from Kepler, we have more precise and detailed information than we'd ever had before," says astrophysicist Eric Ford, who was part of the Kepler science team. Ford and his colleagues at Penn State's Center for Exoplanets and Habitable Worlds are building on the legacy of Evan Pugh Professor Alex Wolszczan, who discovered the first known exoplanets in 1992 using surveys from ground-based instruments. "Kepler found thousands of planets," Ford says. "Astronomers would love to learn more about all of them, but there is not enough telescope time. Since people are particularly interested in learning more about those that may resemble Earth, we plan to concentrate on characterizing planets in the habitable zones of their planetary systems."

The habitable zone is a region within a solar system—a distance not too close and not too far from a sun—where a planet would have the conditions necessary to have liquid water on its surface, an important requirement for the existence of carbon-based life as we know it. James Kasting, Evan Pugh Professor of Earth Sciences, was one of the early developers of the concept. The planet's surface temperature must be above the freezing point of water and below the boiling point. Other conditions also come into play, including the planet's mass, rotation, and atmosphere. Among the Kepler exoplanets that have been analyzed so far, several dozen are considered to be in the habitable zone of their star.

Eric Ford, a member of the Kepler science team, studies how planets form and evolve, both in our solar system and in others. Many of the systems found by Kepler are very different from ours, raising new questions about how planetary systems develop and why they occur in such diverse forms. The Kepler instrument was named for German astronomer Johannes Kepler, who in the early 1600s formulated three laws of planetary motion.

How to find an exoplanet

In its search for exoplanets, the Kepler mission employed the transit method, using digital-camera-like technology to detect and measure tiny dips in a star's brightness as a planet crosses in front of the star. With observations of transiting planets, astronomers can calculate the ratio of a planet's radius to that of its star—essentially the size of the planet's shadow—and with that ratio they can calculate the planet's size. "We know the size of thousands of planets thanks to the transiting method," Ford says.

Although its solar-powered electronics could continue working for a long time, this past fall, Kepler ran out of the hydrazine fuel needed to orient itself precisely, and NASA retired the spacecraft. It's now 94 million miles away, in an orbit trailing Earth around the Sun. But the mission produced enough data to keep astronomers busy for years to come. And now, a new NASA mission is expanding on Kepler's census of exoplanets by targeting closer, brighter stars.

TESS (Transiting Exoplanet Survey Satellite), which launched last April, is scanning almost the whole sky, one patch at a time, looking for transiting planets around the nearest stars. While the typical stars Kepler observed were from 300 to 3,000 light-years away (one light-year is about six trillion miles), TESS is looking at stars that are mere tens of light-years away. And rather than spending years looking at one patch of sky, as Kepler did, TESS will shift its view from one patch of sky to the next.

Using TESS observations of brighter stars—on average 30 to 100 times brighter than the stars Kepler surveyed—astronomers will be able to inspect planets more closely and make follow-up observations more easily. "With TESS, we're focusing on searching for planets around stars that are closer to us, since we'll be able to characterize them more efficiently," Ford says. Data from TESS will provide information on a planet's size and orbital period, and follow-up observations with other instruments will allow researchers to measure the masses and describe the atmospheres of these planets.

But as valuable as the transit method is to planetary studies, it has its limitations. "Transits only let you see planets that happen to cross between us and the star we are looking at," explains astrophysicist Fabienne Bastien. "Radial velocities enable us to see planetary systems in other orientations."

Also called Doppler spectroscopy, the ground-based radial velocity method was actually the first technique to detect exoplanets hosted by Sun-like stars. It's based on the fact that a star wobbles slightly in response to an orbiting planet's gravitational tug. These tiny movements affect the star's light spectrum, or color signature. As the star moves slightly away from an observer, the wavelength of its light lengthens slightly, shifting toward the red end of the spectrum. As the orbiting planet pulls the star slightly toward the observer, the star's light shifts toward the blue. Through repeated observations of changes in the star's spectrum, researchers can calculate the planet's mass.

Bastien, whose research focuses on the host stars of planetary systems, combines transit data with radial velocity studies to learn more about distant suns. "These suns have spots and flares and all kinds of activity that can either mimic or mask an exoplanet signal," she says. "Much of my work involves disentangling the planetary signal from the stellar signal, so we can confirm it's actually a planet that we're seeing. Penn State is already a radial velocity powerhouse, and I'm excited about two new spectrographs that are much more sensitive than what we've had to date and that will dramatically advance our studies."

These new world-class, highly sensitive spectrographs, built by a Penn State team led by astrophysicist Suvrath Mahadevan, are about to change the radial velocity landscape. They'll measure radial velocities extremely precisely to characterize low-mass planets in or near the habitable zones of their stars. One spectrograph is designed for optical study of nearby Sun-like stars, and the other for detecting cooler, fainter, lower-mass stars using infrared light.

"I can't wait to use these spectrographs to explore some ideas I have for finding habitable exoplanets," Bastien says. "I want to start a planet search around some stars that haven't received much attention because they're too noisy—there are complicating factors around them that make them difficult to study. The group here is enthusiastic and collaborative and open to new ideas, so there are all sorts of possibilities."

Fabienne Bastien studies the host stars of planetary systems. It's fairly easy to find a star, but knowing whether it has planets orbiting around it is much harder. Two approaches Bastien uses are the transit method and the radial velocity method.

Astrophysicist Fabienne Bastien studies stars that host planetary systems, and how their characteristics affect our ability to detect and learn about exoplanets. A new generation of spectrographs, such as the NEID that will soon be deployed at Kitt Peak National Observatory, shown here, will provide precise details about distant stars and their planetary systems. Credit: Mark Hanna/NOAO/AURA/NSF/Michelle Bixby

All planetary systems are not alike

As researchers learn more about potential habitable zones of distant solar systems, they also want to learn about how those systems might have formed and evolved. That's the research focus of astrophysicist Rebekah Dawson. "It's an exciting time because so many new planets have been discovered in other solar systems and they're very different from the planets in our solar system," she says. "Exoplanet discoveries forced us to change our understanding of solar system and planet formation."

For example, Kepler found a lot of planets with sizes between that of Earth and Neptune (about four times Earth's diameter), that are as close to their stars as Mercury is to the Sun, or even closer. "These planets are common in other planetary systems, and we have nothing like them in our solar system," Dawson says. "So we're going back to the drawing board with some of our theories for how planets form and what happens early in planetary systems, now that we don't have just our solar system to judge these theories against."

Dawson's research on planetary systems can in turn inform and provide context for studies of individual planet formation. By understanding what might have been happening early on in a planetary system, she and her colleagues can develop theories about how planets might form in that system. For example, as giant planets gravitationally interact with each other, they could be sending asteroids and comets into regions where terrestrial planets are forming, and that could influence the composition of those planets.

Among Dawson's research interests are hot Jupiters, some of the first exoplanets ever discovered. Similar in mass to our Jupiter, these giant gas planets are much closer to their sun than Jupiter is to our Sun. They complete an orbit in three to four days. "That's not where we expected to find giant gas planets in their solar systems," Dawson says. "We're trying to understand their origin and how they could be so close to their star. One theory is that after these hot Jupiters formed, they were put into an extremely elliptical orbit that would bring them close to their star, and then tidal friction—tides raised on the Jupiter by the star—caused the orbit to shrink and become more circular.

"I sometimes think of a planetary system as an ecosystem that could support a potentially habitable planet, and we have to understand how the whole thing functions to really understand if that planet is habitable and what its formation history is," Dawson continues. "When we started to learn about those hot Jupiters and how their orbits might have been altered, that has implications for the rest of the planetary system. If that were happening, it would probably wipe out any planets in between the hot Jupiter and the star, so that region wouldn't be a likely place to find a habitable planet"—even if it's the right distance from the star to be in the habitable zone.

Rebekah Dawson studies how planetary systems formed and evolved. Kepler has revealed that many of the planets in other systems are very different from the planets in our own solar system, and that just because a planet is in a system's habitable zone doesn't mean that it is habitable.

Where do we go from here?

Fabienne Bastien recalls the sense of wonder she felt when, as a graduate student, she heard Kepler scientist Natalie Batalha speak of her own realization that the stars we see at night are more than distant suns. "Now we know that they're not just stars, they're planetary systems," she says—each one potentially home to habitable worlds.

With everything astronomers have learned about that potential, there's still much that remains a mystery. Current methods are just beginning to characterize the atmospheres of exoplanets and determine whether a planet in the habitable zone might have a surface that is conducive or hostile to life. Recent progress gives scientists a better idea of what questions to ask and what kinds of instruments are needed to address them.

"When astronomers have just discovered a planet, we could say it's potentially habitable, but that is more a statement of our limited knowledge than of the properties of the planet," Ford says. "We want to design a hypothesis that is testable through observations we're able to make. If we can find 100 rocky planets in the habitable zone and characterize their atmospheres to look for water and biomarkers, then we might find some really fascinating planets—but there's also the possibility that we conclude that none of them are suitable for Earth-like life."

One long-term goal for astronomers is direct detection of exoplanets, rather than having to infer their existence through transit or radial velocity studies. Dawson is now serving on a team laying the groundwork for a Large UV Optical Infrared Surveyor (LUVOIR), a multi-wavelength space observatory concept being studied by NASA's Goddard Space Flight Center. LUVOIR is envisioned to be a twelve- to fifteen-meter diameter telescope that would operate about a million miles from Earth. It would allow scientists to recognize planets directly, as small bright bodies against the dark of space. Once a planet is identified, other techniques could then be used to measure its mass and examine other important features.

As researchers look to new technologies such as the new spectrographs, LUVOIR, and other future missions, they're optimistic that one day we'll know whether our solar system is a rare phenomenon or if life does indeed exist on other planets.

"If you think about it, it's amazing that Earth has both continents and oceans, as well as an atmosphere and climate that sustain life," Ford says. "Is that significant? Is it just the right balance? Is Earth a great coincidence or does planet formation often produce similar planets?"

"Before exoplanets were discovered, I think a lot of us expected every planetary system to look like the solar system, or we thought most stars don't have planets," Dawson adds. "But instead, what we're seeing is that most stars do have planets, and a lot of these planetary systems are very different from our solar system. Does that make the solar system unusual? We don't know yet. Despite our best instruments and technology, we're still only looking in our own little neighborhood of the galaxy.

"Luckily, I don't think we necessarily need to look at all the stars in the galaxy to know whether our solar system is unusual. And every time there's a new mission or a new instrument that can do something different or dramatically improve the quality of data, there's something surprising that keeps us excited."

Provided by Pennsylvania State University

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