

Last light for the Kepler space telescope

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After more than nine years of unprecedented discovery of worlds beyond our Solar System, NASA's Kepler space telescope has exhausted its supply of fuel needed for scientific operations. On October 30, the agency officially retired its tenth Discovery-class mission, leaving behind a legacy of exploration that revolutionized humanity's understanding of our galaxy's planets and the stars they orbit.

During its primary and extended mission, the Kepler spacecraft observed 530,506 stars, discovered 2,681 exoplanets, found 2,899 candidate exoplanets that have yet to be confirmed and watched 61 supernovae as they exploded. There have been 2,946 scientific papers published from the 678 gigabytes of data collected by the telescope and beamed back from Kepler's Sun-circling orbit, which trails further and further behind that of the Earth.

Kepler was the culmination of decades of research and development into new methods to detect Earth-sized planets across interstellar distances. NASA researcher William Borucki began work on extrasolar planet detection in 1983 and published a paper with Audrey Summers in 1984 noting that while the instruments of the time, operating from the Earth's surface, could detect Jupiter-sized planets, it would take a space-based telescope to find smaller exoplanets, those which might be closer to the Earth in size or composition. This idea was refined for many years until Kepler was finally approved in 2001 and launched on March 6, 2009.

The telescope's primary mission had a single purpose: to continuously observe a particular region of space and watch for any periodic dimming of the stars in its field of view that would indicate a planet coming between the star and the telescope. In doing so, it would provide the data needed to find out how common planets are around the observed stars and, by extension, in the galaxy and the universe as a whole.

In order to find such planets, Kepler was made using some of the most advanced astronomy technology of the time. The sensor array on the telescope is comprised of 94.6 million individual pixels and was slightly curved to minimize distortion from incoming light reflected off the telescope's 1.4-meter diameter mirror. It viewed an area of the sky 33,000 times as large as that observed by the Hubble Space Telescope and recorded an image every six seconds. The total package cost about \$792 million over two decades to develop, build, launch and operate, the equivalent of 0.1 percent of this year's Pentagon budget.

The telescope's first target was a small region in the constellation Cygnus that contains 170,000 observable stars up to 3,000 light years (about 28 million billion kilometers) away. For four years (half a year longer than its original mission parameters), Kepler observed this region and found hundreds of confirmed exoplanets and thousands of potential candidates. In the years since, further analysis and follow up observations with other ground- and space-based telescopes have helped to confirm thousands more, with further thousands of candidate planets awaiting review.

Kepler's mission was modified after the second of the telescope's four reaction wheels, gyroscopes needed to orient and stabilize the telescope, failed in May 2013. For the next several months, NASA developed a plan to hold the spacecraft steady with the two remaining reaction wheels, small amounts of fuel and the minute but constant pressure of sunlight. While this setup was not as precise as the original telescope configuration, it allowed Kepler to continue operations for another five and a half years.

The database now available as a result of Kepler's observations stands in stark contrast to the state of exoplanet astronomy only 26 years ago, when the first planets were discovered orbiting a pulsar. Even through the 1990s, it was not certain whether the discoveries

that had been made at the time were statistical anomalies and or whether our Solar System was just a fluke in the cosmos. Kepler has conclusively shown that planets are a common occurrence, a fact that has become a mainstay in the scientific research of the astronomical community and the cultural life of the world's population.

It has also revealed that planets and their systems are extraordinarily varied. After Kepler detected its first five planets and many more shortly after, it quickly became apparent that each star likely does have at least one planet orbiting around it. Astronomers were also surprised that very few extrasolar systems fell into any of the theoretical models that had been developed about solar system formation. Some of the earliest discoveries were "hot Jupiters," massive gas giants that orbited closer to their star than Mercury does to the Sun.

Another interesting type of star system includes multiple small rocky planets orbiting close to very small stars. Moreover, some of these systems, such as Kepler-186, have planets approximately the size of Earth, likely rocky and orbiting around their parent stars at a distance where liquid water could exist on their surface, in what is called the habitable zone. To date, no "typical" planet or solar system has been discovered, forcing astronomers to develop more refined and subtle models of planetary formation, models which will remain under development and revision for the foreseeable future.

The crown jewel of Kepler's dataset is the planet Kepler-452b. It is the most Earth-like planet discovered to date, with a radius close to that of Earth, a likely rocky composition and an orbit around a star similar to the Sun and within its habitable zone. So far, such planets have proven to be rare, yet if even one exists, it provides a tantalizing hint of thousands and possibly millions more.

Some of these may have already been discovered by Kepler or other exoplanet searchers, such as the one which uncovered seven Earth-sized planets in the Trappist-1 system. Among all the confirmed exoplanets (not just those found by Kepler), 1211 have a radius less than twice that of Earth's, 135 have an estimated mass less than three times Earth's and 361 orbit within their star's habitable zone. While planets in any one of these categories are only rarely also in the other two, it is only a matter of time before even more potential

"exo-Earths" are discovered.

Alongside the empirical evidence, there have been a variety of probabilistic studies using Kepler data to predict how many Earth-sized planets there are in the galaxy. One such study, done in 2013, predicts 11 billion Earth-sized planets orbiting Sun-like stars in the Milky Way. Based on the statistics, the closest of these is likely within 12 light years, our cosmic backyard, and a prime target for further study. The Kepler method only detects planets whose orbits are precisely aligned to block the light of their parent star, so other techniques will be necessary to find these likely nearby neighbors.

The next step in our study of exoplanets is to determine how many Earth-sized planets in their star's habitable zone are *Earth-like*, that is, whether or not they have an atmosphere that humans might be able to breathe and if they actually have standing bodies of liquid water on their surface. While it will take more specialized missions such as the Transiting Exoplanet Survey Satellite (TESS), which launched in April, or the James Webb Space Telescope, slated to launch in 2021, to start answering these questions, the Kepler space telescope showed that there are likely thousands if not millions of such worlds for humanity to explore.



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