

The Kepler Mission Legacy

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ABSTRACT

The Kepler Mission, [NASA Discovery mission #10](#), is specifically designed to survey our region of the Milky Way galaxy to discover hundreds of Earth-size and smaller planets in or near the habitable zone and determine the fraction of the hundreds of billions of stars in our galaxy that might have such planets. Despite the loss of two of its four reaction wheels by the fourth year of its primary mission, the Kepler Mission, in its first four years, has been successful in detecting nearly 4,600 planet candidates in its survey of over 150,000 stars. Nearly 2,300 of those planet candidates were confirmed with a number of planets deemed to be near Earth-size in the habitable zone. Even after the loss of a second reaction wheel, the Kepler Mission team reconfigured the spacecraft to continue surveying the Milky Way galaxy for exoplanets and to further studies in a wide range of astrophysics. NASA has several near-term follow-on missions ready-to-launch, and others in more long-term conceptual stage, that will build on the legacy of Kepler and other missions.

1 KEPLER SCIENCE OBJECTIVES

As stated on the official NASA webpage, the scientific objective of the Kepler Mission is to explore the structure and diversity of planetary systems. This is achieved by surveying a large sample of stars to:

- Determine the percentage of terrestrial and larger planets that are in or near the habitable zone of a wide variety of stars
- Determine the distribution of sizes and shapes of the orbits of these planets
- Estimate how many planets there are in multiple-star systems
- Determine the variety of orbit sizes and planet reflectivities, sizes, masses and densities of short period giant planets
- Identify additional members of each discovered planetary system using other techniques
- Determine the properties of those stars that harbor planetary systems.¹

2 THE TRANSIT METHOD OF DETECTING EXTRASOLAR PLANETS

Using transit photometry is a simple concept for detecting extra-solar planets. An observer measures the change in brightness of a star when it is “eclipsed” by an object, such as a planet, passing in front of it. When a planet passes in front of a star as viewed from Earth, the event is called a “transit”. On Earth, we can observe an occasional Venus or Mercury transit. These events are seen as a small black dot creeping across the Sun—Venus or Mercury blocks sunlight as the planet moves between the Sun and us. Kepler finds planets by looking for tiny dips in the brightness of a star when a planet crosses in front of it—we say the planet transits the star (Figure 1)².

¹ https://www.nasa.gov/mission_pages/kepler/overview/index.html

² https://www.nasa.gov/mission_pages/kepler/multimedia/images/transit-light-curve.html

Once detected, the planet's orbital size can be calculated from the period (how long it takes the planet to orbit once around the star) and the mass of the star using Kepler's Third Law of planetary motion. The size of the planet is found from the depth of the transit (how much the brightness of the star drops) and the size of the star. From the orbital size and the temperature of the star, the planet's characteristic temperature can be calculated. From this the question of whether or not the planet is habitable (not necessarily inhabited) can be answered.³

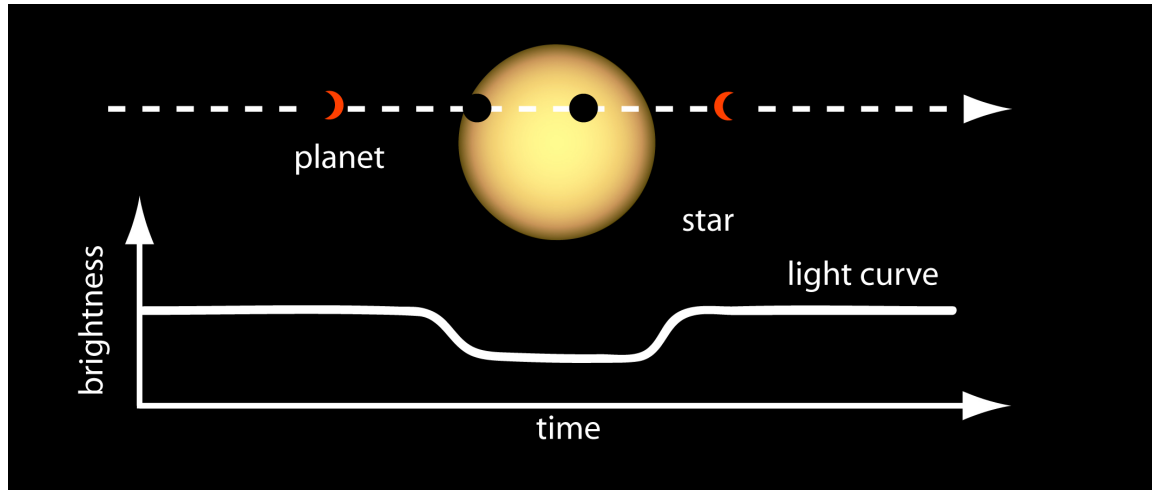


Figure 1. Transit Photometry

3 WHERE TO LOOK FOR EXTRA-SOLAR PLANETS?

The team settled on a region within the Cygnus constellation, near Lyra (Figure 2). The Field of View was nearly 110 square degrees. If one held his/her hand at arms length, that would represent the “handprint” of Kepler’s Field of View against the sky. Compared to usual ground based telescopes, that is an enormous field of view. This was necessary to allow a survey of over 150,000 stars to complete the original mission.

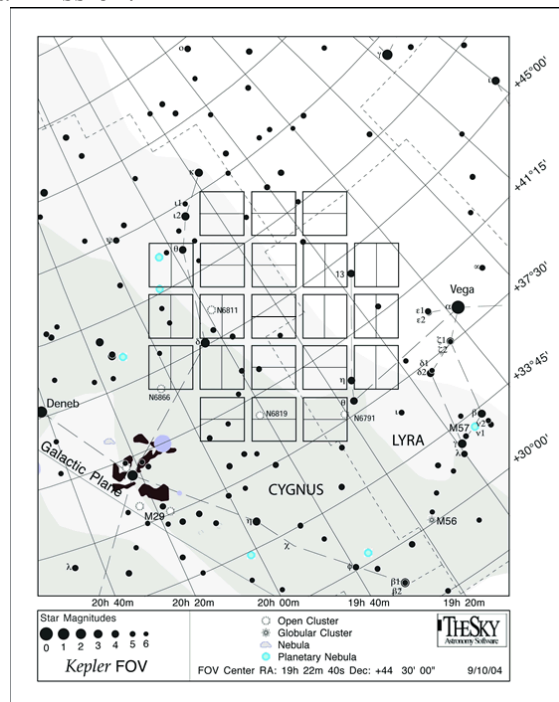


Figure 2: Kepler Field of View (FOV)

³ https://www.nasa.gov/mission_pages/kepler/overview/index.html

4 Spacecraft/Instrument/Orbit/Mission Design

The NASA Kepler webpages provide an excellent synopsis of the mission. The following paragraphs are derived from the official NASA Kepler website. The Kepler spacecraft provides the power, pointing and telemetry for the photometer. Pointing at a single group of stars for the entire mission greatly increases the photometric stability and simplifies the spacecraft design. Other than the small reaction wheels used to maintain the pointing and an ejectable cover, there are no other moving or deployable parts. The only liquid is a small amount for the thrusters which is kept from slosh by a pressurized membrane. This design enhances the pointing stability and the overall reliability of the spacecraft.⁴

The Kepler photometer is a simple single purpose instrument. It is basically a Schmidt telescope design with a 0.95-meter aperture and a 105 square deg (about 12 degree diameter) field-of-view (FOV). It is pointed at and records data from just a single group of stars for the three and one-half or more year duration of the mission. The photometer is composed of just one "instrument," which is, an array of 42 CCDs (charge coupled devices). Each 50x25 mm CCD has 2200x1024 pixels. The CCDs are read out every three seconds to prevent saturation. Only the information from the CCD pixels where there are stars brighter than about R magnitude of 16 is recorded. (The CCDs are not used to take pictures. The images are intentionally defocused to 10 arc seconds to improve the photometric precision.) The data are integrated for 30 minutes. The instrument has the sensitivity to detect an Earth-size transit of an $m_v=12$ G2V (solar-like) star at 4 sigma in 6.5 hours of integration. The instrument has a spectral bandpass from 400 nm to 850 nm. Data from the individual pixels that make up each star of the 150,000 main-sequence stars are recorded continuously and simultaneously. The data are stored on the spacecraft and transmitted to the ground about once per month.⁵

An Earth-trailing heliocentric orbit with a period of 372.5 days provides the optimum approach to meeting of the scientific objectives. In this orbit the spacecraft slowly drifts away from the Earth and is at a distance of 0.5 Astronomical Unit (AU) (worst case) at the end of four years (Figure 3).

Another advantage of this orbit is that it has a very-low disturbing torque on the spacecraft, which leads to a very stable pointing attitude. Not being in Earth orbit means that there are no torques due to gravity gradients, magnetic moments or atmospheric drag. The "largest" external torque then is that caused by solar pressure. This orbit also avoids the high radiation dosage associated with an Earth orbit, but from time to time is subject to solar flares. Telecommunications and navigation for the mission are provided by [NASA's Deep Space Network \(DSN\)](#) (Figure 3).⁶

The mission was designed to last at least 3.5 years to allow 3-4 transit detections of earth-size planets around sun-like stars. At least 3 transits were deemed necessary as part of validation/confirmation of a planet.

⁴ https://www.nasa.gov/mission_pages/kepler/spacecraft/index.html

⁵ https://www.nasa.gov/mission_pages/kepler/spacecraft/index.html

⁶ https://www.nasa.gov/mission_pages/kepler/spacecraft/index.html

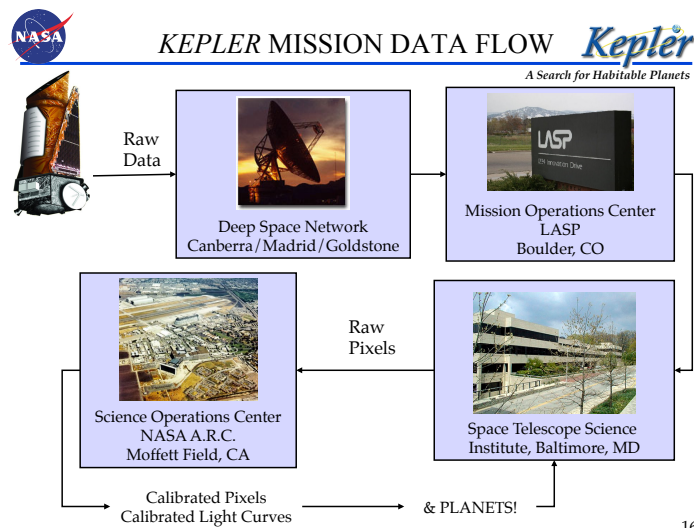


Figure 3: Kepler Data Flow

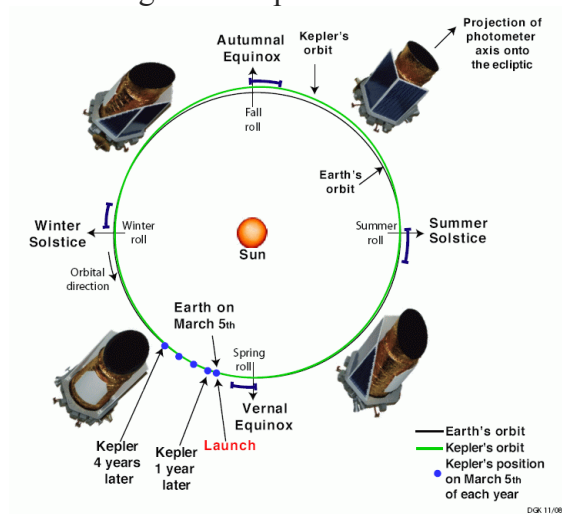


Figure 4: Kepler Orbit

5 RESULTS

Results from the mission have been outstanding. It is worthwhile to note the “before and after” images of the Kepler Field of View. Figure 6 shows the 3 known planets that were in Kepler’s Field of View (FOV) before it began its “planet-hunting” operations. The end of the Kepler baseline operations had found over 4,500 planet candidates, of which more 2,342 had been confirmed⁷. Of those, 50 had been determined to be Earth-or-near-Earth-size in the habitable zone of host stars. Figure 7 is a depiction of many of the Kepler candidate planet locations. In an interview with Kepler graphics and media personnel, it had become increasingly difficult to show locations of all the planet candidates because they were so numerous and it was becoming difficult to place “dots” on the FOV to represent every detected planet.⁸ This was a gratifying result for the Kepler team; it affirmed what many had believed, that planets were plentiful. Indeed, one of the general Kepler results that is often mentioned is that one can easily say that planets far outnumber stars.⁹

⁷ https://exoplanetarchive.ipac.caltech.edu/docs/counts_detail.html

⁸ Kepler Mission, NASA Ames Research Center (W. Stenzel) (updated)

⁹ Personal interview between author and Jessie Dotson, Kepler Mission Scientist, January 2018.

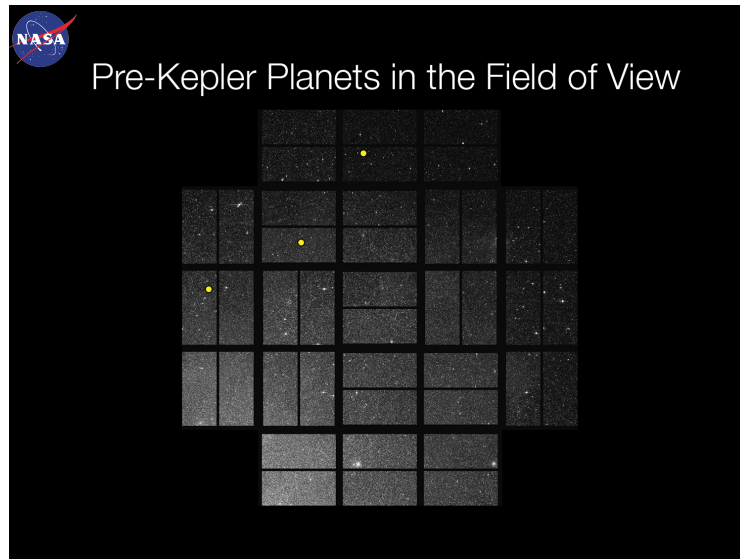


Figure 6: Kepler FOV (before Mission start)

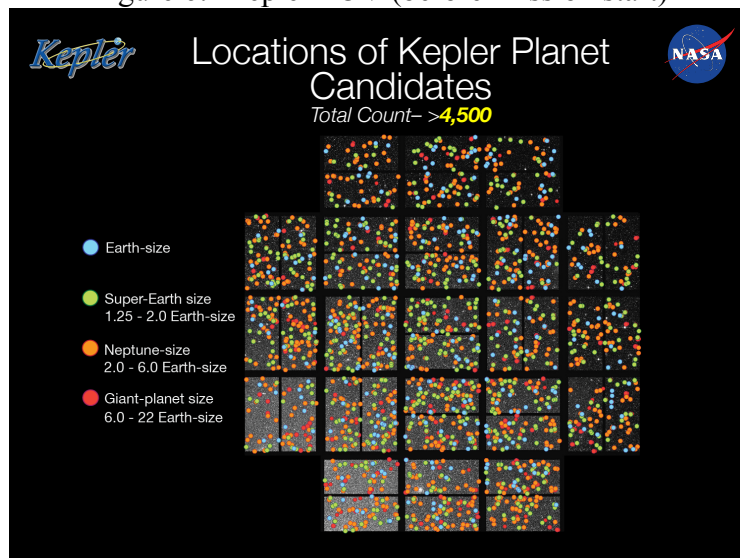


Figure 7: Kepler FOV with Kepler Planet Candidates

Let's take a macroscopic view of these discoveries. Scientists have binned the number of planets by "planetary systems". As you can see (Figure 8)¹⁰, most of the detections were for single planets orbiting a single star. There have been many detections of multi-planet systems, including the detection of two stars each hosting 8 planets. The Kepler data are, of course, biased. There were only 4 years of data collected in the baseline mission. Kepler would not have been able to detect more than one transit of planets with similar orbital patterns as Saturn, Jupiter, Uranus, or Neptune. Their orbital periods are just too long to allow that.

¹⁰ <https://www.nasa.gov/image-feature/ames/planetary-systems-by-number-of-known-planets>
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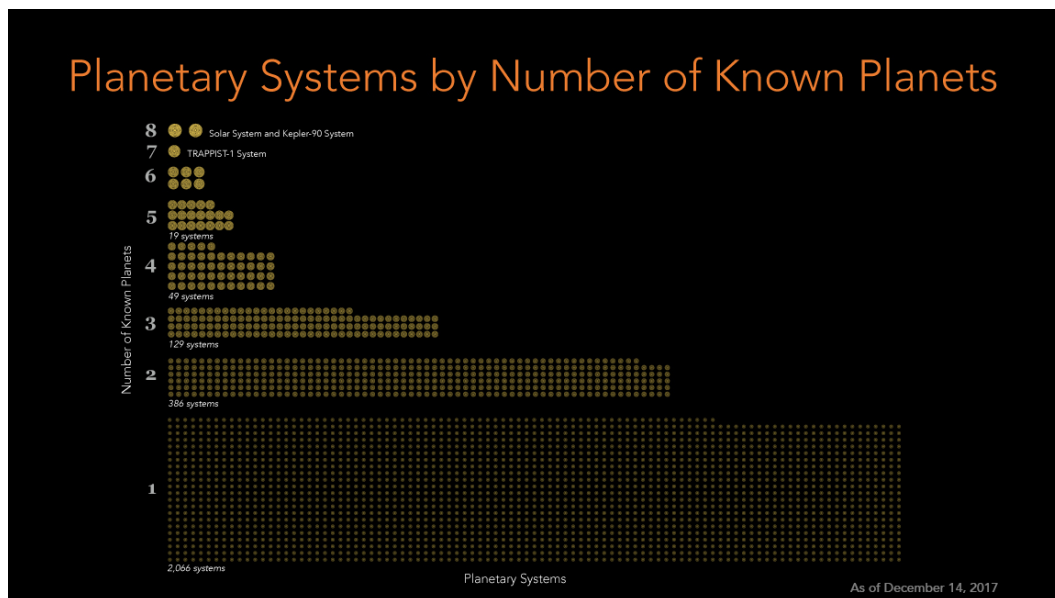


Figure 8: Planetary Systems by Number of Known Planets

Credit: NASA/Ames Research Center/Wendy Stenzel and The University of Texas at Austin/Andrew Vanderburg

Of course the primary objective has been to find earth-size planets, particularly those in the habitable zone of the host stars. The habitable zone, for Kepler's purpose, was defined as that region around the star that was neither too hot, nor too cold, so that water may pool on the surface of the planet (Figure 9)¹¹. Results have been rewarding. The first planet smaller than Earth, Kepler-20e, was discovered in December 2011 orbiting a Sun-like star slightly cooler and smaller than our sun every six days. But it is scorching hot and unable to maintain an atmosphere or a liquid water ocean. Kepler-22b was announced in the same month, as the first planet in the habitable zone of a sun-like star, but is more than twice the size of Earth and therefore unlikely to have a solid surface. Kepler-186f was discovered in April 2014 and is the first Earth-size planet found in the habitable zone of a small, cool M dwarf about half the size and mass of our sun. Kepler-452b is the first near-Earth-Size planet in the habitable zone of a star very similar to the sun.¹² Figure 10 is an artist's depiction of those first earth-size worlds found by Kepler.¹³

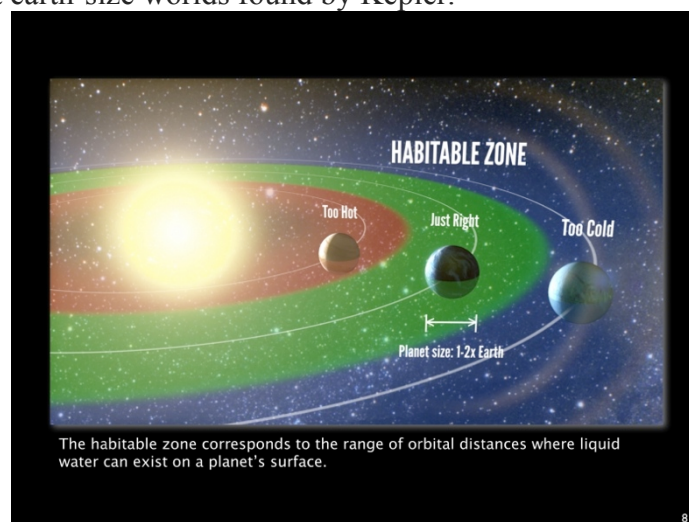


Figure 9: Habitable Zone

¹¹ Courtesy: G. Marcy

¹² <https://www.nasa.gov/ames/kepler/searching-for-habitable-worlds>

¹³ <https://www.nasa.gov/ames/kepler/searching-for-habitable-worlds>, depiction courtesy W. Stenzel
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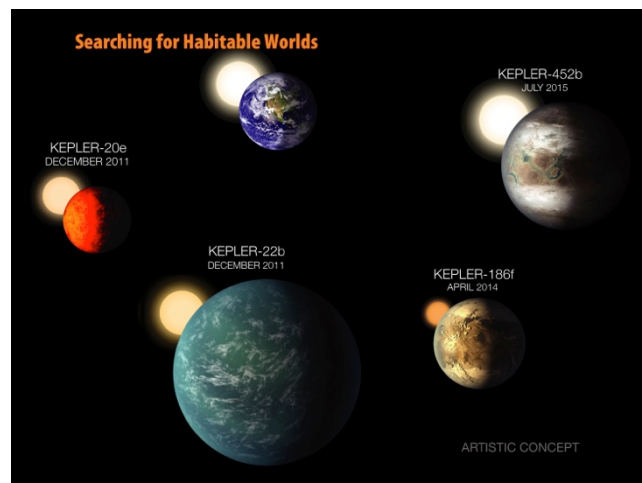


Figure 10: Searching for Habitable Worlds (Kepler)

A few more words about Kepler-22b are warranted. Announced on December 5, 2011, it was the FIRST habitable zone planet announced by the Kepler team, and the first confirmed habitable zone planet to be announced from any team. As it was the first, the team wanted to be sure the planet was, indeed, confirmed. As noted in the paper that was released confirming the finding: “[t]he system passes a battery of tests for false positives, including reconnaissance spectroscopy, high-resolution imaging, and centroid motion. A full BLENDER analysis provides further validation of the planet interpretation by showing that contamination of the target by an eclipsing system would rarely mimic the observed shape of the transits. The final validation of the planet is provided by 16 radial velocities obtained with HIRES on Keck 1 over a one year span.”¹⁴

A more recent and intriguing find from Kepler was the Kepler 452b. “[Measured at approximately 1.6 Earth-radii], the planet was found in the habitable zone of a G2 star at a mean separation of 1.05 AU. It represents the closest analog to the Earth–Sun system discovered in the *Kepler* data set to date with respect to the orbit and spectral type of the host star. Moreover, the small radius of this planet provides a reasonable chance between 49% and 62% that it is rocky, although in this case it is unlikely to have an iron core of significant mass.”¹⁵

So, with discoveries of planets in the Kepler data of planets designated as Kepler 22b, and Kepler 452b, the team had found super-Earth size and near-Earth size planets orbiting Sun-like stars at Earth-like distances. The most recent update to the NASA Kepler webpage shows that 30 small habitable zone planets have been confirmed¹⁶. With those discoveries, the subject of occurrence rates (what fraction of stars in our Milky Way Galaxy harbour Earth-size planets in the stars’ habitable zone comes to the fore.

Some papers have been submitted for consideration on occurrence rates. Christopher Burke and team published, in 2015, an analysis for “Terrestrial Planet Occurrence Rates for the Kepler GK Dwarf Sample”¹⁷. In a discussion with Jessie Dotson, Kepler Mission Scientist, the “occurrence rate” for small habitable zone planets remains under investigation, and, that analysis in that area continues. Evidence does indicate that planets outnumber stars; evidence indicates each star has at least one orbiting planet; and other small, habitable-zone Earth-and-near-Earth-size planets do exist.

¹⁴ <https://arxiv.org/abs/1112.1640>

¹⁵ <http://iopscience.iop.org/article/10.1088/0004-6256/150/2/56/meta#aj515345s11>

¹⁶ https://www.nasa.gov/mission_pages/kepler/main/index.html

¹⁷ <https://arxiv.org/abs/1506.04175v1>

6 The K2 Mission

In July 2012, and in May 2013, Kepler suffered two successive reaction wheel failures. Part of the spacecraft's Attitude Determination and Control Subsystem, the spacecraft's four reaction wheels were necessary to maintain precise pointing for the spacecraft's Planet-Hunting mission. However, the Kepler team was able to recover the mission, using an ingenious concept to control the spacecraft with the two remaining reaction wheels, and solar wind pressure against the spacecraft (Figure 11). After one year offline, and after extensive testing, the Kepler K2 mission was approved with a repurposed vision and commenced in May 2014.¹⁸ As noted in the approval, the approval provided two years of funding for the K2 mission to continue exoplanet discovery, and introduced new scientific observation opportunities to observe notable star clusters, young and old stars, active galaxies and supernovae.¹⁹ However, the concept of operations had to change. Though the team was able to recover the mission, and "repurpose" it, Kepler could no longer point at the original target FOV in the Cygnus constellation. Using the solar wind pressure, Kepler could point along the ecliptic plane, and had to be repointed every 85-or-so days to avoid sunlight entering the Kepler space telescope's barrel.

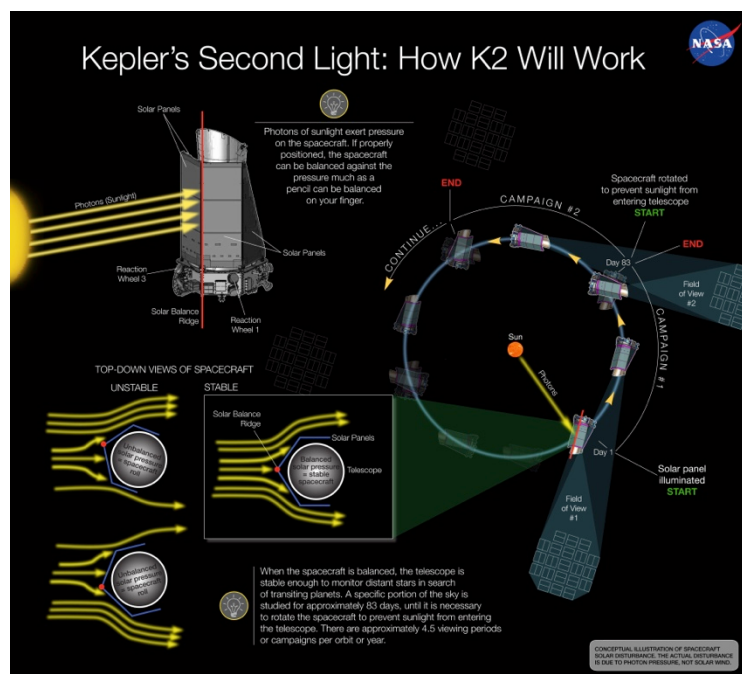


Figure 11: How K2 Will Work

Results have been outstanding from an exoplanet hunting perspective. The K2 mission has been extended beyond its original two-year extension and continues to date. With over 307 confirmed planets and 479 planet candidates identified, the mission is well on its way to potentially adding 1000 planet candidates to the mission's tally. As K2 exoplanet detections were made, astrophysics observations with K2 will include studies of young open clusters, bright stars, galaxies, supernovae, and asteroseismology.

7 The Impact of Kepler

¹⁸ <https://www.nasa.gov/content/ames/kepler-mission-manager-update-k2-has-been-approved>

¹⁹ <https://www.nasa.gov/content/ames/kepler-mission-manager-update-k2-has-been-approved>

The Kepler mission has had an incalculable impact on exoplanet science. The numbers of exoplanets discovered, by all means tabulated in Figure 12, have been largely attributed to Kepler. Kepler has discovered more exoplanets than all other exoplanets detections combined (Figure 12)²⁰.

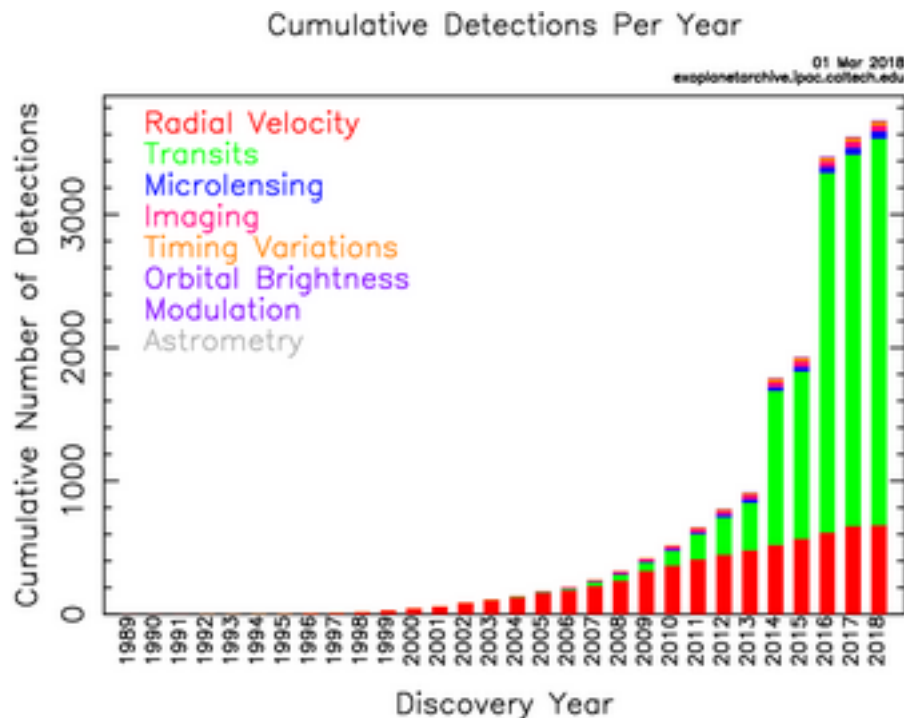


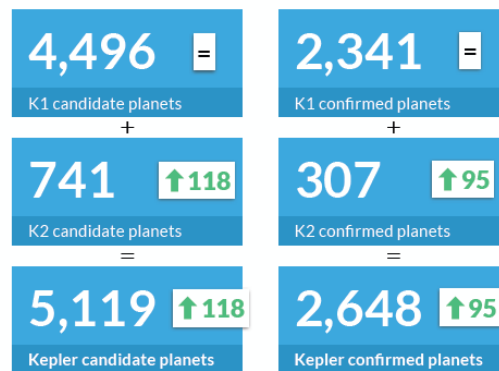
Figure 12: Cumulative Exoplanet Detections per Year

Fifty terrestrial-sized planets are reported from the Kepler data²¹. The NASA Exoplanet Archive also offers a “dashboard” for cumulative finds through March 2018 from both Kepler and the Kepler K2 missions (Figure 12a). Given that, Kepler team members offer an occurrence rate for terrestrial-sized, habitable-zone planets from the Kepler data, but also add a caution that issues and biases still exist in the calculation. Those issues/biases include pipeline detection efficiency, astrophysical reliability, and imperfect stellar information. With those in mind, Jeff Coughlin reports that the occurrence rate for earth-size planets, in the habitable zone, across the Milky Way Galaxy, ranges between 2%-to-25%. That is a large number of “other Earths”, regardless of whether you pick the lower rate, or the higher.

²⁰ <https://exoplanetarchive.ipac.caltech.edu/exoplanetplots/>

²¹ <https://arxiv.org/pdf/1710.06758.pdf>, page 32.

Exoplanets Dashboard Mar 2018



Source: NASA Exoplanet Archive

Figure 12a: Exoplanets Dashboard

8 The Way Ahead

The Kepler baseline mission ended in May 2013, after the failure of a second reaction wheel. Ingenuity allowed Kepler to continue as a “repurposed” Kepler K2 mission, still able to find exoplanets while providing valuable astrophysics and stellar physics discoveries. Yet, the Kepler spacecraft is on the verge of its end-of-life, when all remaining propellant on the spacecraft will be exhausted. However, another exo-planet mission, the Transiting Exoplanet Survey Satellite (TESS) will launch in 2018 to continue the survey for exoplanets. TESS will be an all-sky survey, in our own stellar neighbourhood. TESS will discover thousands of exoplanets in orbit around the brightest stars in the sky. In a two-year survey of the solar neighborhood, TESS will monitor more than 200,000 stars for temporary drops in brightness caused by planetary transits. This first-ever spaceborne all-sky transit survey will identify planets ranging from Earth-sized to gas giants, around a wide range of stellar types and orbital distances. No ground-based survey can achieve this feat.²² Following that, the James Webb Space Telescope (JWST) is scheduled to launch in 2019. Webb will tell us more about the atmospheres of extrasolar planets, and perhaps even find the building blocks of life elsewhere in the universe²³. Still yet, concepts are being developed for starshade technologies for future telescopes.

The starshade (also known as an external occulter) is a spacecraft that will enable telescopes in space to take pictures of planets orbiting faraway stars. The starshade is designed to fly in front of a telescope and block the immense glare from a star’s light before it enters the telescope, allowing the planet’s reflected light to pass through and be collected (Figure 13)²⁴.

²² <https://tess.gsfc.nasa.gov>

²³ <https://jwst.nasa.gov/science.html>

²⁴ <https://science.nasa.gov/technology/technology-stories/starshade-enable-first-images-earth-sized-exoplanets>

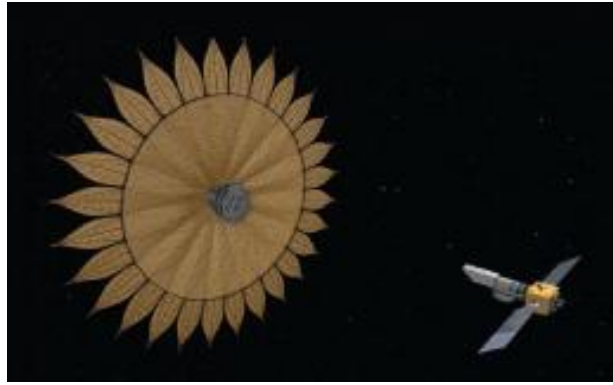


Figure 13: Artist concept for Star-shade telescope

TESS and the James Webb Space Telescope are real and the near-horizon for NASA missions. A star-shade technology is in development. Other missions are in conceptual stages. The Large UV/Optical/IR Surveyor (LUVOIR) is a concept for a highly capable, multi-wavelength space observatory with ambitious science goals (Figure 14)²⁵. This mission would enable great leaps forward in a broad range of science, from the epoch of reionization, through galaxy formation and evolution, star and planet formation, to solar system remote sensing. LUVOIR also has the major goal of characterizing a wide range of exoplanets, including those that might be habitable - or even inhabited.

LUVOIR is one of four Decadal Survey Mission Concept Studies initiated in Jan 2016. The study was planned to extend over three years and to be executed by the Goddard Space Flight Center, under the leadership of a Science and Technology Definition Team (STDT) drawn from the community.²⁶

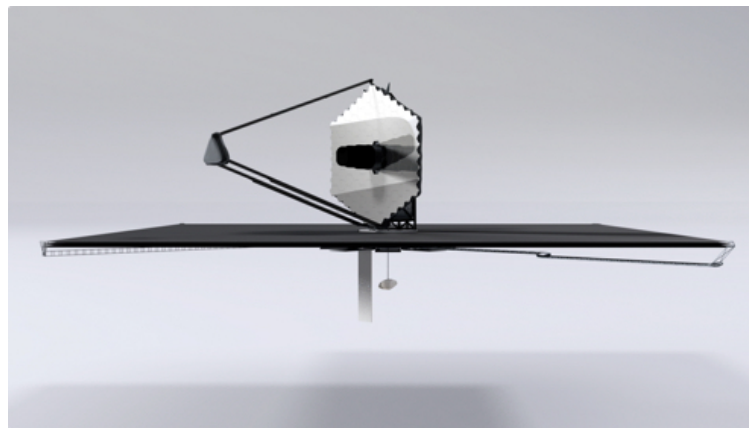


Figure 14: LUVOIR (Artist concept)

9 Conclusions

Kepler's profound impact on exoplanets science and astronomy will go on for years. Though fashioned for a 3.5-year baseline mission, the spacecraft has survived the loss of two reaction wheels and 3 of its 21 science CCD modules since its launch in March 2009. Despite those malfunctions, the Kepler mission has returned many terabytes of precise photometric data on many stars, galaxies, and clusters that will give astronomers a treasure-trove of data to exploit for many years to come. Kepler's propellant tanks will empty this year, and the Kepler spacecraft will be decommissioned. But the mission will live on, thanks to the vast amount of data it collected and

²⁵ <https://asd.gsfc.nasa.gov/luvoir/design/>

²⁶ <https://asd.gsfc.nasa.gov/luvoir/>

remains to be analysed. One of its parting gifts was a photo of Earth, taken by Kepler, at a distance of 94 million miles (Figure 15)²⁷.

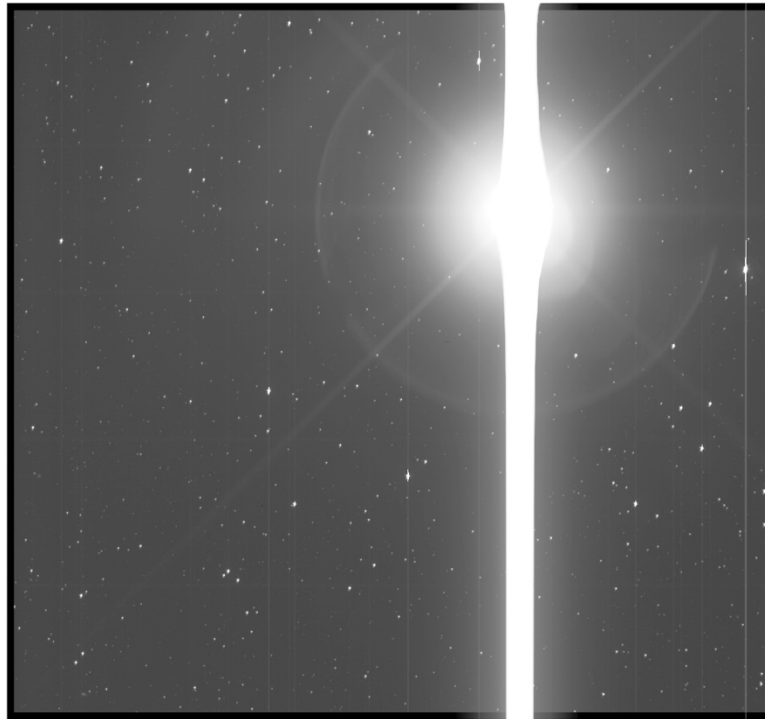


Figure 15: Earth, as seen by Kepler, December 10, 2017

10 REFERENCES

[1] https://www.nasa.gov/mission_pages/kepler/main/index.html.

²⁷ <https://www.nasa.gov/image-feature/ames/earth-is-a-beaming-beacon-in-kepler-s-eyes>
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